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Control of technological processes during underground construction in the historical centre of megacities in weak soils using interactive geotechnical monitoring

Contrôle des processus technologiques lors de la construction souterraine dans le centre historique des mégapoles dans des sols faibles à l'aide d'une surveillance géotechnique interactivedu

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ABSTRACT: The development of historical cities naturally consists in the development of underground space. The article considers an integrated approach to the preservation of buildings - monuments on the example of the city of St. Petersburg, which has a large capacity of weak soils in its geological structure and a significant building area, which is a World Heritage Site protected by UNESCO. The article analyzes the experience of using various geotechnologies to minimize the impact of underground construction on the surrounding buildings. The high role of geotechnical monitoring for the preservation of monuments located near the site of underground construction is noted. The use of modern laser scanning systems and traditional methods of assessing deformations of buildings allow us to take into account the features of a unique object during monitoring. Prospects for the use of high-precision spatial monitoring of architectural monuments suggest the introduction of a new tool for monitoring the state and risk analysis of historical heritage. 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 the city of St. Petersburg.

RÉSUMÉ: Le développement des villes historiques consiste naturellement en l'aménagement de l'espace souterrain. L'article considère une approche intégrée de la préservation des bâtiments - monuments sur l'exemple de la ville de Saint-Pétersbourg, qui a une grande capacité de sols faibles dans sa structure géologique et une zone de construction importante, qui est un site du patrimoine mondial protégé par l'UNESCO. L'article analyse l'expérience de l'utilisation de diverses géotechnologies pour minimiser l'impact de la construction souterraine sur les bâtiments environnants. Le rôle important de la surveillance géotechnique pour la préservation des monuments situés à proximité du site de construction souterraine est noté. L'utilisation de systèmes de balayage laser modernes et de méthodes traditionnelles d'évaluation des déformations des bâtiments nous permet de prendre en compte les caractéristiques d'un objet unique lors de la surveillance. Les perspectives d'utilisation de la surveillance spatiale de haute précision des monuments architecturaux suggèrent l'introduction d'un nouvel outil de suivi de l'état et d'analyse des risques du patrimoine historique. Les données sur la mise en œuvre des études décrites sont confirmées par la mise en œuvre réussie de la construction d'un espace souterrain sur des sols faibles dans les quartiers historiques de la ville de Saint-Pétersbourg.

Keywords: Additional deformations; historical building; geotechnical monitoring; geotechnics; plaxis.

1 INTRODUCTION

The development of historical cities naturally consists in the development of underground space. Consider the option of creating predominantly pedestrian streets, while developing transport infrastructure under existing roads, canals, buildings. Using the example of a city with a large capacity of weak soils and widespread existing buildings in the status of objects of cultural significance, geotechnical construction involves the study of not only complex soils, but also the structures of palaces and monasteries built hundreds of years ago. Under these conditions, over the past 10 years, experience has been accumulated and analyzed in the application of various technologies for the construction of piles, enclosing structures and strengthening the foundation soils (Mangushev and Nikiforova, 2017).

At the same time, significant expenditures of the construction budget were spent on measures aimed at ensuring the safety of historical buildings. The laws of construction in such areas require a practical lack of impact from new construction. So, the additional sediment should not exceed 0.5 cm. On weak thixotropic clay soils, any construction work leads to the risk of destruction of the existing building (Mangushev et al., 2018). The answer to each of the technological challenges of underground space development is the appearance of a new technology on the construction equipment market, which allows solving a new range of tasks taking into account the requirements and peculiarities of local ground conditions. In this regard, we are convinced that even the most advanced technological methods should be adapted to local geotechnical conditions. For example, in the conditions of weak thixotropic clay soils of St. Petersburg, the modulus of deformation of which can be 2...3 MPa, the role of control of technological operations is enhanced. An example of such development can be considered the accumulation of research experience on the construction of pit fences by the "Wall in the ground" method and the 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.

In this regard, the role of monitoring the behavior of the object of protection and the instrument of operational control of its structures is being strengthened. At the same time, the role of soil surveys and structures of the cultural heritage object becomes a priority, determining the principles of modeling and implementation of construction. Improving the quality of risk assessment at the stage of project development is also ensured by improving the methods of monitoring spatial deformations of the building and its parts. Traditional monitoring systems monitor only certain points on the object. At the same time, an increase in the number of points will lead to an increase in the cost of geodetic works. The use of scanning systems to obtain a point cloud, as well as a digital double of an object, can be a useful tool that allows you to present a complete picture of deformation, including the presence of defects and cracks in the structure.

In addition, the building of historical buildings 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 efforts in the structure, allow you to take into account all the details of a unique object when monitoring its safety.

Comparable modeling and monitoring capabilities of the facility allow for operational control of the stress-strain system. In addition, spatial monitoring using laser scanning provides an analysis of the impact of construction on cultural heritage sites, and the accumulation of such experience makes it possible to develop models of materials of load-bearing structures and verify the method of their modeling based on the results of comparison with actual deformations. 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 method for processing a point cloud. The prospects of using high-precision spatial monitoring of architectural monuments suggest the introduction of a new tool for monitoring the condition and risk analysis of historical heritage. 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 the city of St. Petersburg.

2 LITERATURE REVIEW

Reducing the amount of additional deformations in the building of the surrounding building naturally leads to the choice of an enclosing structure of greater rigidity. At the same time, we are increasing the technological component of additional precipitation. A number of authors (Mangushev et al., 2020, Sapin, 2014) under the guidance of Professor Mangushev were engaged in studies of the nature and methods of calculating technological sediments in the construction of pit fences. In his research, D.A. Sapin (Sapin, 2015) showed that the technological component of the toughest enclosing structure – the trench wall in the ground reaches 80% of the total additional deformation of the building of the surrounding development. The results of field and laboratory modeling of static immersion of steel sheet piling, performed by A.V. Gursky, (Mangushev and Gursky, 2016), allowed us to conclude that additional technological deformations of the tongue-and-groove device will be less than in the case of a trench wall in the ground, however, the subsequent additional deformations of the building caused by the horizontal movement of the flexible retaining tongue-and-groove wall are comparable, and even exceed the technological risks from the trench wall in the ground. The main problem that forms these risks is a large thickness of weak clay soils, during the operation of equipment in which thixotropic structural disturbances begin to occur and are always accompanied by large movements (Mangushev and Osokin, 2019). Under these conditions, the deformations of the surrounding historical buildings can be 150...600 mm (Ulitskiy et al., 2013, Paramonov, 2009). As we noted earlier, the permissible amount of precipitation is 5...20 mm. The negative effects of these values of deformations are always enhanced by the presence of a large unevenness of deformations, which leads to the formation of cracks and the destruction of the building.

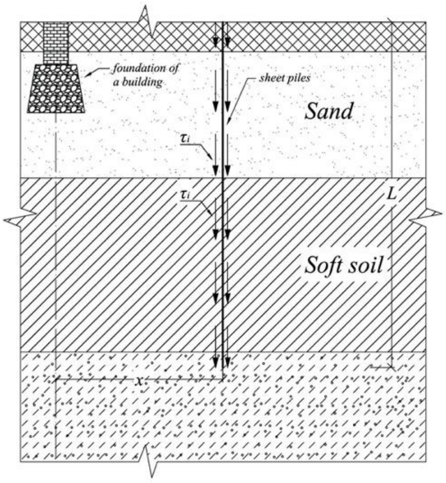

Figure 1. Additional settlement of an existing building under the technological influence of the device of the enclosing structure.

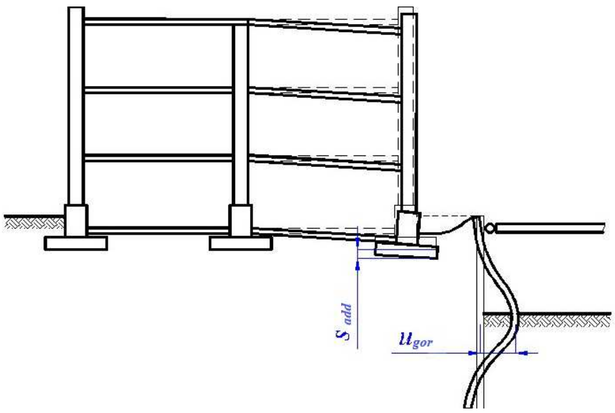

Figure 2. Additional settlement of the existing building from the horizontal displacement of the fence during excavation of the pit

In the case under consideration, a comprehensive solution is proposed, which consists in the construction of a fence structure "wall in the ground" of drill-cut piles d = 350 mm, performed under the protection of a geotechnical barrier with preliminary multi-stage reinforcement of the foundations and foundations of existing historical buildings (Osokin et al., 2019). Thus, at the stage of fencing construction, technological precipitation of manufacture was minimized. And in order to avoid negative consequences when digging a pit, jet–grouting technology was proposed as a spacer plate below the bottom of the pit.

Geotechnical monitoring plays an important role in assessing the effectiveness of the technology, operational adjustment of the speed and sequence of work. At the same time, the main role should be given to geodetic spatial observations of aboveground structures and structures of the pit fence, which can be performed using both classical equipment (leveling, total station) and modern scanning systems and aerial photography. Spatial monitoring allows you to get an interconnected field of points. The area where the field of points is built can include both the building itself and adjacent territories with structures and structures. Long-term satellite positioning of the points system can improve the accuracy of scanning with a measurement error of vertical deformations of 1...2 mm, horizontal displacements of 2...5 mm. This technology is indispensable in conditions of difficult accessibility to the object of observation. The complexity of the information obtained allows us to evaluate complex deformations of individual structures, the development of cracks. The basis for ensuring the accuracy of measurements by laser scanners and unmanned aerial vehicles (UAVs) is always the measurement procedure, the rules of which come out of geodetic standards. However, a significant increase in productivity can be considered the use of a list of equipment that allows you to get a point cloud of good quality, which will require less time for in-house processing. One of such developments is a new type of stamp developed by researchers of the Department of Geodesy of the St. Petersburg University of Architecture and Civil Engineering made on a polymer 3D photo printer that provides the necessary surface quality of the stamp. The effectiveness of the use of this type of stamps, which also consists in increasing the scanning speed, has been demonstrated in laboratory conditions, at research sites and has already been successfully implemented by us in construction production at the stages of spatial monitoring.

The results and application of spatial monitoring are increasingly in demand with the increasing use of joint calculations of the "building-base" system. In this situation, you can monitor the complex deformation of the entire building, with further comparison and refinement of the design model. For existing historical buildings built hundreds of years ago, only such an approach is possible, which can compensate for the lack of complete detailed design documentation, as is the case with new construction.

3. METHODS

The above design scheme of the excavation enclosure was used in the construction of an underground structure in the center of St. Petersburg. At the same time, the construction under construction was erected in close proximity to 6 buildings - objects of cultural heritage.

At the same time, the engineering and geological conditions of the construction site are represented by a significant thickness of weak clay soils. The construction project involved the development of a 3.5 m deep excavation in close proximity to existing cultural heritage sites. To ensure their safety, taking into account the above data, a device for fencing the pit using the technology of boring piles was chosen. This technology involves the construction of fencing from drilling piles under the protection of bentonite mortar. From the point of view of the preservation of buildings of the surrounding development, a significant advantage of this technology over the technology of trench wall in the ground is a significantly smaller amount of excavation for the device of one section of fencing, and before the technology of the device of tongue–and-groove fencing - the absence of transmission to the ground base of static or dynamic loads during immersion.

At the same time, a significant disadvantage of this technology can be called a significantly lower bending stiffness of the enclosing structure than in the cases of sheet piling and trench wall in the ground. To compensate for the insufficient rigidity of the fence, at the design stage, it was provided for the installation of a ground-cement jet-diaphragm below the bottom of the pit, contributing to an increase in the overall rigidity of the enclosing structure. The general scheme of the pit enclosure is shown in Figure 3.

The experience of the construction of pit fences using this technology in the conditions of St. Petersburg shows that the technological precipitation of the surrounding buildings, even when they are directly adjacent to the construction site, does not exceed 1 mm. In this regard, when assessing additional sediments of cultural heritage objects, only additional sediments caused by the excavation were evaluated.

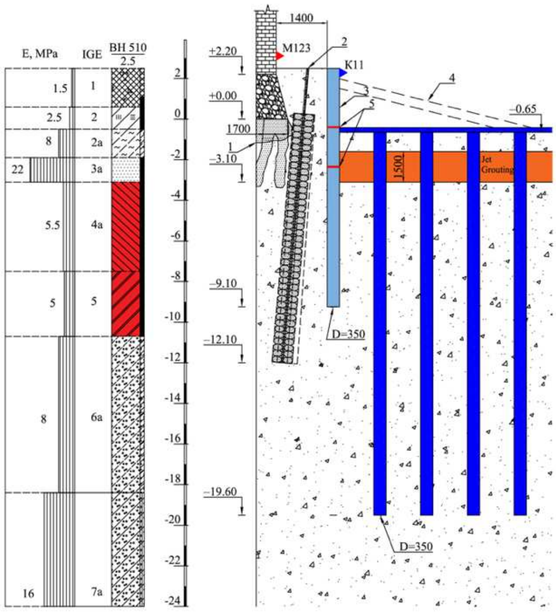

Figure 3. Applied structures of fencing, fixing of the pit, reinforcement of the existing building and geotechnical barrier device.

Figure. 4. The spacer system of the pit at the stage of excavation to the bottom of the pit.

When performing a computational analysis of the development of additional sediments, the following factors were taken into account (Kuznetsov et al., 2023):

1. The stage of work.
2. Nonlinear behavior of the foundation soils (using the Hardening Soil model).
3. Undrained behavior of weak clay soils (drainage type – undrained B).
4. Reinforcing effect of a pile field made for the projected building (using Embedded Beams elements)
5. Nonlinear behavior of reinforced concrete of the enclosing structure and the pile foundation (using the M-k diagram).

Due to the complexity of sampling of sufficiently high quality in the conditions of St. Petersburg, the specific resistance to undrained shear of weak clay soils was determined on the basis of static sounding data according to the formula: $s_u=q_c / 19$ (Shashkin, 2014).

Construction of a graph of the dependence of the bending stiffness of reinforced concrete piles was performed numerical simulation of the cross section, taking into account the peculiarities of the work of concrete in tension and compression (Osokin et al., 2023). The calculated cross-section of the reinforced concrete pile and the obtained dependence of the bending stiffness on the acting bending moment are shown in Figure 5.

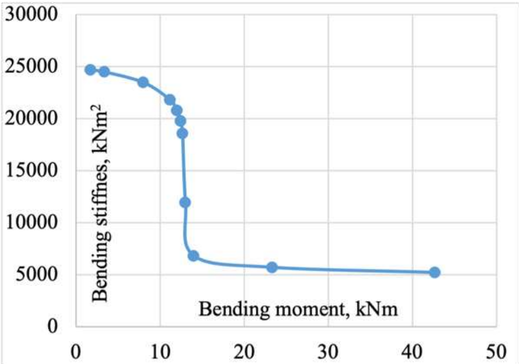

Figure 5. Dependence of the bending stiffness of the pit fence on the acting bending moment.

Below, Figures 6-7 presents the results of numerical modeling of the impact of the development of the pit on the buildings of the existing development.

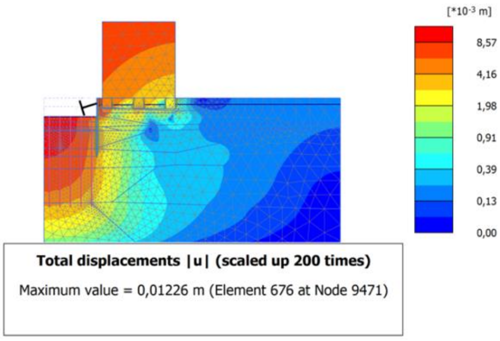

Figure 6. Isofields of complete displacements of the soil mass.

Figure 7. Diagram of deformations of the settlement of surrounding buildings.

4. CONCLUSIONS

1) The development of underground space is an integral part of the development of urban space in the central part of historical cities;

2) In the conditions of complex engineering and geological conditions, represented by a significant capacity of weak clay soils, one of the most important aspects of the preservation of historical buildings is the correct choice of technology for the construction of enclosing structures of the pit;

3) In order to ensure the preservation of the surrounding historical buildings, when developing pits up to 5 m deep in close proximity to existing buildings, a structural scheme of the enclosing structure is proposed, which is a combination of small diameter borehole piles, a spacer system and a deep jet diaphragm;

4) On the example of a real object in the conditions of the historical center of St. Petersburg, the effectiveness of this variant of the enclosing structure is shown;

5) To predict the development of additional sediments of the existing development, a design scheme is proposed that takes into account the undrained behavior of the foundation soils, the preliminary arrangement of the pile field within the contour of the pit, the nonlinear behavior of the soil mass and reinforced concrete enclosing structures.

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