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Reduction of additional pressure from ground construction on the subway escalator tunnel

A.A. Sokornov[1*], *A.N.* Konkov[1], and *V.D.* Konstantinov[1]

[1] Emperor Alexander I St. Petersburg State Transport University, 190031, 9 Moskovsky pr., Saint Petersburg, Russia

Abstract. The study considered options for reducing the additional pressure from the construction of a single-storey building on the underground structures of a deep shallow metro station. In the 3D formulation, the efficiency of the unloading «bridge» over the escalator tunnel was evaluated by the finite element method. It was found that the stiffer the grillage plate of the unloading «bridge», the more effectively the additional pressure from the building is transferred to the soils below the bottom of the escalator tunnel. However, in this case it is impossible to completely eliminate the additional pressure. In this regard, the option of creating an underground floor was considered. In this case, the weight of the selected from the excavation soil compensates the load from the building. The required depth of the basement floor was determined analytically, calculations were performed in characteristic sections on 2D models, and the operation of all structures in combination was considered on a general 3D model. Based on the results of the study, a rational algorithm was proposed for calculating the additional pressure from ground construction on underground subway structures.

1 Introduction

In cities with a developed metro system, with an increase in building density, there can arise some situations when new building is under construction above the already operated subway structures. And while the impact of subway tunneling on existing buildings has been studied comprehensively and thoroughly [1-9], the distribution of additional pressure from above-ground construction on existing underground structures is an urgent scientific direction [10-12]. The main calculation criterion in this case is the amount of additional pressure that can be absorbed by an underground structure in addition to existing loads.

The amount of additional pressure from above-ground construction should be regulated depending on the deformability of the underground structure. Thus, it is advisable to allow more additional pressure on the lining of single-track interstation tunnels than on the lining of a station tunnel, and it is advisable not to transfer additional pressure on the lining of an escalator tunnel at all, since even a slight change in the geometry of the structure will necessitate the escalator systems reconfiguration. At the same time, in the case of a deep underground station, the territory above the escalator tunnel with a length of one hundred

* Corresponding author: scarlunch@mail.ru

meters or more turns out to be very tempting for the developer, provided that he is able to minimize the impact of ground construction on the escalator tunnel.

In construction, there is a well-known option for constructing unloading "bridges" on massive bored piles-columns located in a plan with a certain pitch on both sides of the escalator tunnel and going several meters deeper than its lower part, thereby ensuring the transfer of pressure from the building not to the escalator tunnel lining, but to the ground massive. From the point of view of structural mechanics this option is reliable, but it is very expensive and time-consuming. In the case of low-rise construction on the territory above the escalator tunnel, there can be taken a more original solution: to arrange an underground floor, thereby reducing the additional pressure by replacing a solid volume of soil with a "hollow" system of building structures with its loads.

The object of the study was a projected one-storey commercial and household building located above a deep-shallow station complex, including an escalator tunnel. The purpose of this study was to investigate the effectiveness of the additional pressure reducing from one-storey ground construction on the escalator tunnel of a deep- shallow metro station.

To achieve this purpose, the following tasks were completed:

– building a 3D model to evaluate the effectiveness of various options of unloading "bridges" over an escalator tunnel;

– construction of 2D models in sections above the escalator and station tunnels to assess the effectiveness of the basement floor;

– creation of a general 3D model of the building foundations with a basement, ground massiveive and underground structures;

– comparison of modeling results in two- and three-dimensional settings.

2 Materials and methods

The study considered a one-storey building with a complex outline in plan, measuring 138 x 133 m, constructer above a deep-shallow metro station complex. A characteristic feature of the building under construction is the circular courtyard, created to provide the necessary access to the ventilation shaft of the station complex. At the same time, two sections of the building foundation are located directly above the escalator and station tunnels (Fig. 1). The depth of laying (from the ground surface to the top of the lining) of the station tunnels is 57 m. The minimum depth of the escalator tunnel in the area of the building under construction is 27.6 m

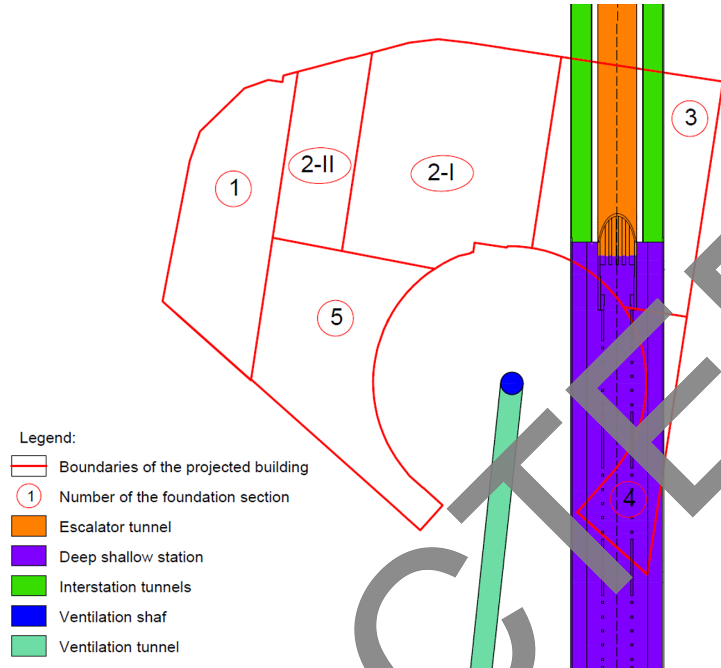

Fig. 1. The scheme of the building under construction and the subway structures location

The loads from the foundation sections No. 1 – No. 5 (the sum of permanent and temporary loads, taking into account the own weights of foundation slabs and piles) are summarized in Table 1.

Table 1. The sum of permanent and temporary loads, taking into account the own weights of foundation slabs and piles

Section number	Distributed load, kPa	Pile load, kN/m^2	Characteristics of the foundation
1	35	1750	Cast reinforced concrete plate 0.4 m; bored piles ∅0.6 m, L 20 m
2-II	–	2050	Cast reinforced concrete plate 1.0 m; bored piles ∅0.6 m, L 20 m
2-I	111	–	Cast reinforced concrete plate 1.0 m
3	111	–	Cast reinforced concrete plate 1.0 m
4	37	–	Cast reinforced concrete plate 0.4 m
5	–	2050	Cast reinforced concrete plate 1.0 m; bored piles ∅0.6 m, L 20 m

The main condition put forward by the operating organization was not to transfer additional pressure to the escalator tunnel at all and no more than 15 kPa to the station tunnels.

Studies of additional pressure impact on subway structures were carried out using mathematical models built in the MIDAS GTS NX program complex based on the finite element method. This complex is widely used in the scientific community and is used in calculations of complex systems such as "foundation – ground" or "lining – ground", and the results of mathematical modeling in a number of studies had high convergence with nature [13-16].

2D and 3D models of the ground massive accommodate the conditional foundation of the building and the lining of underground subway structures. The Mohr-Coulomb model was used to describe the mechanical properties of finite elements of ground massive. The mechanical characteristics of the soils are summarized in Table 2.

Table 2. The mechanical characteristics of the soils

Description of the soil	Modulus of elasticity E, MPa	Poisson's ratio ν	Volumetric weight γ, kN/m^3	Cohesion C, kPa	Angle of internal friction φ, deg
Bulk soil: loams with plant residues with fragments of wood	5	0.30	17.3	3	7
Stiff clay with sand	13	0.35	19.5	43	21
Firm – stiff clay with sand	11	0.35	19.3	28	17
Firm – stiff clay with gravel and layers of silt and sand	11	0.35	20.5	32	20
Stiff clay with gravel and sand	15	0.35	20.6	55	22
Very stiff dislocated layered clay with sandstone fragments and layers	25	0.42	20.5	105	17
Very stiff dislocated layered clay with sandstone layers	32	0.30	20.9	115	19
Very stiff layered clay with sandstone layers	200	0.23	21.5	126	22

The same calculation stages were set for both 2D and 3D models. At the first stage of the calculation, a ground massive was considered to create an initial stress field. At the same time, the final elements of the lining were assigned soil characteristics. After of the first stage calculation, all movements were reset to zero. At the second stage of the calculation, the constructing of underground structures was simulated. As it was shown in previous studies [11], the value of the additional pressure is not affected by the method of tunnel modeling (activation of the lining finite elements in a stressed massive or taking into account the initial deformations of the tunnel excavation). Therefore, at this stage of the calculation, the final elements of the excavation (of the soils inside the tunnels) were turned off, and the linings final elements were assigned the appropriate characteristics of structure materials. At the third stage, the construction of the building was modeled by including loads on the soles of the slab foundation sections and sections of pile foundations, considered as conditional foundations – so that the load from these sections was modeled not as from individual piles, but as from a solid foundation bounded from the bottom by edging piles (for more information, see [10]).

An elastic model was used to describe the mechanical properties of the underground structures lining finite elements. Prefabricated tubing linings were modeled using the reduced rectangular sections in accordance with [17]. This technique is legitimate due to the negligible change in contact pressures when modeling the linings using the reduced section method in comparison with a more detailed modeling.

The mechanical characteristics of the linings are presented in Table 3.

Table 3. The mechanical characteristics of the linings

Structure	Description of the structure	Height of the reduced section, m	Modulus of elasticity E, MPa	Poisson's ratio ν	Volumetric weight γ, kN/m^3
The escalator tunnel lining	Cast iron tubbings	0.234	110 000	0.22	76.5
The station tunnels lining	Reinforced concrete tubbings	0.323	34 500	0.2	24.5
The station columns	Steel pipes	0.268	200 000	0.25	77.2

3 Results

3.1. The effectiveness of the unloading «bridge» over the escalator tunnel

The first design and technological option to minimize the additional pressure on the escalator tunnel was to create an unloading «bridge». The effectiveness evaluation of this method in existing geological conditions was performed on a 3D model (Fig. 2), which includes a ground massive, an escalator tunnel section and a grillage based on bored piles. The piles were buried 1 m below the escalator lining to transfer the load to the ground. The load on the slab corresponded to the maximum evenly distributed load from the building under construction (111 kPa).

The model considered three cases:

1) the absence of an unloading «bridge» – the transfer of load from the building to the plate;

2) the device of the unloading «bridge» – the transfer of load to the grillage on piles;

3) an increase in the elastic modulus of the plate by 10 times, the case of a «hard» grillage.

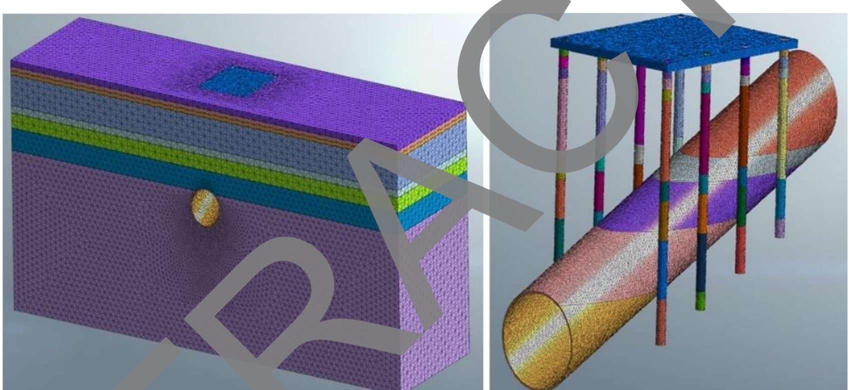

Fig. 2. General view of the unloading «bridge» and the section of the escalator tunnel model

As a result of calculations, the pressure values at the contact «lining – ground massive» were obtained for each of the calculated cases. Along the length of the escalator tunnel, values at 15 points were considered (point No. 15 is at the maximum depth). A comparison of the values of the additional pressures is shown in Fig. 3.

When transferring the load from the building to the plate without piles, there is a sharp increase in the additional pressure on the escalator tunnel lining directly at the edge of the plate (109 kPa) with attenuation as the depth of laying increases. In the case of resting the grillage on the columns, the additional pressure is reduced by almost 4 times compared to the foundation plate (27 kPa). This indicates the effectiveness of the unloading «bridge». With an increase in the stiffness of the grillage, the maximum additional pressure was 6.4 kPa, which is almost 17 times less than with a conventional plate. Obviously, this variant of the unloading «bridge» design is the most effective in application and can be implemented by including cross beams connecting column piles into the structure.

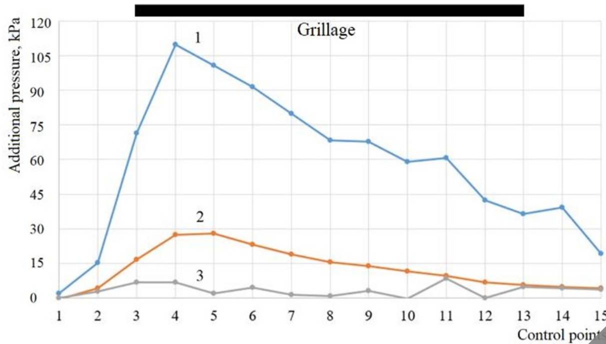

Fig. 3. Graphs of the distribution of additional pressure on the escalator tunnel lining: 1 – in the absence of an unloading «bridge» (load transfer to the plate); 2 – the device of the unloading «bridge»; 3 – an increase in the stiffness of the grillage by 10 times

3.2. The effectiveness of the basement floor

Despite the effectiveness of the unloading «bridge», the operating organization has put forward a radical requirement – reducing the additional pressure to zero. In this regard, the authors proposed an original solution with the creating of basement floors under the sections 2-I and 3 (see Fig. 1). The simplest analytical calculation showed that the installation of a basement floor with a depth of 6.7 m compensates for the load from a single-storey building and provides «negative» additional pressure on the escalator tunnel. The influence of section 4, located directly above the station tunnels, was estimated at 3.1 kPa and was determined by the attenuation coefficient according to the method described in the previous work of the authors [10].

However, in this example, the analytical calculation could not be considered sufficient, since the calculation did not take into account the cumulative impact of all the foundation sections.

Therefore, at the next stage, two flat finite element models were constructed in characteristic cross sections affecting the escalator tunnel and the platform section of the station (Fig. 4).

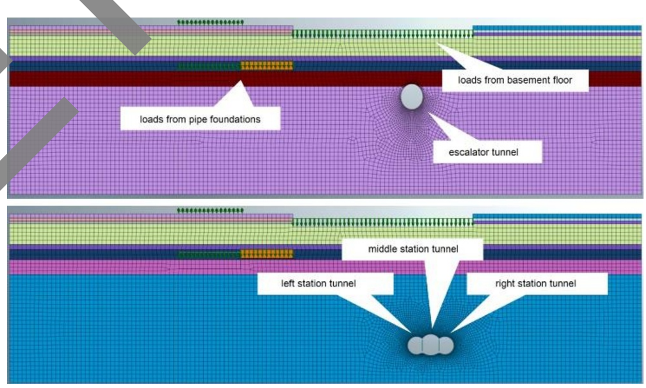

Fig. 4. 2D finite element models in cross sections along the escalator tunnel and the platform section of the station

The building under construction was set by distributed loads acting on the soles of plate foundations and on the soles of conditional foundations of pile fields.

The calculation results showed the absence of additional pressure from new construction on the escalator tunnel and additional pressure within 2 kPa on the station tunnels due to the influence of neighboring sections of pile foundations.

Since the building under construction has a complex outline in plan, and the underground structures are interconnected in space, in order to make a final decision on the possibility of construction, the entire system was calculated in a 3D setting.

Figure 5-6 shows the general views of the finite element 3D model of the building under construction and the complex of the main underground structures of the metro station. The following objects are indicated by numbers:

– 1, 2-II, 5 – plate-pile foundations of the building, modeled as conditional foundations;
– 2-I, 3 – sections with a basement and foundation plates;
– 4 – low-load section of the building with a distribution base plate;
– 6, 7, 8 – ventilation shaft, trunk yard and ventilation tunnel, respectively;
– 9 – station tunnels;
– 10 – escalator tension chamber;
– 11 – escalator tunnel;
– 12 – interstation tunnels.

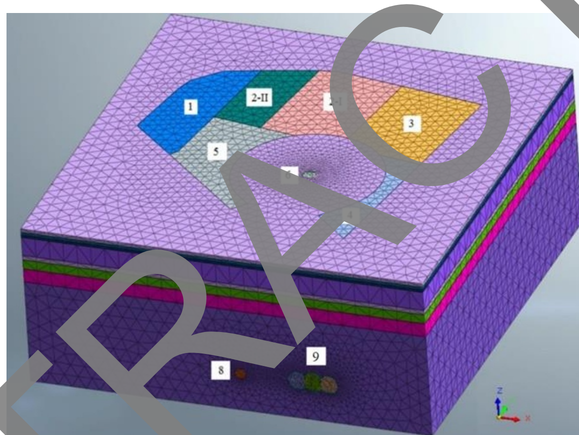

Fig. 5. General view of the 3D model from the side of the station tunnels

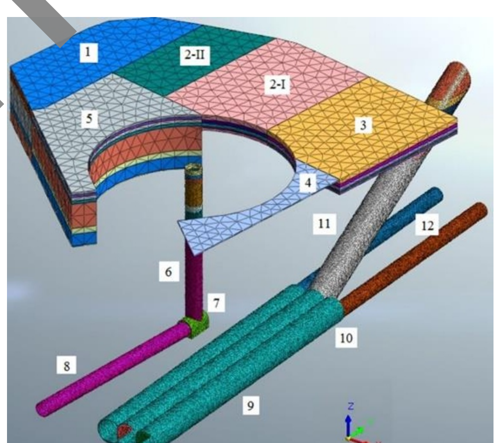

Fig. 6. General view of the 3D model (the ground massive is not shown)

In both 2D and 3D models, the simplification of the design scheme was modeling the fastening of pits by prohibiting horizontal movement of soil, since in the excavation process only vertical movements of the pit the bottom have the decisive importance (Fig. 7).

Subsequently, this drawback of the design scheme was eliminated because of the decision taken by the builders to install a firing system of steel pipes installed on the binding belt of the excavation fence and the base plate (Fig. 8).

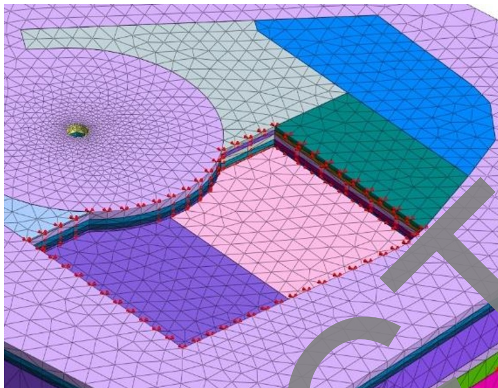

Fig. 7. Modeling of the foundation pit fastening by prohibiting horizontal movement of soil in a 3D model (sections of the foundation № 3, 2-I)

Fig. 8. The firing system installed on the binding belt of the foundation pit fence (using the example of the foundation section № 3)

4 Discussion/ Analysis of the results

The results of the analytical calculation were compared with calculations using the finite element method in 2D and 3D formulation (Table 4). It is noteworthy that the values obtained by different calculation methods correspond qualitatively to each other: thus, the additional pressure on the escalator tunnel turned out to be negative, and the additional pressure on the station tunnels was predominantly positive.

Table 4. The results of the analytical calculation

Comparison criteria	Analytical calculation	2D modeling	3D modeling	
			min	max
Additional pressure on the escalator tunnel, kPa	Negative value	-10.4	-8.2	-1.0
Additional pressure on the left station tunnel, kPa	+3.1	-2.4	+1.0	+6.1
Additional pressure on the center station tunnel, kPa	+3.1	+1.8	+2.0	+6.1
Additional pressure on the right station tunnel, kPa	+3.1	-0.8	-2.0	+5.1

Quantitatively, the 3D model shows the cumulative effect of structures on each other: the additional pressure on the escalator tunnel is negative, but closer to zero due to the influence of neighboring sections of the pile foundation.

The results of the performed study correlate with each other, but are based on a general assumption: the sections of the pile foundation of the building were considered in the calculations as conditional foundations and the load from the building was entirely transferred to the level of the pile cut. In reality, a significant part of the load is transferred to the massive due to friction along the side surface of the piles. In this sense, the calculations performed go into a significant margin. On the other hand, the constructed models do not take into account the horizontal component of the stresses transmitted to the ground massive, which can increase the additional pressure on individual underground structures. But even in this case, unloading the massive from the creation of the basement floor should have a decisive effect on the distribution of additional pressure.

5 Conclusion

1. Based on the results of 3D modeling, an assessment of the efficiency of the unloading «bridge» above the escalator tunnel was performed. It was found that the unloading «bridge» is able to reduce the amount of additional pressure up to 17 times compared to the operation of the plate foundation. With an increase in the rigidity of the grillage, the transfer of additional pressure to the soils below the sole of the escalator tunnel becomes more effective, but it is almost impossible to completely reduce the additional pressure to zero.

2. The constructed 2D models with basement floors on the foundation sections directly above the escalator tunnel showed the effectiveness of this solution: the additional pressure on the escalator tunnel became negative. At the same time, the station tunnels received an additional pressure within 2 kPa due to the influence of neighboring sections of pile foundations.

3. The general 3D model of the building foundations, the ground massive and underground structures made it possible to evaluate all the structures work in its combination. Compared with the 2D model, the additional pressure on the escalator tunnel shifted from negative values to zero, and the additional pressure on the station tunnels increased to maximum values of 6.1 kPa.

4. A comparison of the simulation results in 2D and 3D formulations showed their qualitative convergence. Quantitatively, the values of additional pressure on underground structures in the 3D model turned out to be somewhat large due to the consideration of the influence of all sections of the building foundation in the aggregate.

Summarizing all the results of the study, we can propose the following algorithm for assessing the impact of surface construction on underground structures. At the initial stage of solving problems of this class, it is premature to proceed to the construction of a 3D model. You should start by building simple analytical models that consider the system abstractly in the form of additional pressure and its attenuation in depth to the level of the underground structure. Despite this simplified approach, already at this stage of solving the problem, it is possible to estimate the amount of additional pressure in the first approximation, to determine whether it fits into the permissible values set by the owner of the underground structure.

Moreover, with a negative value of the additional pressure along the base of the foundation, in the absence of the influence of other buildings, buildings or sections of the foundation being constructed, the analytical calculation immediately gives an objective result that can be accepted even without making finite element models.

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