The Choice of Effective Geotechnologies to Ensure the Preservation of Historic Buildings During Their Renovation with the Underground Space Development

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Abstract. The research was conducted on the effectiveness of modern geotechnologies providing minimal soil mass deformations under historical buildings and monuments renovated with underground part development. Analysis of the worldwide experience in renovation of historical buildings and architectural monuments revealed trends in application of geotechnologies concerning underground part development. As a result of numerical experiments with a use of PLAXIS and MIDAS GTS software conducted in 2D and 3D for Moscow typical geology conditions and on-site deformation measurements during renovation of historical buildings with underground part development the method for the settlement prediction at the initial phase of design was proposed. For engineering calculations the graphical interpretation is presented describing the settlement formula for buildings with foundations underpinned by jet piles during the underground floor construction. Recommendations have been done for applying geotechnologies in renovation of historical buildings and monuments with underground part development.

1. Introduction

Underground space is developed during renovation of historical buildings and monuments located in the central parts of the cities. The underground part during renovation can be arranged below the building structure, extend out of a building outline or adjoin it.

Buildings having a long period of exploitation are often in unsatisfactory technical condition and permissible additional settlement values are rather low for them (according to SP 22.13330.2016 standard). So for the renovation to be provided there is a need in specific methods of construction to ensure preservation of such buildings.

Among modern innovative geotechnologies the following methods are used in renovation with underground development:

- the arrangement of retaining structures such as a diaphragm wall, structures made using jet grouting, deep mixing, the CFA method, also with strengthening of soil mass behind the retaining structure of the excavation and below its bottom with the use of controlled jet grouting;
- the arrangement of a support system using steel pipes with jacks or reinforced slabs (top-down and semi top-down methods);
• the arrangement of mitigation measures: compensation grouting, piles made by new pile technologies.

2. Research aim.
The research was aimed at choice recommendations of effective geotechnologies to ensure the preservation of historic buildings during their renovation with the underground space development

Until now in Russia modern geotechnical technologies have been applied locally at certain objects of historical monuments’ renovation without generalization and systematization considering structural design of underground parts and soil conditions.

Based on the analysis of the Russian and worldwide experience in the renovation of monuments [1-7], research directions have been established.

3. NUMERICAL AND ON-SITE EXPERIMENTS

3.1 Settlement calculation for foundations of building renovated with underground part development

At initial phase of design for the settlement calculation for foundations of building renovated with underground part development the formula (1) suggested in [8] could be used.

\[ S_{\text{exp}} = K_{ct} \cdot K_{e} \cdot K_{H(1)t} \cdot K_{r} \delta \varphi(x) + q/k \]  

where \( x \) is the coordinate of a foundation point (\( x=0 \) on the nearest end of a foundation to a pit); \( k \) is the subgrade reaction coefficient; \( q \) is the foundation pressure of strip or slab foundation; \( K_{r} \) is the coefficient, based on type of bracing structures for a pit [11]; \( K_{ct} \) - reduction coefficient for predicted settlement without mitigation measures [9,10]; \( K_{H(t)} \) - the coefficient of settlement reduction due to increased soil characteristics under the foundations of historical buildings over a period of their exploitation; \( K_{H(1)t} \) - the coefficient of settlement increase during a construction of an extra floor of an existing renovated building.

Coefficients \( K_{ct}, K_{e}, K_{H(1)t} \) were obtained according to the experimental research on stress-strain condition of soil mass during an underground part construction of renovated historical buildings carried out by numerical modeling and analysis of geodetic monitoring.

3.2 Numerical modeling

According to the classification of Moscow geological conditions [12], the following types were considered: I - dense and medium-density sands, II - clayey soils, with very stiff, stiff, firm-stiff consistency, III - clayey soils with firm, soft-firm and very soft-soft consistency or loose sands. Type III also characterizes the weak clayey soils of St. Petersburg. Renovation specificity for buildings with underground part in loose saturated sands reviewed in [13].

Numerical research was conducted for the renovated architectural monuments in the center of Moscow: an administrative building with the construction of an underground part below the building structures in the inner courtyard space (soil conditions type-I) (MIDAS GTS 3D, Plaxis 2D (Fig.1)); a multifunctional complex, the underground part of which adjoined the renovated historical buildings (soil conditions type – I-II) (PLAXIS 2D) (Fig. 2); three administrative buildings of 2, 5 and 7 stories high adjoined by underground part with (12-18 m deep) (soil condition type IIIa) (PLAXIS 2D), etc.

During the renovation of the administrative building (Fig. 1) excavation was braced with struts and soil under foundation was strengthened with Microdur. For the multifunctional complex (Fig. 2), the soil was strengthened by the technology of jet grouting under the foundation of each building. The excavation adjoined three administrative buildings was retained by diaphragm wall 600-800 mm thick supported by steal pipe struts. The pressure under the strip foundation of the building \( q \) was assumed to be at 100, 200 and 300 kPa for 3, 5 and 7-storey buildings, respectively [14]. The depth of adjoined underground part was 12 and 18 meters. The strip foundations of renovated buildings were underpinned by jet grout columns 600, 800 mm in diameter and 13, 20 m in length with spacing of 3 m. For the calculation in Plaxis 2D software Hardening soil model was chosen. Effective deformation
modulus for a soil strengthened with jet grout columns was calculated in accordance with recommendations [15].

For the Hotel Moskva on Manezhnaya Square in Moscow (soil conditions type II) with the construction of a 2-level and 4-level underground part below the building structures during its renovation, the calculations were done taking into account the increase in the characteristics of the soil under the historical building for a long period of exploitation according to the method contained in TKP 45-5.01-67-2007 (02250) [16].

3.3 Geodetic monitoring
The analysis was performed for geodetic monitoring data collected for two renovation objects: the building of the Bolshoi Theater with the construction of an underground part below the building structures (soil type II) (Fig. 3) and the Neglinnaya-Plaza complex in Moscow with the construction of a 2-5 level underground part in the inner courtyard space (soil type III) (Fig. 4).

3.4. Results of the experimental research
For multi-storey and single-storey historical buildings or architectural monuments (with load-bearing brick walls without reinforcement) under renovation with underground development the main deformation criterion for the their soil base was defined – the additional curvature of the foundation footing $\rho_{ad, u} = 4 \cdot 10^{-5}$ m$^{-1}$ [8].

The obtained coefficients of settlement reduction of the renovated buildings with various types of mitigation measures (pile underpinning, soil strengthening with Microdur injection, etc.) considering the technological settlement [18,19] are listed in table 2. Also experiments allowed to obtain the coefficient of settlement increase of historical buildings renovated with the development of the underground part and the construction of the extra floor $K_{H/1} = 1.1 \ldots 1.2$ and the coefficient of settlement reduction due to increased strength and deformation characteristics of the soil under the foundations of historical buildings and monuments over a long period of their exploitation $K_r = 0.8 \ldots 0.9$.  

![Fig. 1. Shadings of vertical displacements. The renovation of the administrative building – architectural monument in the center of Moscow.](image1)

![Fig. 2. Shadings of horizontal displacements. The renovation of multifunctional complex.](image2)
**Table 1.** Coefficient for predicted settlement without mitigation measures $K_\text{ct}$

| Type of mitigation measure                                                                 | $K_\text{ct}$ |
|-------------------------------------------------------------------------------------------|---------------|
| Compensation grouting (vertical and horizontal); prestressed strutting structures (struts with jacks); controlled jet-grouting; jet piles in combination with micropiles or jet piles with drill pipe left in a pile | 0.2           |
| Compensational micropiles for underpinning; soil strengthening with Microdur                | 0.1           |
| Underpinning with piles                                                                   | 0.5-0.7       |

The modeling of underpinning with jet grout columns for foundations of three adjacent administrative buildings showed reduction of additional settlement to normative value for $q=100$-$200$ kPa, $H_k=12$ m (soil conditions I). Besides that in all cases the difference between settlements doesn’t exceed normative values.

Additional settlements along the length of renovated building for the range of $q=100$-$300$ kPa and $H_k=12$-$18$ m could be obtained by empirical formula (2). Table 2 also contains coefficients for soil conditions IIIa and IIIb. Technological settlement could be considered by recommendations contained in [20]. The graphical interpretation of the equation is shown in Fig.5.

$$S \left( \frac{x+1}{H_k}, q \right) = K_1 + K_2 \cdot \left( \frac{x+1}{H_k} \right) + K_3 \cdot q + K_4 \cdot \left( \frac{x+1}{H_k} \right)^2 + K_5 \cdot \left( \frac{x+1}{H_k} \right)^3 + K_6 \cdot \left( \frac{x+1}{H_k} \right)^4 + K_7 \cdot \left( \frac{x+1}{H_k} \right)^5 + K_8 \cdot \left( \frac{x+1}{H_k} \right)^6 + K_9 \cdot \left( \frac{x+1}{H_k} \right)^7 \cdot q,$$

(2)

where $x$ is the coordinate along the length of the building; $K_1$...$K_9$ – empirical coefficients (see table 2).

**Table 2.** Equation (2) coefficients to define a settlement of renovated building underpinned with jet grout columns

| Type of soil conditions | $K1$  | $K2$  | $K3$  | $K4$  | $K5$  | $K6$  | $K7$  | $K8$  | $K9$  |
|------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| I                      | -10.09| 8.346 | -0.05329 | -2.19 | 0.03262 | 0.1674 | -0.006613 | 0.003165 | 0.0004405 |
| IIIa                   | -8.746 | 4.871 | -0.07475 | -0.22 | 0.04446 | -0.216 | -0.00951 | 0.02548 | 0.0007336 |
| IIIb                   | 2.418 | -12.57 | -0.3377 | 7.521 | 0.2117 | -1.502 | -0.04594 | 0.09911 | 0.00331 |

Fig. 3. Underground part design of the Bolshoi Theater in Moscow [17]  
Fig. 4. Inclinometric boreholes in the diaphragm wall of the Neglinnaya-Plaza
Fig. 5. The settlement of renovated building adjoined by underground part considering technological settlement (type I of soil conditions). Underpinning with jet grout columns.

4. THE CHOICE OF EFFECTIVE GEOTECHNOLOGY FOR RENOVATION OF HISTORIC BUILDINGS WITH THE UNDERGROUND SPACE DEVELOPMENT

The choice of the technical solution for initial phase of historical buildings renovation with underground space development is influenced by a number of factors, such as the rigidity of the retaining structure, water permeability, the value of the settlement caused by the increased load on existing foundations during the renovation of the above ground part, and also the value of the technological settlement dependent on working processes.

Choice recommendations for geotechnologies in mitigation measures for existing historical buildings and monuments with an underground space development as part of their renovation are included in table 3 [8] depending on the category of technical condition of their structures.

| Type of building                  | Category of structures’ condition | Mitigation measures                                                                 |
|----------------------------------|-----------------------------------|-------------------------------------------------------------------------------------|
| Monument, historical             | III, II                           | Compensation grouting; controlled jet-grouting; compensatory micropiles; prestressed strutting structures |
| Monument, historical on reconstruction | III                              | Underpinning piles (micropiles, jet grout columns, jacked piles);               |

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