Ensuring the safety of geotechnical works in the historical center of St. Petersburg in soft soils using interactive monitoring

Garantizar la seguridad de los trabajos geotécnicas en el centro histórico de San Petersburgo en suelos blandos mediante monitoreo interactivo

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ABSTRACT: The article presents the results of the practical experience of reconstruction on weak soils in the historical center of St. Petersburg using a new technique for protecting old buildings from any technological impact. Here, the important conditions are operational control tools and a system for monitoring the condition of the structure, the presence of an active numerical model to assess changes in the stress-strain state in the soil mass and structures during construction. Careful attention to monuments by tracking spatial deformations of the building ensures a high quality risk assessment at the stage of project development. The presented method of interactive monitoring is based on scanning systems, which creates a digital duplicate of the object, which allows you to get a complete picture of deformation, including defects and cracks in the structure during construction work. The high accuracy of modeling and monitoring tools allows for operational control of the stress-strain system.

KEYWORDS: soft soil, monuments, deformations of the building, interactive monitoring, scanning system, the digital twin of the object.

1 INTRODUCTION.

Active construction activity in historical parts of megacities such as St. Petersburg requires close attention to ensuring the safety of any geotechnical work in relation to buildings adjacent to the construction site, and first of all, to historical buildings - architectural monuments.

It should be noted that in many ways the category of geotechnical complexity of works on the construction of foundations and underground structures, including the adaptation of architectural monuments to the modern use with the development of underground space, is determined by the soil conditions of the historical parts of St. Petersburg.

A feature of the engineering and geological structure of the historical districts of the city is the presence of a large thickness of weak dusty clay soils in a water-saturated state. Such finely dispersed watered soils include: bulk soils, powdery sands and sandy loams, layered and ribbon loams, which are fluid or fluid in their consistency. As a rule, such soils do not allow responsible structures with heavy loads to be built on them without pile foundations and without the use of special geotechnical measures to stabilize soil massifs in order to increase their stability and bearing capacity.

Over the past 20 years, experience has been accumulated and analyzed in the application of various technologies for the installation of piles, enclosing structures and strengthening the foundation soils. At the same time, significant material expenses were spent on measures aimed at ensuring the safety of historical buildings. The construction conditions in the central areas of the city require a practical absence of impact from new construction - additional precipitation should not exceed 0.5 cm. On weak thixotropic clay soils, any construction work leads to the risk of additional precipitation of existing buildings. An analysis of the research of the staff of the Department of Geotechnics of St. Petersburg State University of this issue shows that technological influences during construction, for example, even when installing sheet pile fencing by static immersion, can lead to additional deformations of the bases of neighboring structures, which many times exceed the permissible values (Dalmatov B.I. 1986,2000; Ulitsky V.M. 2003, Ilyichev V.A. 2012, Mangushev R.A. 2017, 2019;, Shulyatyev O.A. 2016).

Currently, new technologies have been developed and applied in the development of underground space, which allows solving a number of tasks taking into account the design requirements and characteristics of soil conditions (Ulitsky V.M. 1995, Konovalov P.A. 2000, Bogov S.G. 2005, Ermolaev V.A. 2008, Mangushev R.A. 2017, 2018).

At the same time, it is obvious that even the most advanced technological methods must be adapted to local geotechnical conditions.

An example of such an adaptation can be considered the accumulation of research experience on the construction of pit fences using the trench "wall in the ground" method and from bored piles, immersion of the sheet pile by static and vibration method. Within the framework of these studies, criteria for the technological performance of work were determined, such as speed, sequence of operations and calculation method for a preliminary analysis of the safety of work (Mangushev R.A. & Nikiforova N.S. 2017). At the same time, in the conditions of weak thixotropic clay soils of St. Petersburg, the modulus of deformation of which can be E = 2 ... 3 MPa, the role of control of technological operations increases.

In this regard, the role of monitoring the behavior of the reconstructed security facility, surrounding buildings and tools for operational control of its structures is being strengthened. Traditional monitoring systems allow you to control only certain observation points on the structures of objects. At the same time, an increase in their number will lead to a significant increase in the cost of geodetic works and their time. The use of scanning systems to obtain a point cloud, as well as a digital double of an object, is a modern and useful tool that allows you to present a complete picture of the deformation of a structure, including the presence of defects and cracks in the structure.

In addition, each building of historical development requires an individual approach both in design and monitoring. The use of laser scanning systems in interaction with scanning drones, and traditional methods for assessing movements and forces in the structure, allow us to take into account all the details of a unique object when monitoring its safety.

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In order for the scanning in the monitoring system to meet the requirements for measurement accuracy, it was necessary to develop a survey methodology that includes new types of geodetic signs (spherical prisms), the use of unmanned aerial vehicles to build an additional point cloud, as well as a point cloud processing technique. The prospects of using high-precision spatial monitoring of buildings, including architectural monuments, allows us to talk about the introduction of a new tool for monitoring the condition of building structures and risk analysis during their reconstruction or new construction, and near them. The data on the implementation of the described studies are confirmed by the successful implementation of the construction of an underground space on weak soils in the historical districts of St. Petersburg.

1. GENERAL INFORMATION

This article considers the solution of a complex engineering problem of the underground space arrangement carried out as part of restoration work to adapt for modern use the museum and exhibition complex of the western part of the palace of the object of cultural heritage of federal significance "The Palace of D.P. Naryshkin (Shuvalova S.L.), built in 1790.

The dimensions of the restored part of the building corresponded to historical measurements and amounted to 18.37 x 29.35 m. (Fig.1) The basement, necessary for the purpose of adapting the structure to modern use, had a design depth of 4.37 m from the surface of the courtyard.

The main building of the palace has a complex shape with two courtyards and is a one- to three-storied brick building with a basement and an attic. In 2013, it was initially reconstructed to fit it into a museum building. The foundations of the building are ribbon, rubble. During the inspection, wooden sills and piles of logs were found under the rubble masonry. The condition of the wood of the logs and piles is satisfactory, without signs of rotting. In 2006-2011, the foundations were reinforced with drilling-injection piles, as well as cementation of rubble masonry. The exterior and interior walls of the palace building are made of baked clay bricks on lime-sand mortar. The thickness of the outer walls is 840...1280 mm.

When analyzing the geotechnical situation, the zone of influence from the proposed works was determined. The buildings of the surrounding buildings fell into this risk zone, which were multi-stores stone buildings with a height of 3 to 6 floors built in the late XVIII, early and mid-XIX centuries. The foundations of these buildings, according to the materials provided by the technical inspection materials, are made of rubble masonry on lime-sand mortar; wooden beds with partial damage to the surface layer of wood by putrefactive destruction were found under part of the buildings. Cracks of different opening widths (up to 5 mm) are marked in a number of walls adjacent to the construction site.

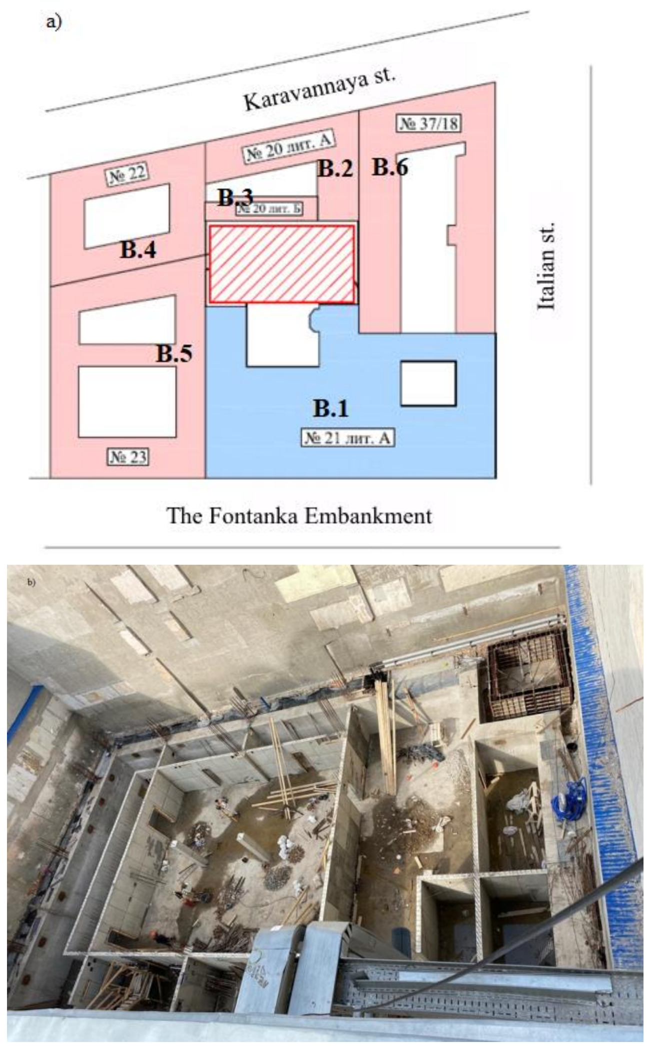


Fig.1. a- the constructive scheme of the "Palace of D.P. Naryshkin (S.L. Shuvalova)". The blue color indicates a building whose reconstruction has been completed; the pink color indicates the buildings of the surrounding development that fall into the zone of influence of the construction of the wing; the hatching indicates the construction site of a new wing with an underground space; b – the type of the completed underground space

Table 1 shows the values of the categories of technical condition of the reconstructed and neighboring buildings and the normative permissible values of their additional precipitation.

Table 1. Values of the category of technical condition of buildings and limit values of additional precipitation according to normative requirements

The main indicators for the assessment of buildings	B.1	B.2, B4	B.3, B6	B.5
Technical condition category	II	III	II	IV (III)
Maximum permissible additional precipitation, mm	15	5	10	0 (5)*
The relative difference in precipitation	0,0009	0,0004	0,0006	0 (0,0004)

Notes: B.1 – the preserved part of Building №21 lit. A along the Fontanka River embankment; B.2 – Building №20 lit. A along Karavannaya St.; B.3 - Building 20 lit. B along Karavannaya Str.; B.4 – Building № 22 along Karavannaya Str.; B.5 - Building № 23 along along the Fontanka River embankment; B.6 – Building 37/18 on Italianskaya Str.

Taking into account the overhaul and assignment of the building to a technical condition category not lower than III before the reconstruction of building №. 21 lit. A along the Fontanka River embankment.

2. FEATURES OF THE ENGINEERING AND GEOLOGICAL CONDITIONS OF THE SITE

The geological structure of the construction site locat ed in the central part of the city to the depth of the survey dri lling of 40.0 m involves postglacial (lake-marine), lake-glacial and glacial deposits of the quaternary stratigraphic complex, o verlain from the surface by a layer of asphalt and bulk soils [24]. Thus, the engineering and geological structure of the site is characterized by the following stratification (Fig.2):

Technogenic deposits (*tg* $_{IV}$) are represented by asphalt and bulk soils: medium-sized sands, less often sandy loams, with construction debris in the form of brick chips, wood chips, with a capacity of 1.85-3.0 m.

Deposits of lake-marine genesis (lm_{IV}) are represented by peat, blocked soils, loams and sandy loams flowing with layers of fluidplastic, with an admixture of organic substances, dusty sands of medium density, medium-sized loose sands, coarse and gravelly loose sands, loams and sandy loams flowing with layers of fluidplastic.

Upper quaternary deposits of glacial genesis (g_{III}) are represented by plastic sandy loams, dense gravelly sands, refractory loams with semi-solid interlayers, plastic sandy loams with semi-solid loam interlayers.

The Vendian deposits of the Kotlin horizon are represented by hard, dislocated and hard clays.

Fig.2. Characteristic engineering and geological section of the site of the restoration object

From a hydrogeological point of view, the site under consideration is characterized by the presence of one aquifer of groundwater confined to the bottom of man-made formations, a layer of lake-marine sandy and sandy loam soils and dusty-sandy layers in lake-glacial loams. This aquifer is non–pressurized with a free surface, its nutrition is carried out by infiltration of atmospheric precipitation. The groundwater level was recorded at depths of 1.0- 1.4 m from the level of the daytime surface. The normative and calculated values of soil characteristics are given in Table . № 2.

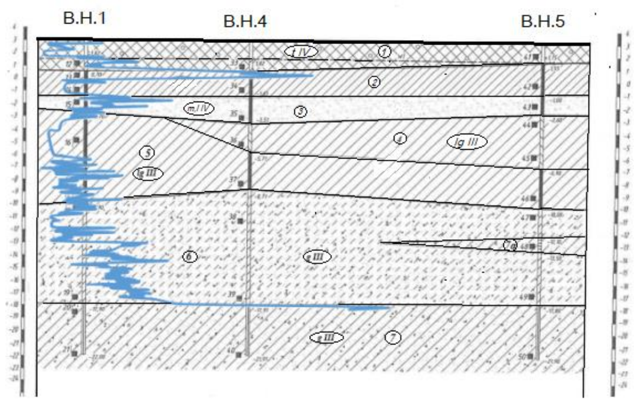


Table № 2.Normative and calculated values of soil characteristics

Name of the soil, Geologist. index	W I_L	γ, kN/m^3	E, MPa	φ, degr.	c, kg/cm^2
Bulk soils, t_{IV} [IGE 1]	0,23 0,13	19,6	-	-	-
Dusty plastic loams, m,l_{IV} [IGE 2]	0,84 3.09	14,8	2,5	4	0,05
Sandy loams are dusty, m,l_{IV} [IGE 2a]	0,24 0,69	19,0	8,0	16	0,12
The sands are gravelly, m,l_{IV} [IGE 3]	-	20,0	30,0	38	-
The sands are dusty with layers of peat, m,l_{IV} [IGE 3a]	-	20,0	22,0	29	0,03
Loam is heavy, soft-plastic, lg_{III} [IGE 4]	0,28 0,65	19,6	9,0	17	0,17
Loam is light and dusty, lg_{III} [IGE 4a]	0,32 1,21	19,1	5.5	10	0,08
loam is heavy and dusty, lg_{III} [IGE 5]	0,43 1,34	17,9	5,0	8	0,07
Sandy loam plastic with gravel, g_{III} [IGE 6]	0,19 0,56	21,0	9,5	23	0, 14

Loam is light and refractory, g_{III} [IGE 7]	0,16 0,40	21,8	12,5	18	0,23
The loam is powdery with gravel, g_{III} [IGE 7a]	0,18 0,20	21,4	15,0	21	0,30

According to the results of numerical modeling performed in the process of scientific and technical justification using the PLAXIS 3D software package (SPbGASU 2017, CJSC Geostroy 2018), the maximum calculated values of additional sediments of the monument building adjacent to the site of geotechnical work do not exceed the maximum permissible values established by regulatory documents, provided that preventive reinforcement of the foundations is performed buildings of the surrounding development before the start of any construction work.

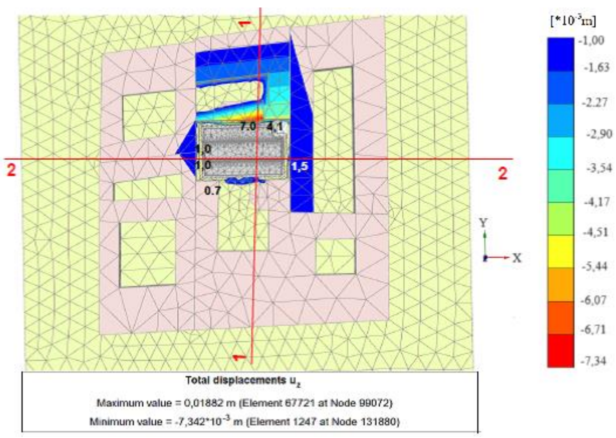


Fig. 3. Estimated zone of influence (zone of additional precipitation of 1.0 mm or more at the surface level) and additional settlements of existing buildings caused by the excavation

3. THE TECHNICAL CONDITION OF THE FOUNDATIONS OF NEIGHBORING BUILDINGS

In the immediate vicinity of the site of restoration work related to the adaptation of the building to modern use with the organization of underground space, there is an object of cultural heritage of regional significance – the I. Forsh Residential House, which is in disrepair. The first performance of Tchaikovsky's opera "Eugene Onegin", 1878, took place here in the music salon of Yu.F. Abaza (Geoizol 2015, Beskit 2017).

The building adjacent to the work site is a 2-5-storey building with two courtyards. The structural system of the building is a wall system with load–bearing longitudinal and transverse walls. According to the results of the technical inspection, cracks with an opening of 20 mm in the vaulted ceilings of the first floor, corrosion of beams, deflections of wooden beams with their sagging in the span along with filling were revealed (Fig.4). The floor structures are both in a limited working condition and in places in an emergency condition (Vasenin V.A. & Shashkin A.G 2022).

Fig.4. – View of a room with destroyed wooden floors (a) and a lighthouse installed on a crack for observation during geotechnical monitoring (b)

The technical condition of the foundations was assessed as limited-operable. Based on the materials of the survey of the foundations of the building, it was noted that the foundation in the upper part (basement) is made of red clay bricks of normal firing with dimensions of 260×120×65 mm. The walls of the building are plastered with lime-sand mortar with a thickness of 40 mm, both from the outside and from the inside. The measured humidity values of the brickwork of the wall exceeded the permissible values by 1.8-2.6 times and a capillary rise of moisture along the brickwork of the walls was recorded. The foundations of the building are ribbon, shallow laying on a natural foundation. The shape of the foundations of the longitudinal wall is trapezoidal-stepped; the transverse wall is rectangular. During the survey, the groundwater level in the pit was recorded below the level of the daytime surface by 2.09 m. At the same time, it was noted that the beds are located below the groundwater level.

The foundation below the brickwork is made of crushed limestone with a longitudinal stone size from 300x80 mm to 510x160 mm on lime-sand mortar, and from -1.53 m to -1.86 m (from the level of the day surface) – of granite stones with longitudinal dimensions from 200 mm to 380 mm on lime-sand mortar. A distinctive feature of this foundation is the presence at its base below the granite masonry of logs wooden beds with a diameter of 220 mm, which are laid on a layer of granite stones with a height of 140 mm (Beskit 2017). The wood is of a dark gray color, with the destruction of the macrostructure of the annual layers. The darkening of the upper layers of the root and its damage by rot to a depth of 1/4 of the cross section, that is, 25 mm, was recorded. The strength of the sill's wood has been reduced by about 50% compared to standard indicators. Signs of the development of wood-destroying (house) fungi have not been registered. The growth of a large number of bacteria, as well as single colonies of soil microscopic fungi *Penicillium sp*, has been recorded on nutrient media.

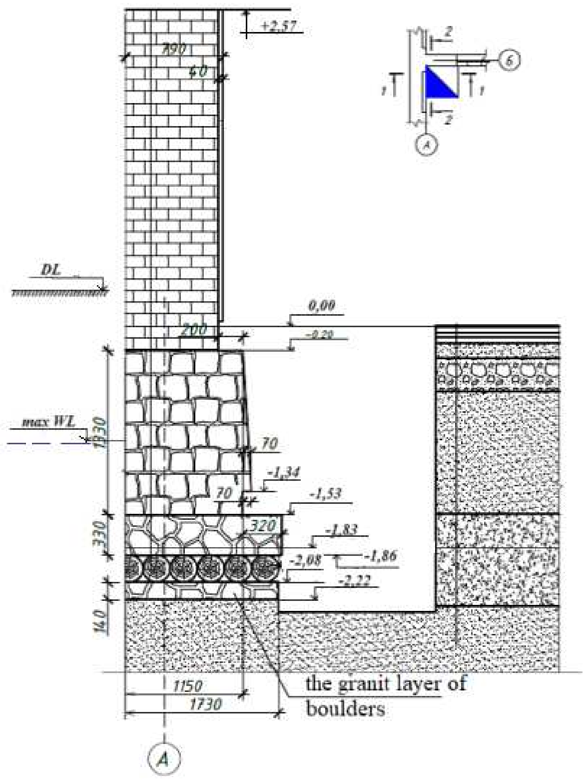


Fig.5. – Diagram of the foundation section based on the results of a technical inspection of the facility (Beskit 2017)

According to the results of the survey, a number of defects were recorded: leaching of masonry mortar in individual surface joints of the foundation masonry from 30 to 60 mm, and in the lower part of the foundation to the depth of the foundation sole – to the depth of the outer row (2-4 rows of masonry); lack of horizontal waterproofing between the wall and the foundation; lack of vertical waterproofing of brickwork in places of wall contact with soils. The base of the foundations, according to the results of field and laboratory studies of the soil, is a sandy loam. According to regulatory requirements, the building is classified as an emergency category of technical condition and additional deformations are not allowed.

4. SUBSTANTIATION OF METHODS OF PREVENTIVE REINFORCEMENT OF FOUNDATIONS

For the purposes of preventive strengthening of the foundations of existing buildings falling into the zone of influence of underground construction, various constructive and technological methods are used, among which one can distinguish (Polishchuk A.I. 2004):

- creation of a reinforced concrete jacket with increased rigidity of the foundation structure; - compensatory injection of injection solutions using cuff columns;
- injection fixing of soils using various injection solutions (grouting);
- fixing of soils at the base of reinforced foundations using high-pressure injection technology, called Jet Grouting in the technical domestic literature (Ulitsky V.M., Shashkin A.G., Shashkin K.G. 2010) ;
- the device of drilling piles with the transfer of part or full load from the reinforced building to them;
- creation of separation walls, geotechnical barriers and screens (Mangushev R.A.& Nikiforova N.S. 2017).

Injection and jet technologies are often used to stabilize soils in order to impart anti-filtration properties to soil arrays. The latter is especially important for the trouble-free constructi on of construction pits in water-saturated soils, in the vicinity of operated buildings. Currently, the construction industry uses a wide range of various geotechnical equipment, which has pr oven itself in practical use when strengthening foundations, cre ating dividing walls, geotechnical barriers and screens. Among them, domestic drilling complexes should be highlighted: drilli ng rigs SBG-PM3 "Sterkh", drilling walls SBU-100 (Fig.6), drilling rigs of the company "CST Malinin Group" Figaro 200, 300,400, etc.

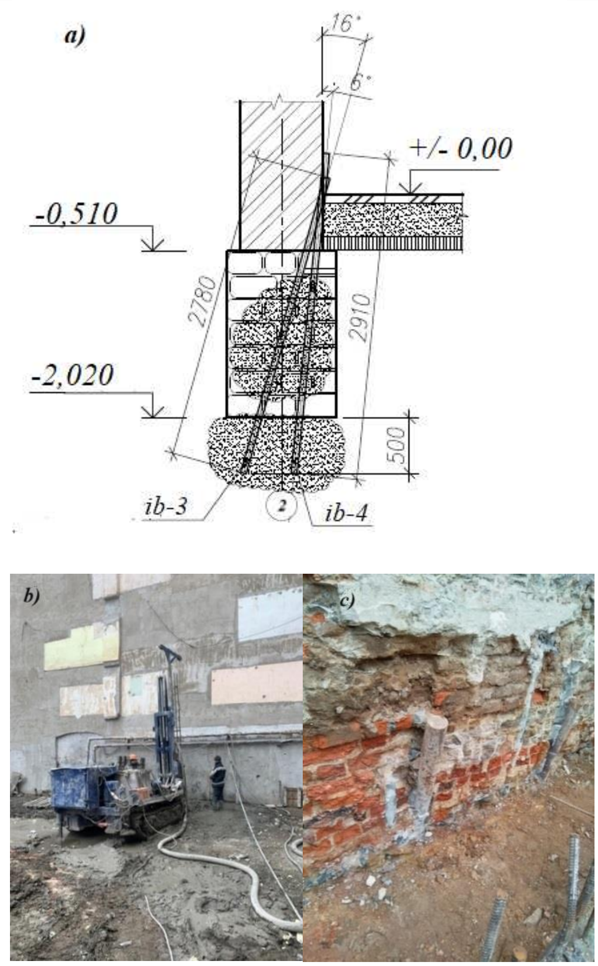


Fig.6. Drilling operations for injection reinforcement of foundations a – scheme for strengthening the foundations of neighboring ones; b- work on

strengthening the foundations of buildings; c - type of injection wells in the structure of the basement of the building

As an effective technology, injection technology usin g cuff tubes and double packers (obturators) should be highlig hted. For its application in various ground conditions, special designs of cuff tubes, double packers, as well as special clip s olutions with adjustable properties and using local Cambrian cl ays for the preparation of a clip solution, with which the locat ion of the cuff columns in the well is fixed (Ermolaev V.A. et al., 2008).

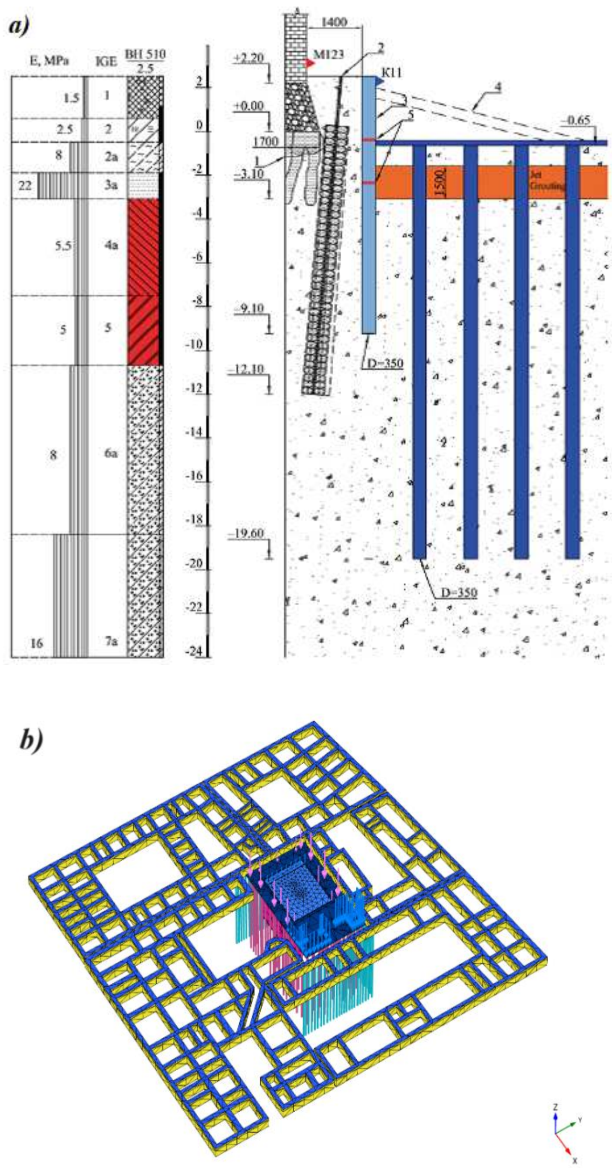


Fig. 7. The scheme of the underground part in the courtyard of the palace (a), the calculation scheme of the FEM for modeling the scheme of the underground part in the courtyard (b)

For the reconstruction object under consideration, when choosing the technology for strengthening the foundations of buildings, various technical solutions were considered, taking into account the need for gentle work. As a result, the following sequence of reinforcement of existing foundations was chosen:

- cementation fixation of the foundation body;
- strengthening of the "contact zone" foundation-soil by injection method;
- the device of reinforcement wells using cuff technology, the supply of solution to which is carried out during the excavation of the pit in case of additional deformations.

The purpose of the strengthening cementation work was to fill voids in the body and under the sole of the foundation, to consolidate the foundation soil with the creation of a soil-cement array under the foundations to improve the physical and mechanical characteristics of the foundation soil and prevent additional structural deformations in the form of deflections and cracks.

During the development of the excavation, work was additionally carried out on the construction of a fence made of bored piles with a length of 12 m and a cross section of 350 mm. Additionally, in order to reduce the impact of excavation on additional precipitation of adjacent buildings, which should be 1.5 m below the sole of existing foundations, a separation barrier (Jet key) was performed by jet cementation (Jet Grouting) with a width of 400 mm and a depth of 4.5 m, as well as a spacer deep diaphragm (Jet plate) with a thickness of 1.5 m, located 1 m deeper than the future bottom of the excavation. Drilling piles with a length of L = 14 m and a diameter of D = 450 mm were carried out under the slab of the projected underground structure, before the excavation began. The layout of the underground part in the courtyard of the palace is shown in Fig. 7a.

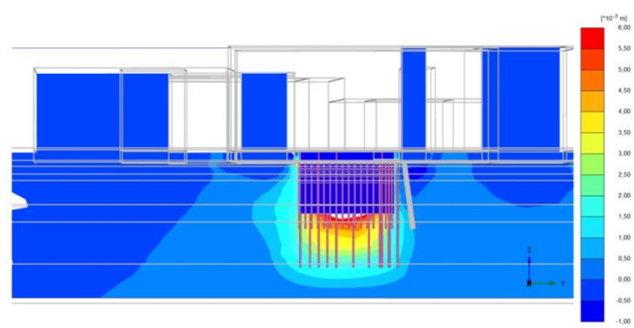


Fig.8. Characteristic sections - final additional deformations of the soil mass from the excavation. Total displacement u_z: $\Delta s_{max}=0{,}01760m$; $\Delta s_{min}= -1{,}216*10^{-3}$ *m*.

Variant calculations in the Hardening Soil Model of the Plaxis 3D software complex made it possible to justify the accepted design of the underground part of the reconstructed palace, as well as the technology of opening the pit, taking into account safety for the object itself and buildings of neighboring buildings (Fig.7b, 8) (Mangushev R.A., SPbGASU 2016).

5. FEATURES OF THE ORGANIZATION OF GEOTECHNICAL MONITORING AT THE RECONSTRUCTED FACILITY

During the implementation of the complex of reconstruction works, geotechnical monitoring was organized and performed with the determination of deformations of buildings of the surrounding development, control of the disclosure of existing cracks using crack gauges, observation of deformations of the binding beam of the excavation fence, control of the level of vibrodynamic effects on the structures of monument buildings located in the immediate vicinity of the construction site.

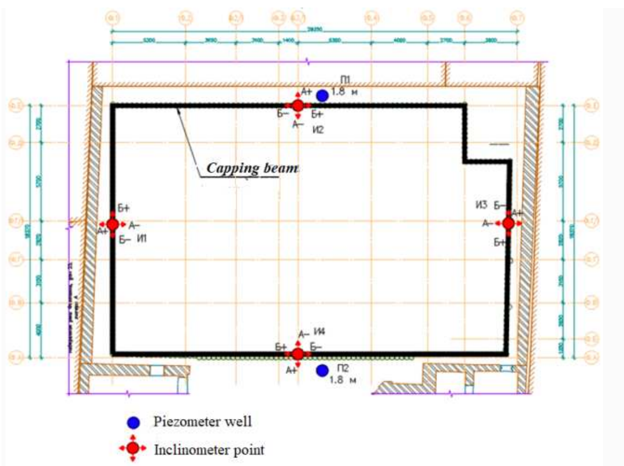


Fig.9. The layout of the inclinometric wells with the designation of the axes

In order to control the deformations of enclosing structures during excavation of the pit, inclinometric wells were regularly monitored, which were located on all sides of the pit (Fig. 9). Typical results of measurements of deformations of enclosing structures using inclinometers are shown in Fig. 10.

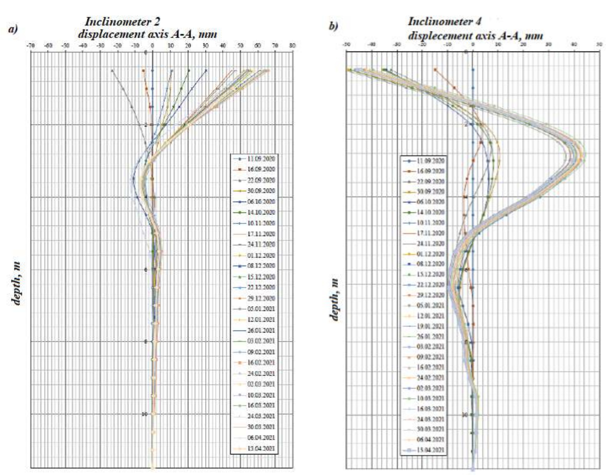


Fig.10 . Results of measurements of deformations of enclosing structures by inclinometric wells № 2 (a) and № 4 (b)

Regular piezometric studies of observation wells were an important component in predicting deformations of buildings in the surrounding area and identifying the effect of construction water reduction during excavation work on the position of the groundwater level around the construction site (Fig. 10).

The measured values of the precipitation of the reconstructed and neighboring buildings turned out to be comparable with those predicted by the results of numerical calculations and did not exceed the values of the maximum permissible deformations for buildings of the corresponding category of technical condition, which confirmed the validity of the accepted methods of design and construction in conditions of dense urban development (Fig. 11, Table 3).

Fig. 11. View of a part of an arranged excavation with an angular spacer system

Table №3. Comparison of calculated and measured values of settlements of surrounding buildings

Construction, Building	$S_{calc,}$ mm	S_{u} , mm	S_{fact} (April 2021) mm
B.1	3,8	10	5
B.2	4,7	5	5
B.3	5,2	10	6
B.4	3,9	5	2
B.5	3,9	5	4
B.6	4,6	5	4

The use of total station methods in conjunction with 3D laser scanning made it possible to expand the volume of controlled parameters during geotechnical monitoring. To this end, a Program was developed that included continuous online monitoring of the following additional parameters: • crack opening width; • relative deformations; • rolls. Examples of the results of laser scanning and orthophotography are shown in Fig. 12 and 13.

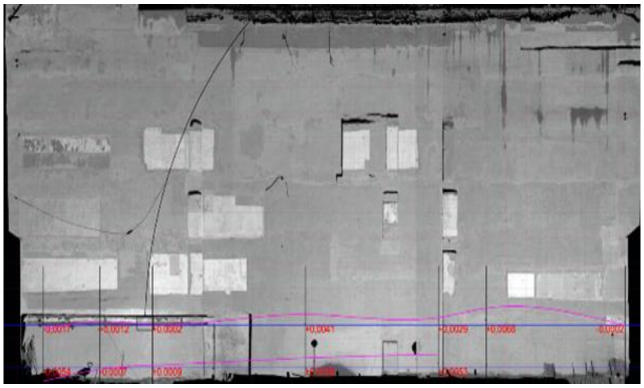


Fig.12. The results of laser scanning - monitoring of vertical deformations for 6 days, performed by 3D scanning of the field of points (the values of deformations are presented in meters). The pink line characterizes the magnitude and direction of the deformations. The blue line indicates the location levels of the wall geodetic stamps.

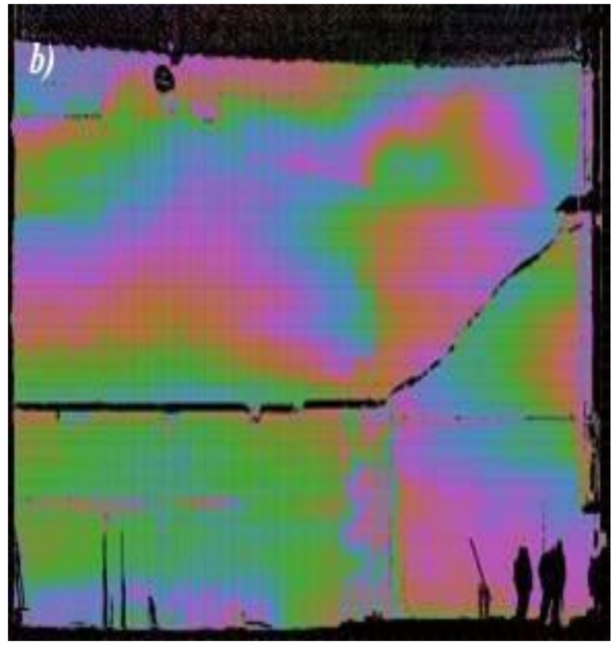
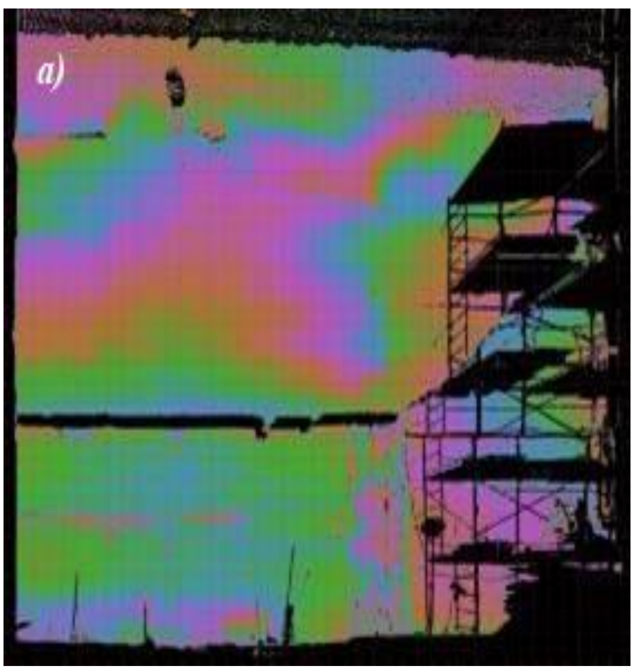


Fig.13.The results of the orthophotoplane survey (zero count) (a) and the first cycle (1 month after zero count) (b)



6. CONCLUSIONS

As the main conclusion from the work and research carried out, it can be said that when performing engineering works to adapt monument buildings to modern use with the development of underground space in the built-up part of the city, the emerging risks of negative impact should be predicted through geotechnical justification, taken into account in the design decision and provided with scientific and technical support for restoration work and safety control from the sides of geotechnical monitoring.

The geotechnical justification, including variant calcu lations, makes it possible to justify the optimal designs of the underground part of the reconstructed palace and the technolog y of opening the excavation, taking into account the safety of the object itself and the neighboring buildings

Scientific and technical support of construction or reconstruction, including comprehensive monitoring of the object and buildings of neighboring buildings using geodetic and optical methods, inclinometers and piezometers, vibrometric observations and crack opening monitoring confirms the reasonable choice of safe structural and technological methods for the construction of the underground part of the structure.

An analysis of the practical experience of construction in the historical center of St. Petersburg shows that the implementation of preventive reinforcement of the foundations of existing buildings falling into the zone of influence is often a condition for safety, reliability and successful implementation of the construction process. In such circumstances, the start of geotechnical monitoring should be scheduled in advance, preferably two months before any construction work.

The measured values of the precipitation of the reconstructed and neighboring buildings turned out to be comparable with those predicted by the results of numerical calculations and did not exceed the values of the maximum permissible deformations for buildings of the corresponding category of technical condition, taking into account the status of cultural heritage objects.

The use of total station methods in conjunction with 3D laser scanning made it possible to expand the volume of controlled parameters during geotechnical monitoring.

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