Contemporary geotechnical solutions for bases and foundations of emergency-deformed buildings-monuments on weak soils

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Abstract: The tasks of strengthening the foundations of emergency deformed buildings and fixing the soil in their base during restoration and restoration work require engineering solutions that allow combining an increase in the bearing capacity of the base and the exclusion of the development of uneven deformations of the reinforced building. Such solutions are possible when using injection methods and the device of drilling-injection piles. The modern material for fixing the soils of emergency-deformed buildings is micro-cement Ultracement-5M and Polygel AFM-K3, which allow excluding the technological impact on the structures of the foundations of rein-forced buildings. The article presents the experience of strengthening the foundations of histori-cal buildings and monument buildings, as well as analyzes the accumulated experience in performing preventive strengthening of the foundation soils as protective measures in the presence of pits and underground structures under construction near buildings.

1 Introduction

In historical cities, one of the directions for creating a comfortable living environment is to ob-serve harmony and balance in a combination of historical appearance and new construction. Today, considerable attention is paid to the preservation of architectural monuments that are objects of cultural heritage and historical buildings located in regulated development zones. Such buildings have a significant service life and are often in disrepair or dilapidated condi-tions [1]. To increase the investment attractiveness of such buildings, it is necessary to solve the problems of adapting the monument to modern use by installing or expanding the volume of underground space. The combination of injection methods of fixing soils in the foundation base, the use of highly efficient modern materials to strengthen the foundations of old build-ings, the transplanting of emergency deformed foundations onto drill-injection piles allow us to solve a wide range of restoration and restoration tasks.

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2 Materials and methods

2.1 Features of the structures of the foundations of old buildings on the example of St. Petersburg

When developing emergency measures for the preservation of buildings-monuments and historical buildings, the main issues of geotechnical engineers are the study of the construction of the foundations of the building, determining its technical condition by the material of the foun-dation and the soils lying in its base. Due to the high architectural and historical value of build-ings-monuments and buildings of historical development, special requirements are imposed on the performance of the foundations of such objects in terms of bearing capacity and the exclu-sion of uneven deformations, as a condition for preserving the historical architectural appear-ance. According to the current Russian standards SP 22.13330.2016 and GOST R 56198-2014, there are restrictions on the maximum values of additional deformations of historical buildings, depending on the category of technical condition of structures, ranging from zero to 10 mm [2].

In conditions of weak soils, this requirement, even at the design level, is difficult to meet, and in conditions of performing restoration and restoration work without preliminary measures that reduce the deformation of the "foundation soils – foundation – building structures" system, it becomes practically impossible to implement.

It should be noted that the foundations of monument buildings and buildings of historical development built in St. Petersburg in the XVIII-XIX centuries are distinguished by a wide va-riety of types: rubble made of bedded or torn rubble/boulders, brick rubble concrete and con-crete foundations [3]. The foundations of the first half of the XVIII century were formed with a dressing "on dry", that is, the joint work of rubble stones was provided by friction. It is known that until the end of the XIX century, rubble foundations in the presence of weak soils at the base were laid on longitudinal sleeper-longitudinally arranged wooden logs with a diameter of 240-320 mm. In the presence of peat at the base of buildings under construction, as well as in some cases when buildings were located along the banks of embankments, the foundations of buildings were arranged on a pile base of wooden piles (Fig. 1).

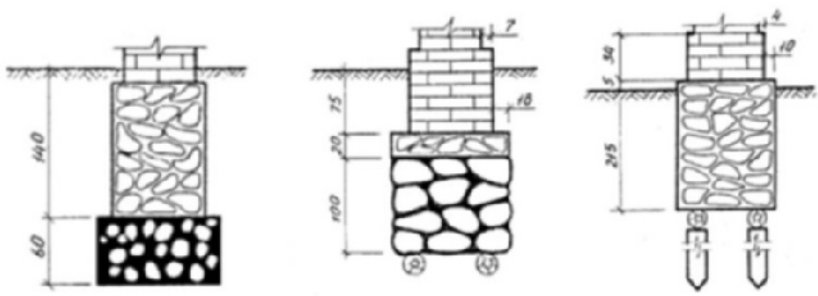

Fig.1. View of the foundations of old buildings (Mangushev R. A. et al. 2018). On the left – a foundation, the lower part of which is made of granite boulders; in the center – a combined foundation, built in the base-ment part of brick on a rubble limestone foundation, the lower part of which is made of granite boulders, which were laid on wooden longitudinal sleeper; On the right – a rubble foundation on a pile base of wooden piles.

Considering the technical condition and wear of the foundation structures, and their high sensitivity to uneven deformations, due to the exhaustion of the bearing capacity of the founda-tion soils and foundations, all measures to strengthen them should ensure minimal impact on the foundation structures and soils, that is, be "sparing". An important condition is

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the use of injection materials that contribute to the rapid inclusion of reinforcement structures in the work after their execution.

2.2 Technical features of practical techniques for strengthening the foundations of monument buildings with uneven deformations

The emergency condition of the foundations may occur due to the loss of the bearing capacity of the foundation structure and its elements or due to the unsatisfactory operation of the soil base. In the conditions of restoration and restoration work, maximum attention is paid to the preservation of all historical structures and materials [4]. Therefore, the method of emergency response work should include the possible removal of the most destroyed elements and structures or their partial replacement with strengthening or improving the physical and mechanical characteristics of the soil base.

In engineering practice, the most effective and safe approach when performing geotechnical work to adapt to modern use with the construction of basements, underground levels in the vol-ume of the building being restored is to perform preventive reinforcement of the foundation us-ing injection methods or drilling piles. The choice of a particular method of strengthening the foundations and fixing the foundation soils is determined at the design stage based on geotech-nical justification.

When designing ditches near historical buildings, an important safety condition is the choice and calculation justification of the method of constructing the enclosing structure of the pit, while the following technical solutions are considered: the indentation of sheet pile profiles; the device of fencing the pit using the "wall in the ground" structure arranged by the grab method. For loosening the walls of the pit at the project stage, the calculated justification of the number of levels is carried out and the calculated choice of structures for loosening the walls of the pit with metal elements is made: pipes or beams, or using the method of constructing an underground structure "Top-Down". In the conditions of cramped urban development in the his-torical part of the city, the device of a spacer structure at the base of the bottom of the pit made of a soil-cement array using jet technology (jet-grouting) has proven itself well as an event that reduces additional technological precipitation [5].

Modern regulatory documents also indicate the requirements for excluding the influence of geotechnical works near buildings-monuments due to the use of protective measures according to SP 361.1325800.2017: strengthening the structures of the protected building; strengthening the foundations and foundation soils; the device of geotechnical cut-off screens, geotechnical barriers, curtains, walls located between the underground structure and the protected building. One of the ways to strengthen existing foundations to reduce the deformations of the founda-tions of buildings is the device of piles: pressed, drilling-injection, piles of the "Titan" type and their varieties [6]. The use of piles allows you to transfer the load from the load-bearing struc-tures to more durable soils that lie at a great depth.

Another way to strengthen the foundations and consolidate the foundations of historical buildings is the use of jet-grouting technology of jet-grouting. The advantage of this method is the speed of production of soil-cement elements, as well as the fact that the same equipment can be used both for fixing the foundations of existing buildings and for the device of protective measures for the protection of the pit to reduce technological precipitation. However, it should be noted that when using the "jet-grouting" technology in the conditions of the monument, there is uncalculated technological precipitation during the work.

In the conditions of the expected uneven deformations of the building, when performing ge-otechnical works in the immediate vicinity, the fixing of the soil of the foundation bases by chemical method and cementation using the cuff technology (hydraulic fracturing) is used. In the practice of injecting fixing of soils, the "geocomposite" method is also used.

The technological differences between these methods are that some are performed by pene-tration of solutions into the pores of the soil, thereby improving the physical and mechanical characteristics, while others are performed with a violation of the structure of the soil when ex-posed to a solution supplied under pressure [7].

2.3 Retrospective analysis of technologies for strengthening the foundations and foundations of historical buildings

During engineering restoration, methods of strengthening structures that visually change the shape of the reinforced structure or element of the monument by creating clips, installing mon-olithic reinforced concrete slabs are excluded from consideration. The use of technical solu-tions that distort or change the perception of engineering solutions of monument structures is not allowed. These requirements are also fundamental for the world community of restorers.

In St. Petersburg in the late 1980s, during the engineering restoration of the Church of St. Catherine, it was found that the building has deformations associated with uneven precipitation of its individual parts. A technical inspection of the foundations showed that wooden longitudi-nal sleepers were laid at the base, some of which were subjected to rotting processes [8]. Dur-ing the restoration of the church, attention was paid to this, and the need for the project and work to strengthen the foundations were determined.

In 1991, the staff of the Department of Geotechnics of SPbGASU, under the scientific guid-ance of Professor V. M. Ulitsky, developed a project to strengthen the rubble foundations of the building of the Church of St. Nicholas. Catherine with the use of 1300 short drill-injection piles with a diameter of 151 mm and a length of 6.0 m (Fig. 2). Before the piles were installed, the body of the rubble foundation masonry was strengthened by injection of a reinforcing compo-site solution, and the contact zone "foundation – ground of the base" (location zone) of wooden beds was injected, that is, a contact layer was formed for the preservation of wooden beds. For the first time in the practice of geotechnical construction of St. Petersburg, the reinforcement of the upper bearing layer of sandy soil with boron-injection piles (the creation of a reinforced cushion) was performed, which is underlain by a large thickness of layered thixotropic loams and sandy loams, which allowed to prevent additional precipitation of the structure. The work was carried out in the cramped conditions of the restoration of the object using technical means for the installation of drilling piles from the premises of the church, as well as from the base-ment.

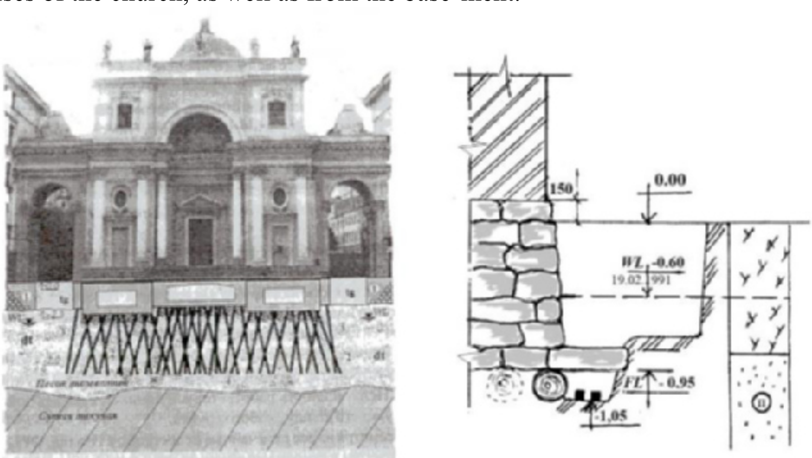

Fig. 2. The use of short drill-injection piles to strengthen the foundations of the Church of St. Catherine.

The principles of an integrated approach to design make it possible to provide the most relia-ble reinforcement of load-bearing structures, which is confirmed by examples of engineering restoration and reconstruction of real objects [9]. The analysis of the domestic experience of strengthening the foundations and soils of the foundations of buildings-monuments and build-ings of historical development on weak soils is presented in Table 1.

Table 1. Factors and decisions.

Factors determining the need to strengthen the foundations and / or consolidate the foundation soils	Constructive decisions taken
Insufficient bearing capacity of the base soils	1.1. Injection fixing of the base soils. 1.2. The transfer of the building to the drill-injection piles based on the lack of bearing capacity. 1.3. Laying a monolithic reinforced concrete slab under the foundation. 1.4. Widening of the sole of the foundation with the device of reinforced concrete double-sided banquettes.
Low load-bearing capacity of the foundation structure, high degree of physical wear	2.1. Injection strengthening of the foundation body. 2.2. Replacement of sections of the destroyed foundation (removal, re-laying). 2.3. The device of reinforced concrete clips.
Uneven deformations during the destruction of wooden foundation structures (longitudinal sleeper, piles)	3.1. Injection fixing of the base soils below the level of the rot-affected beds. 3.2. The use of high-pressure injection to perform a soil-cement array around rot-affected beds with the transfer of load to the soils below the zone of their location. 3.3. The transfer of the building to the drill-injection piles from the condition of full perception by the piles of the increased load from the building. 3.4. Replacement of wooden structures with a reinforced concrete structure (bringing a monolithic reinforced concrete tape under the foundation).
Deepening and creation of basements, arrangement of an underground volume at the base of an existing building	4.1. Injection fixing of soils to the calculated depth using cuff technology (hydraulic fracturing, soil impregnation). 4.2. Transplanting a building to drill-injection piles from the condition of their perception of the full load from the building in combination with injection fixing of soils under the sole of foundations using micro-cements, gels to the calculated depth, considering the expected lowering of the basement floor level. 4.3. Fixing of soils in the base of the building using the technology of high-pressure injection "Jet-Grouting" and transferring the building to drill-injection piles from the condition of their perception of the lack of load from the building, considering the work of the soil-cement array during the initial fixing of the "Jet-Grouting" soils. 4.4. Hanging of foundations on drilling-injection piles with the introduction of monolithic reinforced concrete structures under the foundation.

	4.5. Creation of enclosing structures (tongue-and-groove, construction of drilling-injection piles, construction of a "wall in the ground", formation of an enclosing structure from a soil-cement array, etc.) of an arranged underground volume in combination with injection fixing of soils to the calculated depth.
The influence of the device of pits and geotechnical construction when the object is located in the zone of influence according to SP 361.1325800.2017.	5.1. The device of geotechnical, curtains, walls located between the object of new construction and the protected building. 5.2. Preventive strengthening of the foundations of the building in the zone of influence with the device of drill-injection piles. 5.2. Injection fixing of the foundation soils using cuff technology (active event). 5.3. Preventive injection fixing of the foundation soils and foundations of the protected building (passive event). 5.4. Strengthening of the structures of the aboveground part to increase rigidity and eliminate accidents.

3 Results and discussion

3.1 Retrospective analysis of technologies for strengthening the foundations and foundations of historical buildings

The analysis of soil samples taken from the foundations of several monument buildings in the central part of St. Petersburg showed that the presence of medium-density, water-saturated, dusty plastic sandy loams with a high degree of humidity is one of the factors affecting the formation of additional sediments during geotechnical impact.

The authors propose to perform soil fixing based on the method of soil impregnation with fix-ing solutions with high penetrating ability (Figure 3,4).

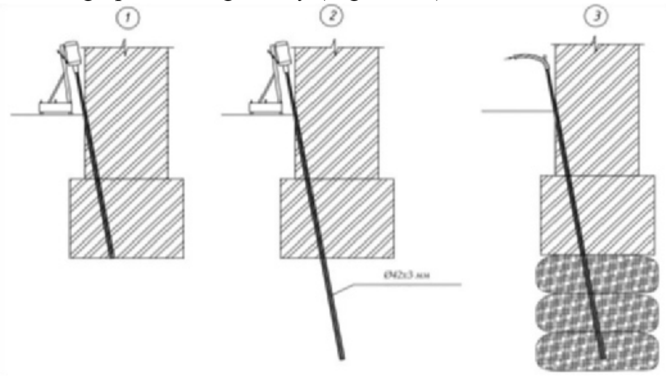

Fig. 3. Technological scheme of work on the injection fixing of soils in the base of the monument.

Injection of the injection solution is carried out at the following operating parameters:
- initial injection pressures (for breaking the clip solution) up to 1.5 Mpa;
- working pressure: 0.1 - 0.2 Mpa;
- the final pressure (failure): 0.3 MPa.

a b

Fig.4. Comparative analysis of the penetrating ability of cement mortars in sand Dparts of sand=0.2 mm: a- portlandcement, b-micro-cement

As the experience of scientific and technical support of work on strengthening foundations has shown, when performing injection fixing of soils with the use of Portland cement of the M400/500 grades, sharp jumps in the injection pressure with the technical complexity of con-trolling the boundary of the formation of hydraulic fracturing are possible, as a result of which an uncontrolled rise of the building occurs. This happens at the moment when an injection solu-tion based on ordinary cement shifts the soil particles, reducing the size of the channels of the pore space, colmatating the pore space around the cuff column, and blocking the further spread of the solution in the soil mass. This leads to an increase in the supply pressure and the transi-tion from impregnation technology to hydraulic fracturing technology.

Based on the conducted studies, a nomogram of the applicability of various injection materi-als according to their penetrating ability for solving the problem of soil stabilization is con-structed (Fig.5).

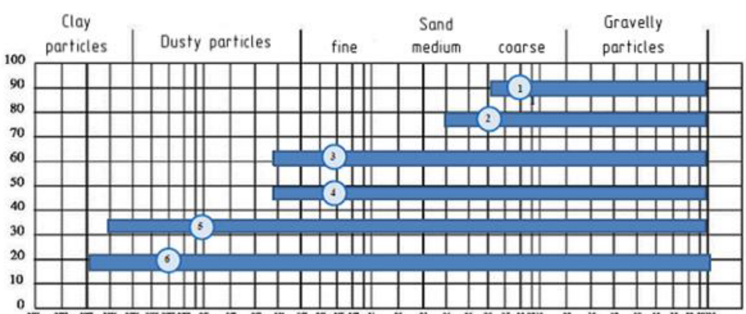

Fig. 5. Nomogram of the penetrating ability of injectable materials. 1-Portland cement M5600D0; 2-cement with bentonite; 3-an aqueous solution of sodium silicate (liquid glass) Na2O (SiO2); 4-an injection solution based on micro-cement Ultra-cement 5M; 5-polyurethane resin; 6-Polygel ASM-K3 with additives.

The modern approach to strengthening foundations and foundation soils is to minimize the technological impact on the foundation soils. To solve this problem, we have studied the possi-bility of using micro-cements of the Ultra-Cement-5M type and ASM-K3 Polygel without changing the technology of work production. However, this technology with the use of modern injection materials requires additional research in watered soils.

4 Conclusion

The conducted scientific and technical research has shown that the use of injection solutions of a suspension based on micro-cement (for example, 5M ultra-cement) or ASM-K3 Polygel with modifying additives makes it possible to exclude the occurrence of uneven technological de-formations of monument buildings on weak soils.

Scientific and technical support of the objects of engineering restoration has shown that the success of the project is largely determined by the accuracy of the calculations performed with-in the geotechnical justification with the determination of the predicted deformations of build-ings depending on the degree of impact on the foundation soils and considering the technical condition of the structures. A significant role here is assigned to the professional competencies of a specialized organization that directly performs work on the construction site, can solve the tasks set, and is provided with the necessary technical capabilities for the implementation of engineering restoration projects.

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