Constructive solutions to ensure the safety of the object of historical heritage in conditions of weak foundation soils

Igor Gandelsman*

1Vladimir State University named after Alexander and Nikolay Stoletovs, Gorky str., 87, 600000 Vladimir, Russia

Abstract. The article analyzes the results of a technical survey of a cultural heritage object. The building is located on the slope of the Oka River. During its existence, the building was rebuilt several times, which led to various design solutions of its individual parts. Additional complexity is associated with the location of the object on the slope, the presence of a significant thickness of bulk soils located under the foundations, high groundwater level, prolonged flooding of the basement of the building. Part of the foundation is made on wooden piles, partially lost during operation. To analyze the current state and determine the ways of reconstruction of the object, calculation schemes were drawn up to perform calculations of general static stability, the boundaries of the slope landslide zone for various cases and deformation of the base at different load levels were determined. The article identifies possible risks, analyzes the main models of the behavior of the soil foundation taking into account negative factors, carries out variant design of structural solutions to strengthen the foundation and foundation structures - by strengthening the foundations with micropiles of the "Titan" or "Atlant" type, or by fixing bulk soils to improve the geotechnical properties of soils with low resistance. The results of the conducted experimental studies and verification calculations emphasize the possibility of ensuring the regulatory operation of the foundation-foundation system, taking into account the improvement of the engineering and geological parameters of the foundation. This article contains an algorithm for the application of constructive solutions for each proposed variant of strengthening the foundation and foundations for the reconstructed object. The application of the research results allows to preserve the object of historical heritage, ensures the safety not only of the reconstructed building, but also of neighboring objects falling into the zone of influence of the object, the stability of the slope on which the object is located.

1 Introduction

The object under study is a production facility designed for processing grain into flour (flour mill). Construction began in 1914, then the building underwent repeated reconstruction, as a result of which it received two different-profile facades, to which was added a concrete

* Corresponding author: igvlsu@mail.ru
extension on the south side, erected in the 1970s. In the 1960s, after the explosion, the southern wall was dismantled and rebuilt. Currently, the mill building is not in operation. The mill building is an integral element of the Bashkirov mills industrial and production complex and is an example of a Soviet-era industrial structure characterized by an expressive architectural appearance.

Geomorphologically, the site is located at the foot of the steep right-bank slope of the Oka River. The marks of the daytime surface of the earth vary from 74.8 m to 84.4 m. The slope is landslide. To protect the object from adverse effects, a protective structure in the form of a retaining wall is organized near the walls from the eastern upland side of the building. The mill building is trapezoidal in shape, measuring 56.99x17.32 m in terms of external measurement, six-, seven-storey, partially with a basement. In the part of the building under the first floor there is a fire-fighting reservoir with a depth of 3.8 m.

![Fig. 1. Fasade.](image)

The walls of the mill building below the level of the layout are made of ceramic bricks on lime mortar, in their height the walls have a number of ledges with a characteristic increase in the width of the wall to the bottom. At the level of +0.640, a wooden drainage tray was made and the groundwater level was fixed at about the same level. Presumably, the tray serves to maintain a constant groundwater level, in order to preserve wooden piles. At the mark of -1.880 m, the brickwork ends, followed by a monolithic reinforced concrete slab with a height of 1500 mm. In the basement part of the building, the foundations are cross reinforced concrete strips with a height of 1300 mm on wooden piles up to 12 m long.

As a result of the study, it was found that bulk soils in the form of multi-grained quartz sands lie under the sole, in some places with an admixture of loam, with the inclusion of construction debris, coal sludge, in some places with weakly sealed clay, smeared.

Due to prolonged atmospheric effects on the object, changes in hydrogeological conditions, insufficient anti-landslide measures carried out at the object, as well as its reconstruction, a number of issues arose related to the further use of the historical object: maintaining the stability of the slope, ensuring the perception of a new level of loads by the foundation and foundations, maintaining the operability of the foundations themselves.

The theoretical foundations and methods for calculating foundations and foundations under similar conditions are described in the works of the following researchers Z.G. Ter Martirosyan [1-2], V.A. Il’ichev, Y. A. Gotman [3], R. Mangushev [4], A.B. Ponomarev [5-6], G.V. Postoev [7], A. Bishop [8], N. Morgenstern [8-9], G. Gitirana [10], A. Federico
Currently, there are numerous studies related to the issues of the stability of landslide slopes, construction on weak soils, strengthening of existing foundations and foundations. When operating such facilities, it is advisable to monitor the current state of the facility, the soil foundation, and perform dynamic forecasts of reliable joint operation of the "foundation-foundation" system when the initial conditions of their operation change. Only a comprehensive solution to these problems makes it possible to ensure reliable and safe operation of buildings and structures, especially objects of historical heritage [18-22].

The article discusses the issues of the current state of the object, the results of the calculation of options for strengthening the foundation and foundations. According to the results, work on the reconstruction of the mill building is proposed.

2 Materials & Methods

The climate of the design area is moderately continental with moderately harsh and snowy winters and moderately warm summers. The wind regime is formed under the influence of physical and geographical features. Cyclonic activity prevails here for most of the year. The area belongs to the zone of sufficient moisture. The annual precipitation is 527 mm. The height of snow by the end of winter (the second decade of March) reaches 50 cm.

In the geological structure, the studied area is represented by modern technogenic deposits (tQIV) in the form of bulk soils (0.4-9.5 m thick), modern alluvial deposits (aQIV) in the form of refractory, soft-plastic loams (4.2-4.4 m thick), modern landslide deposits (dIQIV) in the form of clays, with frequent interlayers of loam, marl, sand (with a capacity of 3.4-6.8 m), upper Permian deposits of the Tatar tier (P3) in the form of hard, semi-hard clay (with a capacity of 20.5-30.6 m) (see table 1).

The hydrogeological conditions of the site up to a depth of 40.0 m are characterized by the presence of a quaternary aquifer and an aquifer complex of Upper Permian deposits. The groundwater level is recorded at depths of 1.4-4.8 m, which corresponds to the absolute levels of 71.0-74.0 m of the Baltic system. The aquifer is unpressurized, the water-bearing soils are bulk soils, sand layers in clay landslide deposits, alluvial loams. The Upper Permian clays are a water barrier. The Oka River is an area of both supply and discharge of groundwater. The aquifer has a hydraulic connection with the Oka River.

In the course of a detailed study of the results of the pits, it was possible to establish the existing foundation structures under the mill building:
- in the axes "A-H"/"1-5", the foundations are made in the form of a monolithic reinforced concrete slab with a thickness of 1500 mm;
- in the axes "B-N"/"5-8", the foundations are made in the form of a monolithic reinforced concrete slab with a thickness of 1500 mm;
- the foundations for the attached stairwell and shaft in the axes "B"/"7-8" are represented by a monolithic reinforced concrete slab 450mm thick;
- in the axes "B-N"/"8-14", the foundations of the mill building are made in the form of monolithic reinforced concrete cross strips with a thickness of 1300 mm, on wooden oak piles up to 12 m long.

Thus, the object has different types of foundations under different parts of the building. The issue of ensuring their joint work is relevant.

The upper and lower reinforcement grids of reinforced concrete monolithic foundation plate are made with reinforcement of a periodic profile ø22 mm, with a cell 210x210 mm. The protective layers of concrete in the vertical direction are 50 mm, in the horizontal direction are 100 mm.
Table 1. Physical and mechanical characteristics of soils.

<table>
<thead>
<tr>
<th>Name of the engineering-geological element</th>
<th>standard values</th>
<th>calculated values ($\alpha=0.85$)</th>
<th>Calculated values ($\alpha=0.95$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho$, g/s$m^3$</td>
<td>$c$, kPa</td>
<td>$\phi$, deg.</td>
</tr>
<tr>
<td>1 Technogenic (bulk) soil (tQIV)</td>
<td>1.74</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>2 Clay refractory, soft-plastic (aQIV)</td>
<td>1.95</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>3 Clay landslide deposits: clay, with frequent layers of loam, marl, sand (dIQIV)</td>
<td>1.93</td>
<td>48/23</td>
<td>21/11</td>
</tr>
<tr>
<td>4 Clay solid (P3)</td>
<td>2.00</td>
<td>99</td>
<td>21</td>
</tr>
</tbody>
</table>

Fig. 2. Schurf. Foundation.

In addition, the features of the design solution are noted - the supporting part of the column is located in a spherical monolithic reinforced concrete shell with an approximate radius of 1050 mm and a thickness of 50 mm. The reinforcement of the shell is carried out
by separate rods in the horizontal direction from the reinforcement Ø10 of the periodic profile, in the vertical direction from the reinforcement Ø12 of the periodic profile. Apparently, the shell is part of the drainage system encircling the building around the perimeter. Also along the perimeter of the building along the outer walls, drainage channels of triangular cross-section with the dimensions of 500 mm cathets are made, and spherical near the columns. The drainage system was designed to drain groundwater infiltrating through the exterior walls and floor, beyond the perimeter of the building by pumping from the pits.

3 Results

The results of the verification calculations showed that the pressure under the sole of the foundation in the axes "A-H" /"1-7" exceeds the calculated resistance of the foundation soil (p_m = 181 kPa > R= 80 kPa), the sediment exceeds the permissible calculated values (s=151 mm >s_u=150 mm). The pressure under the sole of the foundation in the axes "B-D"/"10-13" exceeds the calculated resistance of the foundation soil (p_m = 280 kPa > R= 201 kPa). The pressure under the sole of the foundation in the axes "B-N"/"8-9" exceeds the calculated resistance of the foundation soil (p_m = 660 kPa > R=80 kPa). In other areas, the pressure under the sole of the foundation does not exceed the calculated resistance of the foundation soil, precipitation does not exceed the maximum permissible values.

The results obtained indicate the need to strengthen the grounds and (or) foundations.

![Stress fields in the foundation plate from the calculated combination of loads. Block A.](image)

3 Results

The slope stability coefficient can be found both using traditional methods of the theory of marginal equilibrium (with or without splitting the slide prism into compartments) and elastic-plastic calculations by the finite element method using the method of reducing strength characteristics [11, 12, 20]. A significant advantage of the strength reduction method in comparison with the limit equilibrium methods is that the sliding surface and the stability coefficient are determined simultaneously during the calculation process. It follows from the calculations performed by the SRM method that the slope stability is not provided. It is necessary, to provide alternative measures to ensure the safety of buildings and structures falling into the landslide zone [23- 25].
4 Discussion

The choice of the method of strengthening the foundation soils is determined [20, 23-26] by the peculiarities of engineering-geological structure, the location of the site, the requirements of the technical specification, the economic factor. For the device of stationary gratings (reinforced base) in the conditions under consideration, the following methods are applicable:

- injection, carried out by pumping chemical or cementing solutions into the ground using injectors or into wells (cementation, silication, tarring of soil);
- drilling mixing (by developing and mixing the soil with cement or cement mortars in wells);
- jet technology, which consists in using the energy of a jet of high-pressure cement mortar or water with an air stream to destroy and simultaneously mix the soil with cement mortar;

- strengthening of foundations with micropiles.

The use of drilling and blasting technology in these conditions with a large volume of reinforced soil and cramped working conditions is economically impractical.

To strengthen the soils of the foundation foundations in these engineering-geological and hydrogeological conditions, injection reinforcement methods or the device of boron-injection pile are mainly applicable.

Such injection methods of soil strengthening as silicification, soil tarring and bitumen grouting are ineffective on water-saturated soils due to the possible partial dilution of the reagent when injected into water-saturated soils, require significant investments and, depending on the reagents used, are environmentally unsafe. Taking into account these circumstances, the most acceptable way to perform reinforcement is the cementation of soils by injection in the mode of hydraulic fracturing (strengthening the soils of the base of structures by forming locally directed hydro fracturing with a strengthening solution).

This method of cementation is used for compaction (reinforcement), operational compensatory changes in the stress-strain state of the foundation soils and is based on the injection of cement-sand-clay solution into the soil thickness through macropores and ruptures in areas of weakened soil (formed during freezing and thawing of the soil), which, when solidified, gives the array the necessary strength and solidity. In the soils of the foundation base, a kind of reinforcing frame is created from lenses and interlayers of hardened
cement mortar, while the soil enclosed in a spatial frame is compacted with the removal of pore water from the reinforcement zone, as a result of which the bearing capacity of the foundation soils increases. The method does not require expensive materials, is quite simple in technological terms and has been tested on many objects of various sizes in conditions similar to the ground conditions of the construction site.

To prevent the development of deformations, it is necessary to strengthen the foundations of the building.

Based on experimental data and preliminary analysis materials, the following gain parameters are proposed. 3 types of solution for injection are considered:

1st in the following ratio: Cement -1 part, Water-0.6 part, Liquid glass-0.03 part;
2nd in the following ratio: Cement -1 part, Water-0.8 part, Liquid glass-0.03 part;
3rd in the following ratio: Cement -1 part, Water-1.0 part, Liquid glass-0.03 part.

After carrying out the control reinforcement and quality control, the optimal composition for these soil conditions is selected and, if necessary, the reinforcement parameters can be adjusted.

In the calculations, the determination of the strength of the soil cement is taken:

\[
R_{stb} = k_t R_{28}, \quad \text{where } k_t = 0.187 \ln \left( \frac{f}{7} \right) + 0.375
\]

The value of the deformation modulus of the soil cement before the experimental work:

\[
E_{stb} = k_s \cdot R_{stb}, \quad \text{where } k_s = 100.
\]

**Fig. 5.** Distance from PileTop / Resultant Shear.

It is recommended to carry out work on strengthening the foundation soils in the following technological sequence: Acceptance of an object with fixed axes; Marking of injection points; Cementation of soils by injection in the mode of hydraulic fracturing.

The solution is injected into the amplification zone by descending zones, separate approaches in increments of 0.5...1.0 m. The approximate flow rate of the solution per running meter of the well is specified during the work. The water-cement ratio in the solution to obtain its necessary mobility is established during injection, depending on the quality and condition of the constituent components and is specified during trial (control) injection.
During the production of works, the composition of the solution can be adjusted. During injection, constant monitoring of the exits (breakthroughs) of the solution to the surface is carried out.

![Graph](image1)

**Fig. 6.** Structural analysis results. Foundation B.

As an alternative, it is possible for this object to use boron-injection piles to transfer the load from the building not to bulk soils, but to the underlying stronger layers of the base. The boron-injection piles are arranged vertically. In accordance with EN 1993-1, drill-injection piles have a maximum shear resistance of 73.3 kN, have a maximum elastic moment of 2.6 kNm. As a result of the calculations carried out, piles with a length of at least 4 m should be selected on site A, and 7 m on site B. (see fig. 3, 4). The calculation results are confirmed by checking in GGU-AxPile.

![Graph](image2)

**Fig. 7.** Inner load carrying capacity boron-injection piles.
5 Conclusions

Based on the results of studies of the historical heritage site, taking into account the existing relief, engineering and geological conditions, the following conclusions can be drawn: to preserve the object, a comprehensive solution is needed, including ensuring the stability of the slope, organizing the flow of surface water, solving the problem of transferring the load from the building to the solid layers of the foundation, restoring damaged elements of building structures.

2. Having considered the possibilities of using various solutions for the prevailing conditions of the historical heritage object, a conclusion was made about the possibility of using - injection, carried out by injecting cementation solutions into the ground with the help of injectors and the use of boron-injected piles to transfer the load from the building not to bulk soils, but to the more durable layers of the base.

3. For the injection method, compositions for fixing bulk soils and the technology of work are proposed.

4. For boron-injection piles- their parameters are determined, the bearing capacity is calculated, the technology of work production.

5. The boron-injection piles is designed to solve a wide range of engineering tasks, including fixing unstable sections of the soil massif. It allows you to quickly and efficiently carry out work in conditions of limited space without negative destructive effects on nearby objects and ensure reliable operation of the foundation for many years. In the case under consideration, with a high level of groundwater, flooding of the basement, it seems to the author more promising.

Acknowledgements

The study was carried out using the equipment of the interregional multispecialty and interdisciplinary center for the collective usage of promising and competitive technologies in the areas of development and application in industry/mechanical engineering of domestic achievements in the field of nanotechnology (Agreement No. 075-15-2021-692 of August 5, 2021). The author expresses gratitude to the representatives of the company ISCHEBECK GmbH for their cooperation in the preparation of the article.

References


