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RESEARCH WORK IN DEVELOPING DESIGN SOLUTIONS ON THE EXAMPLE OF SOIL REINFORCEMENT UNDER THE FOUNDATIONS OF SUPPORTS OF STAIRS TO THE MAGDEBURG LAW MONUMENT IN KYIV

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Abstract

The stairs leading to the oldest existing monument in Kyiv – the Magdeburg Law Monument – stretch along the slope of Khreshchatyi Yar. The last reconstruction was carried out in 2013. In 2019, as part of scientific and technical support work for the construction of a pedestrian and bicycle bridge crossing between the parks "Khreshchatyi" and "Volodymyrska Hirka", research work was carried out aimed at securing the soil base under the columns' foundations of the stairs to the Magdeburg Law Monument. The authors developed scientifically based structural and technological solutions for securing the foundations under the foundations of the staircase columns, which began to shift along the slope during the construction of temporary supports of the pedestrian and bicycle bridge crossing next to them. During experimental studies, the effectiveness of the method of securing soils with polyurethane materials was tested and proven. It was found that due to the introduction of polymeric materials, the soil was compacted, and fastened with strong layers of the soil-polymer mixture that penetrated it. Based on the results of experimental studies, design solutions were developed that provide for the injection of polyurethane material through two separate tubes at two elevation levels from the base of the foundation.

Keywords: *Stairs; Magdeburg Law Monument; Restoration work; Experimental research; Chemical soil consolidation; Polyurethane materials; Structural and technological solutions; Injection*

Introduction

In 2019, construction began on a pedestrian and bicycle bridge crossing between the Khreshchatyi and Volodymyrska Hirka parks in the Pecherskyi and Shevchenkivskyi districts of Kyiv, better known as the pedestrian and bicycle bridge over Volodymyrskyi Descent or the Klitschko Glass Bridge [1].

In terms of geomorphology, the site on which the building is located belongs to the slope of the ancient Khreshchatyi Yar. The terrain of the site is complex, confined to a steep slope

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(Khreshchatyi Park), planned in the form of several terraces, opening onto the Dnipro River valley. According to [2], the territory belongs to the III (complex) category of complexity of engineering and geological conditions. Currently, a staircase runs through the territory of Khreshchatyi Yar. These stairs start from the upper entrance on Volodymyrskyi Descent, repeat the bend of the ravine, and extend to the Magdeburg Law Column and below – to Naberezhne Highway [3]. A general view of the territory with the already-built pedestrian and bicycle crossing and stairs to the Magdeburg Law Monument is presented in figure 1.

Fig. 1. General view of the territory with the already constructed pedestrian and bicycle crossing and stairs to the Magdeburg Law monument.

The upper entrance and stairs (Volodymyrskyi Descent) have the protected status of a monument of civil architecture and are considered at the same time part of the Magdeburg Law Column complex, which is a monument of architecture and history of national importance. The historical territory where the monument is located is included in the State Historical and Architectural Reserve "Ancient Kyiv", and is part of the protected green landscape zone [3]. The peculiarity of these stairs is not only their protected status but also the fact that they lead to the oldest existing monument in Kyiv – the Magdeburg Law Monument or the Magdeburg Law Column, also known as the Monument of the Baptism of Rus or the Lower Monument to Saint Volodymyr [4].

The first stairs to the Magdeburg Law Monument were built in the early 1880s from the Volodymyrskyi (then Oleksandrivskyi) descent. The design of the stairs included an oak base with brick landings. Benches were made for relaxation on the landings, and pavilions for protection from the weather. Then, in January 1908, the Kyiv city authorities announced a competition for the design of a stone staircase to replace the existing wooden one to the Magdeburg Law Monument (then called the Lower Monument to Saint Volodymyr). The winner of the aforementioned competition was the project "Three Concentric Circles" of the Kyiv Construction Bureau of Architects and Engineers under the leadership of the architect-artist V.V. Eisner. However, no work was started, and the condition of the monument and the staircase leading to it only worsened. Only in 1913 architect M. Bobrusov designed a staircase and two gates (Fig. 2). But this project was not fully implemented either [3].

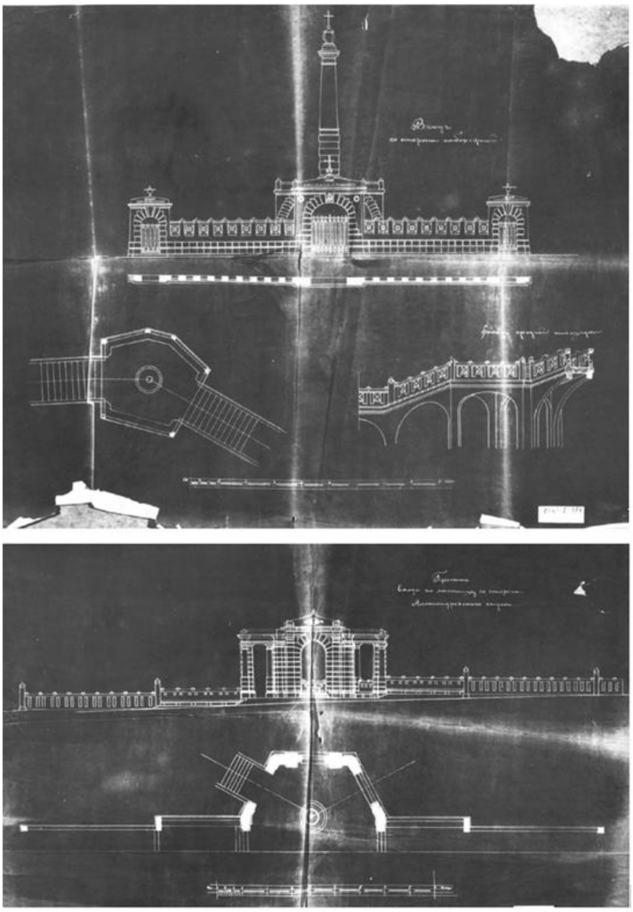

Fig. 2. Staircase design by architect M. Bobrusov: above – entrance from the Embankment; below – entrance from the Volodymyrskyi Descent [3]

The construction of the concrete stairs began in March 1914. Thus, the passage to the Embankment was closed and the wooden stairs, which were in a dilapidated state, were dismantled. At the first stage of construction, an entrance was built from the side of the Oleksandrivskyi (now Volodymyrskyi) descent in the form of a brick arcade and concrete-granite stairs to the column, raised above the ravine on concrete risers [3]. However, further work on the construction of the second stage (the main stairs below the column and the entrance from the Dnipro embankment) was not carried out (Fig. 2). Figure. 3 shows the view of the stairs after their repair [3].

The following ideas for rebuilding the stairs to the Magdeburg Law Monument were voiced in 1936: the stairs, made of reinforced concrete in their upper part, would be reconstructed and extended to the monument itself, around which a colonnade would be built, which would decorate the square, and a monument located along the axis of the stairs would complete the perspective from the slopes. The work was planned to be carried out according to the project of architect R. Kramer. However, this project was not implemented either [3].

Construction work continued only in 1950 – 1953. As a result, granite stairs were built from the monument to the embankment. The implementation of this project is connected with the preparatory work for the construction of the Park Bridge, which was opened in 1957. Another repair of the stairs was carried out in 1974. The last reconstruction of the stairs (Fig. 4) and the colonnade devoted to the 1025th anniversary of the Baptism of Rus was carried out in 2013.

Fig. 3. 1920s. Stairs to the Magdeburg Law Column [4]

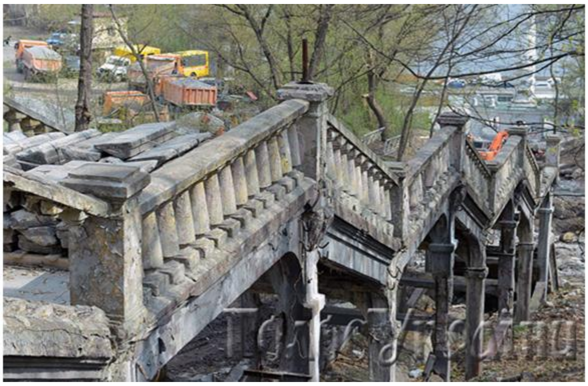

Fig. 4. Condition of the stairs before their reconstruction in 2013 [5]

The approximate length of the stairs is 72.0m. The beginning of the stairs is located on Volodymyrskyi Uzviz Street near the Magdeburg Law. The colonnade at the beginning of the stairs (a stone arcade or arch of a road structure) is the main entrance from the uphill side of the Magdeburg Law Monument.

The staircase structure is represented by flight of stairs and landings supported by supports. The supports of the stairs transfer the load to the columnar foundations, the basis of which is the existing soils reinforced with crushed stone preparation 300mm thick. These foundations are connected by monolithic reinforced concrete beams, which are installed coaxially with the existing foundations. The foundations are two-stage with the sole dimensions of 1300mm. The connection of the foundations with beams was carried out following project 020418-KZB-6 for the “Rehabilitation (reconstruction) of the road structure to the Magdeburg Law Monument” (2013) [6, 7].

A drainage channel is arranged along the bridge axis from pier 18 to pier 10 for collecting and draining surface water. A storm drain is made in front of pier 10. From the observation deck of Khreshchatyi Park, there is a steep slope on which manifestations of modern geological processes can be observed. On the opposite side from the stairs, the slope is gentler, but also not arranged [6].

According to the information contained in [6, 7], the basis of the foundations is pale-yellow loess-like sandy loam and gray sandy loam. The engineering-geological section is composed of the following engineering-geological elements (from top to bottom):

– IGE-1 – embankment – sandy loam, loam, sand (mainly hard sandy loam), with the inclusion of construction waste (crushed stone, wood, broken brick, concrete fragments, etc. > 20%);

– IGE-2 – sandy loam, pale-yellow, carbonate, hard, plastic, according to compression tests, slumped;

– IGE-3 – sandy loam yellow-gray, gray, in places with thin layers and lenses of sand, from hard to fluid consistency.

The appearance of the stairs to the Magdeburg Law Monument after reconstruction is presented in figure 6.

Fig. 6. View of the stairs to the Magdeburg Law Monument after reconstruction: left – view from the Dnipro embankment; right – side view.

The purpose of the work is to analyse, theoretically, and experimentally confirm the effectiveness and develop structural and technological solutions for securing the foundations under the foundations of the supports, which will provide the necessary bearing capacity, and structural safety and ensure further reliable operation of the structure.

Matherials and Methods

During the research, the authors used the following general scientific methods: analytical – when analysing scientific and technical literature; instrumental – when studying the physical and mechanical indicators of structures and experimental soils and samples; experimental – for conducting research to establish the parameters of the research results.

For the purpose of the study, the following sources were used:

1) regulatory framework [8 – 11];
2) issues of preserving historical and cultural heritage [8, 9, 12 – 15];
3) issues related to technologies for restoring operational suitability [10, 11, 14 – 19];
4) issues related to the systematization of damage [20];
5) issues related to the buildings and structures preservation and restoration [16, 21 – 25].

The study of the regulatory and legislative framework and the condition of historical and cultural buildings and structures in need of restoration became the theoretical basis for studying the processed sources and providing recommendations for restoring the operational suitability of objects of architectural and historical value.

Results and Discussion

With the participation of the authors in 2019, within the framework of scientific and technical support (STS) works at the facility: “Construction of a pedestrian and bicycle bridge crossing between the parks “Khreshchatyi” and “Volodymyrska Hirka” in the Pecherskyi and

Shevchenkivskyi districts", scientific and research work was carried out aimed at "Fixing the soil base under the foundations of the columns of the stairs (10-13/A-B) to the monument to the Magdeburg Law" [21]. It was envisaged to develop scientifically based structural and technological solutions for fixing the bases under the foundations of the columns of the stairs, which began to shift along the slope during the construction of temporary supports of the pedestrian and bicycle bridge crossing next to them (Fig. 7).

Fig. 7. View of temporary supports during their construction (2019).

The research and work carried out within the framework of scientific and technical support have scientific value and will be of interest to both contracting organizations conducting similar work and scientists developing scientifically based technical solutions on unique objects. Following the scientific and technical support program, during the construction of the new bridge crossing, geodetic and visual monitoring of the stairs was envisaged.

After analysing the results of engineering and geodetic monitoring and observation of the technical condition of the stairs to the Magdeburg Law Monument, specialists noted the presence and certain development of the deformation process of the structure.

In particular, as of March 13, 2019, the column along axis 11, A reached maximum values of total settlement of 47mm, the column along axis 11, B – 31mm, the column along axis 10, A – 46 mm, the column along axis 10, B – 26mm, the column along axis 12, A – 39mm, the column along axis 12, B – 18mm. Therefore, additional deformations of the base of the foundations of the adjacent part of the existing staircase structure to the Magdeburg Law Monument in some areas exceeded the permissible value of –15mm (Appendix B, [26]), which is defined as the maximum permissible normalized limit of deformation values for adjacent structures in the zone of influence of the new construction. In addition, the relative settlement difference exceeded the permissible value of 0.0012 (Appendix B, [26]) between adjacent columns in the section in axes "10 – 12, A – B" (Fig. 8).

Also, as of March 14, 2019, the appearance of small cracks was recorded at the junctions of columns with transverse beams along axis 11, A up to 1.0mm and along axis 10, A up to 0.2mm.

To prevent further deformations, it was recommended to urgently reinforce the staircase construction site by securing the soil base under the column foundations along axes 10 – 13 and A and B.

Therefore, following the given recommendation, it was necessary to develop structural and technological solutions for securing the foundations under the foundations of the supports, which would provide the necessary bearing capacity, and structural safety and ensure further reliable operation of the structure. Since these stairs are part of the historical complex of buildings, changing the spatial and dimensional parameters of their structures and appearance is prohibited. That is why it was decided to secure the foundation under the foundation, and not to strengthen the foundation itself.

First of all, an analysis of known methods of foundation consolidation was performed, which could be used in specific conditions to achieve the set goals.

In particular, regulatory documentation [11] recommends performing soil consolidation by the following methods: chemical injections, cementation, jet injection, drilling-mixing, thermal. As part of the research work, the specified methods of soil consolidation were carefully analysed. In particular, such methods as jet injection and drill-mixing were rejected due to the inappropriateness of their application in a specific case, which is associated with the need to drill or wash away the soil mass under existing structures, which can weaken the foundation for a certain time and worsen the situation by provoking even greater deformations. The method of thermal consolidation of soils was also rejected due to the lack of the necessary equipment and contractors who could perform such work.

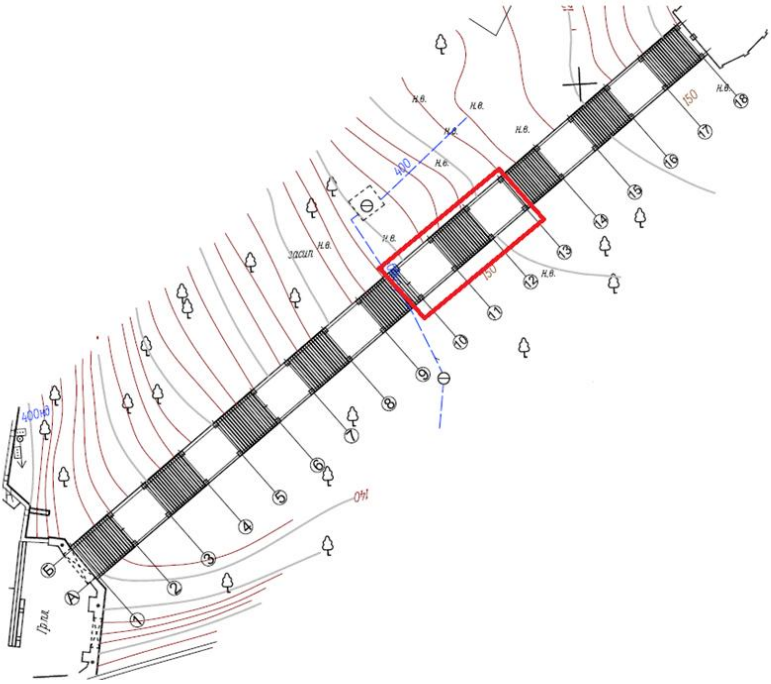

Fig. 8. Layout of the stairs to the Magdeburg Law Monument with highlighted areas requiring foundation reinforcement [21]

Since, according to [11], cementation is used as an auxiliary means for chemical fixation, this method was also not considered further.

We analysed in more detail the method of fixation by chemical injections, in particular by introducing polyurethane materials into the base. At that time (2019), methods of fixation of bases with polyurethane materials were only becoming widespread in Ukraine. At the same time, systematic scientific studies confirming their effectiveness were absent. The use of untested methods on historical objects is prohibited, as this may lead to its damage or destruction, which is unacceptable.

To establish the effectiveness of polyurethane materials as a chemical soil consolidation, it was decided to carry out a scientific justification of this method. For this purpose, several semi-real-life (model) experimental studies were performed.

First of all, semi-real-life studies were carried out, which involved the manufacture of large-scale stands with their filling with soil and the subsequent injection of polyurethane materials into them.

The experimental research program provided for the following sequence of actions:

– design and manufacture experimental stands that will simulate the real operating conditions of polyurethane material when fixing bases under foundations;

– establish soil parameters before its chemical fixing;

– perform chemical fixing of the soil by injecting polyurethane materials into its massif;
– provide a technological break for complete polymerization of the material;
– establish soil parameters after its chemical fixing;
– dig out the soil from the stand so as not to disturb the structure of the chemical fixing and visually inspect it with the establishment of parameters.

First of all, two identical experimental stands were modelled, consisting of a formwork structure that held the specified soil stamp and the loading element unchanged (Fig. 9). Two identical studies were performed to obtain greater reliability of the results obtained.

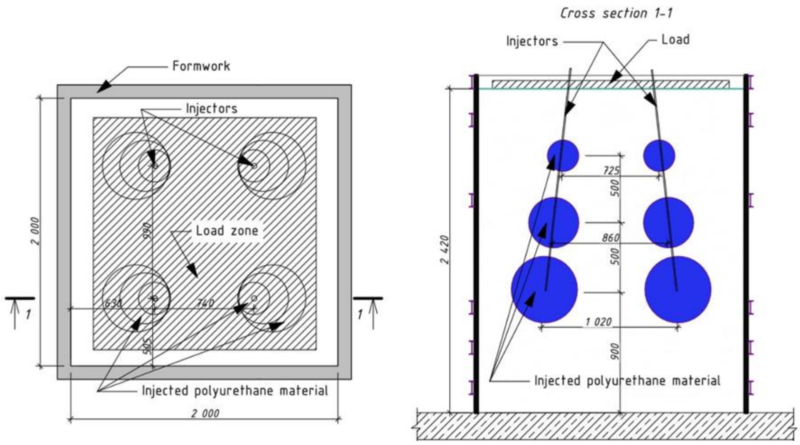

Fig. 9. Model of experimental stands

The limiting structures of the stands were composed of formwork structures (Fig. 10). The main task of the formwork was to hold the specified, initial soil stamp without moving to the sides when acting on it.

Fig. 10. The limiting structures of the stands are made of formwork.

The sandy soil was poured into the formwork structures in layers (10–15cm) and compacted with a light rammer (Fig. 11).

Fig. 11. Sandy soil poured into experimental stands.

At the next stage of manufacturing the stands, a load was applied to the soil, simulating foundations.

Experimental studies to identify the possibility of using polyurethane materials to secure the bases under the foundations were carried out on specially designed stands in the workshop at an air temperature of +5 – +12ºC. It was at this outside air temperature that work on securing the bases at the construction site was planned.

Before the start of experimental studies, sand samples were taken from both stands to determine their properties:

– granulometric composition – sand by mass consists of particles of 0.10mm more than 75% – 96.96;

– bulk density – 1.47;

– specific gravity – 2.66;

– porosity coefficient – 0.8. According to the porosity coefficient, fine sand is on the border between loose and medium density;

– humidity level – low humidity level – 0.3.

Since, according to geological surveys, the soil in the stand has a lower degree of moisture compared to natural conditions, especially considering the work in the autumn period, when soil moisture increases, it was decided to increase the degree of soil moisture by evenly pouring water in the same amount into both stands.

A day after adding water to the soil of the stands, samples were taken from them to determine the degree of moisture, which ranged from 0.5 to 0.7 and depended on the depth of sampling and increased to the bottom of the stand.

Soil samples were taken by drilling cores at intervals of 0.25 m. It was established that the soil in the stand is medium-density sand, with ρ_d=1.65g/cm3 (ρ_s=2.65g/cm^3; e=0.606).

It should be noted that the soil moisture at the same marks in both stands is almost the same.

A day before the experimental studies, polyurethane materials were injected into the soil of the stands to strengthen the sandy soil (Fig. 12).

Injection of polyurethane material was performed as follows. Three injection steel tubes Ø 12mm were sunk into the places indicated in Fig. 9 so that the lower ends of each of the three tubes were placed at a distance of 500 mm from each other, the upper ends were 200 – 350mm above the ground level. Plastic injectors with a check valve were screwed into the upper ends of the injection tubes.

Before the start of experimental studies with the injection of material into the soil, the soil surface around the concrete block that created the load was covered with a solid sheet of plywood and loaded. This action was performed so that during expansion the polyurethane material did not come to the surface and did not lift the upper, light layer of soil.

Fig. 12. Injection of polyurethane materials.

At the beginning of injection, the temperature of the polyurethane material in the hoses was – +45 ºC, in the reactor – component "A" +43 ºC, component "B" +35 ºC.

The injection of the material into the soil volume was started by connecting a special gun to the injector, to which polyurethane material and compressed air are supplied through rubber hoses. By pressing the gun hook, the injected material under pressure passed into the steel tube and the soil.

5.55kg of polyurethane material was fed into each of the four installed injectors, the bottom of which was at a depth of 1.5m from the soil surface. 4.17kg was fed into the injectors, the bottom of which was at a depth of 1.0m, and 1.4kg of polyurethane material was fed into the tubes, the bottom of which was at a depth of 0.5m, respectively. After that, a technological break of 24 hours was maintained for complete polymerization of the material.

Subsequently, soil samples were taken to determine their parameters after chemical consolidation. According to the research results, the soil consolidated with polyurethane has a reduced porosity coefficient compared to the original soil (0.540 in consolidated versus 0.8 in unconsolidated). As stated in the report on engineering and geological research, after the injection of polyurethane material, the chemically consolidated soil turned into semi-rocky (in places where the material itself was exposed to drilling and sampling). The compressive strength of the soil impregnated with polyurethane is 13.8MPa.

At the next stage, the soil was removed from the stands, without violating the structural integrity of the chemical consolidation itself. As a result, it was found that at the points where the injection material exited the tubes into the soil, soil-polyurethane plate-like branches were formed, which broke the soil masses, compacting them and fastening them by binding (Fig. 13). At the lowest points where the largest volume of material was injected, it spread to a distance of up to 80 cm from the point of exit from the tube.

Therefore, based on the results of semi-natural experimental studies, it was found that the injection of polyurethane material into the soil makes it possible to obtain effective chemical consolidation, characterized by the formation of layers of strong material with its branches in the soil massif in the form of "tree roots", which "binds" and compacts the soil. That is, this method of chemical consolidation is well suited for strengthening and consolidating soils under the foundations of the supports of the stairs to the Magdeburg Law Monument, especially considering that they are located on a slope.

The method of soil consolidation with polyurethane was adopted in this project based on its advantages over other possible methods (silicate, cementation, pile consolidation).

Fig. 13. Stand with removed soil and formed chemical fixation.

The proposed solutions provide:

– increasing the bearing capacity of the soils of the foundations of the structure by compacting them;

– redistributing the load from the foundation sole to a significantly greater depth of the soil (2– 3 times);

– reducing the soil filtration coefficient due to its compaction, thereby reducing the risk of severe consequences of soil wetting.

Justification of the adopted method of securing the foundation base:

– the proposed technology will allow implementation design solutions, in approximately, 1 – 3 working days, which is the fastest among the existing methods of performing work;

– when performing work, it does not weaken the foundations under the foundations in the areas of work;

– due to the high polymerization rate of the solution, it has a predictable place of application of forces (does not spread) and material consumption (±3%);

– the polymer fastening method is non-destructive: injection is carried out through holes Ø30-32mm, which are stamped immediately after injection (i.e., heavy equipment is not used, there is no significant impact on the structure of the building, excavation, destruction of adjacent structures, etc. are not used); all consequences are removed in 1 working day;

– this method does not make the foundation base heavier, but thanks to the light root-like structures formed as a result of the work, it reinforces and compresses the soil and pushes water out of it.

Thus, in the future, design solutions were developed for the chemical consolidation of soils under the supports of the stairs. Within the framework of the project, calculations were performed in modern software packages with modelling of different operating conditions of the foundation base with different volumes of polyurethane material (Fig. 14). The parameters of chemical consolidation of the soil in the software package were set according to the recommendations of the material manufacturer and obtained as a result of experimental studies.

The project provides for two injections of polyurethane material into the soil, under each separate foundation, at different depths and in different volumes (Fig. 15). In particular, the upper injection layer is provided 1.0m below the foundation base in the volume of 35kg, and the lower injection layer is provided at a depth of 1.5m below the foundation base in the volume of 45kg.

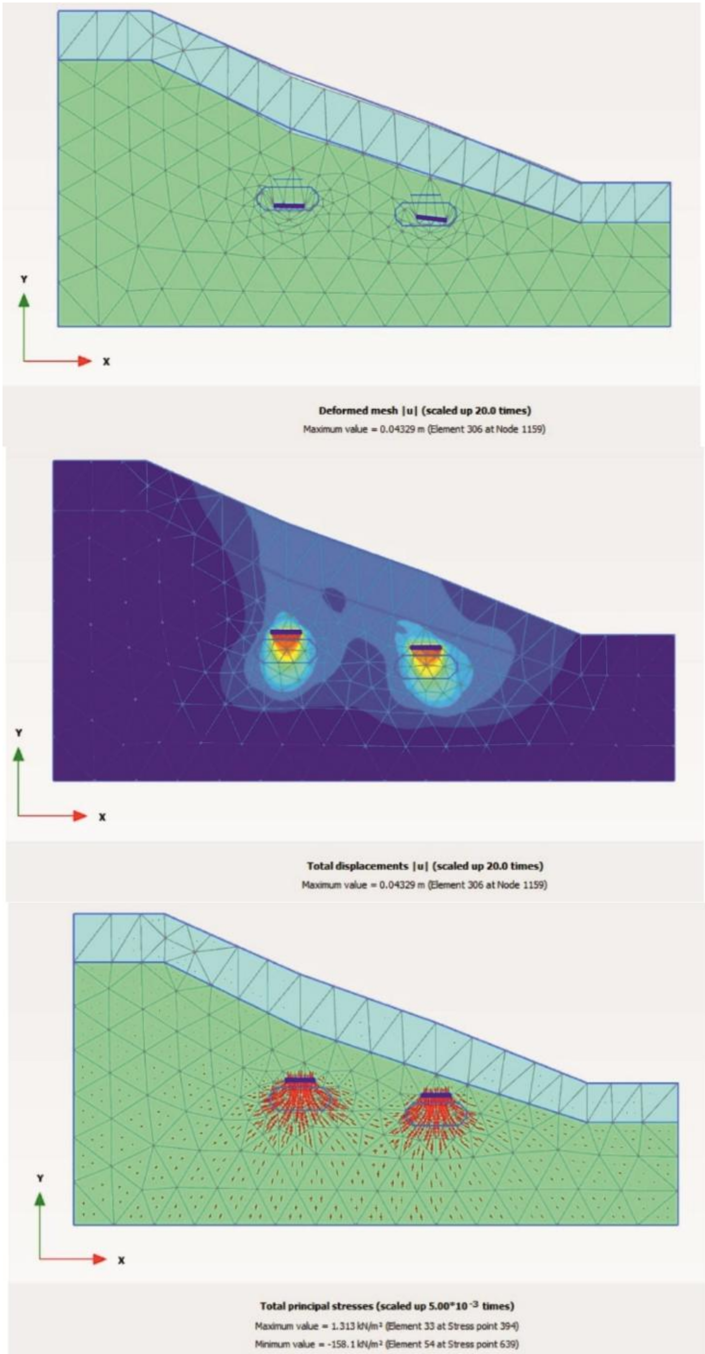

Fig. 14. Calculation results (top to bottom): principal stresses – calculation model; calculation results: deformed model; principal stresses

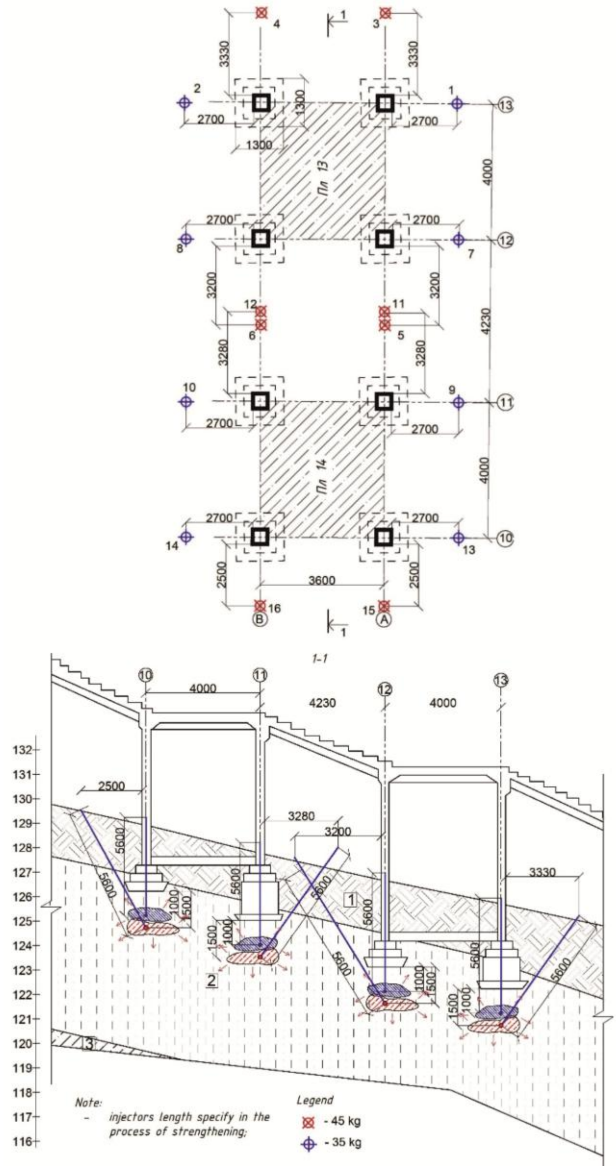

Fig. 15. Design solution for chemical soil consolidation under the foundations of the staircase supports: above – diagram of the foundations with injection sites of polyurethane material; below – section 1-1

At the construction site, chemical soil consolidation was performed in accordance with the developed design solutions in the following technological sequence:

– installation of injection equipment;

– preparation of the technological complex for work;

– injection of polyurethane SPT material;

– the dismantling of injection tubes and tapping of holes.

The process of installing injection equipment was carried out in the following sequence:

– before starting the installation, the injection steel tubes with a diameter of 14*1mm or 16*2mm of the design length were prepared, namely, they were cut;

– to prevent soil from entering the injection tube during its installation, a quick-release disposable steel tip was mounted on the lower end of the tube.

– the steel injection tubes were mounted in the hole to the design depth. If installation was impossible immediately to the design depth, partial finishing of the injection tubes was allowed.

– the free end of the tubes protruded above the soil surface by 100 – 200mm, for the convenience of installing the injectors and connecting the injection gun;

– before installing the disposable injectors, it was checked whether the check valve in the injector was working; when it was triggered, work was continued, or in another case, it was replaced with another one.

Preparation of the technological complex for work:

– before the start of the injection of polyurethane materials, the transport hoses were deployed and all the components of the technological complex (generator, compressor, reactor) were brought into working condition;

– before the start of the injection work, the reactor installation was started and heated to the required temperature.

Injection of polyurethane material. Before connecting the injection gun to the injector, the following was done:

– checked whether the safety switch on the back of the injection gun was in the "closed" position;

– opened the supply of materials A and B on the "liquid collector" on the injection gun;

– moved the safety switch on the back panel of the injection gun to the "open" position.

The injection process begins by connecting the injection gun, with the transport hoses connected to it, to the injector (Fig. 16). Injection begins immediately after pressing the lever on the gun and stops after releasing it.

Fig. 16. The process of injecting polyurethane material into the soil under the foundations of the staircase supports at the construction site.

The injection process was repeated at each designed point in the required volume of material. After the injection, a technological break was maintained, necessary for the material to achieve its maximum strength and dissipate the heat released during the reaction (40 – 60 min). After that, all injectors were dismantled (cut) to a level of 15cm below the soil surface, and the cavities of the tubes and the cavities around the tubes were filled with sand to prevent water or foreign objects from entering the injection holes.

During the construction stage and after (1.5 years after the soil was consolidated), geodetic and visual monitoring of the slope and stair structures was carried out, and no obvious deformations and displacements were detected. This fact indicates that the methodology presented in the publication, which is based on theoretical and experimental scientific research, allows for the effective implementation of the latest construction technologies in construction practice.

Conclusions

Within the framework of scientific and technical support, the problematic situation that developed with the stairs to the Magdeburg Law Monument was studied, and an analysis of scientific and technical literature was performed to identify possible methods of chemical soil consolidation under the support foundations. As a result, it was found that one of the optimal solutions for consolidation could be one of the new methods, which consists of introducing polyurethane material into the consolidation zone through thin steel tubes. However, this method at the stage of the need for its use was new and not tested on the territory of our state.

Following the program of scientific and research work, large-scale experimental studies were carried out to verify the effectiveness of the method of soil consolidation with polyurethane materials. It was found that due to the introduction of polymer materials, the soil was compacted, and consolidated with strong layers of soil-polymer mixture that penetrated it. In this case, there is no need to disturb the existing soil massif or interfere with existing foundation structures.

Based on the results of experimental studies, design solutions were developed that provide for the injection of polyurethane material through two separate tubes at two elevation levels from the base of the foundation.

The solutions provided for by the design were fully implemented at the construction site. The geodetic and visual monitoring of the slope and staircase structures during the construction phase and after it (1.5 years after soil consolidation) indicates that no obvious deformations and displacements were detected.

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переходу між **парками «Хрещатий» та «Володимирська гірка» у Печерському та Шевченківському районах м. Києва. Етап 5: Обстеження та оцінка технічного стану частини сходів до колони Магдебурзького права (довжина ділянки обстеження 72 м) та колонади Магдебурзького права»**, Київ, НДІБК, 2018.).

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