Determination of the excess excavation ratio from the data of geodesic monitoring

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Abstract. Introduction: During constructing tunnels by trenchless method using the shield driving method soil surface subsides. Buildings and structures which fall into the zone of influence of new construction receive additional settlements. To determine it in the calculations it is necessary to take into account the excess excavation ratio. The purpose of the study is to determine the excess excavation ratio for increasing the sample and determining the normative values of the ratio for application in design.

Materials and methods: in the article there is examines the construction of a tunnel in the city of Moscow. Calculations are carried out using the PLAXIS software package in two-dimensional and three-dimensional formulations. In the calculations the normative excess excavation ratio was included and a backward calculation was also carried out in order to determine the actual excess excavation ratio according to the data of geodesic monitoring.

Results: the results showed that the excess excavation ratio varies from 0.1% to 1.2%. It is much less than the values that are included in the project according to the regulatory documentation.

Conclusions: due to the fact settlement is less than the calculation settlement, the cost of building tunnels can be reduced by reducing the cost of protective measures for buildings and structures, as well as reducing the number of buildings that can receive excess settlement.

1. Introduction
The rapid growth of cities and population in the modern world make the development of the city’s transport infrastructure important. In large cities the movement of elevated transport is very difficult due to the large number of cars which is constantly increasing every year. To reduce the load on elevated transport it is necessary to develop underground space for the construction of metro facilities. They will ensure the constant movement of transport and, therefore, the rapid movement of people around the city. In connection with the possibility of additional deformations of soil surface and nearby buildings and structures as a result of TBM tunneling it is necessary to assess the impact of construction on nearby buildings and structures located in the pre-designated zone of influence in order to ensure their safety and performance reliability [1].

In study using numerical modeling Strokova [2] showed that the methods of driving tunneling and changing the distance between the axes of double tunnels have a significant impact on additional movements of buildings. The type of soil has a lesser effect on the additional movements: at approximately the same depth of the tunnel the sediment in clay soils was 13-17 mm, in sandy soils - no more than 20 mm.

Kim K.Y. [3] and co-authors proposed an empirical model for predicting the settlement of soil surface depending on the work of TBM machine in rocky soils. The RMR parameter has the greatest impact on TBM machine performance. In some foreign studies, various methods of assessing the influence of the parameters of the TBM machine on the deformation of the soil massif were considered [4-9]. Comparison analytical calculations with field observations Cao L. et al. [10] showed
the influence of the "longitudinal effect" when pumping a concrete mixture behind the lining on soil subsidence along the axis of the tunnel. The authors of [11] determined by the method of backward calculation the actual excess excavation ratio for a section of a line tunnel with a diameter of 10.3 m from st. "Okskaya street" to the station "Stakhanovskaya street". The results of numerical simulation in the PLAXIS 2D software package showed that the actual excess excavation ratio exceed the project ones by 6 times. The actual excess excavation ratio ranges from 0.55 to 1.30. Similar calculations were carried out by Rezaeri A.H. et al. [12-13] to determine soil volume loss in percent during the construction of two lines of the Tabriz metro using the shield driving method. The same studies Fargnoli V. et al. [14] carried out for the new line 5 of the Milan Metro. If there were no sites with similar engineering and geological conditions and the type of tunneling equipment then soil volume loss was determined according to the Gaussian empirical curve. In [15] the authors propose to consider four components of the volume loss for more effective forecasting of soil surface settlement during taking into account monitoring data. It is important to note that at the moment in the normative literature the values of the excess excavation ratio are presented exclusively for communication tunnels. The values of the excess excavation ratio in the construction of subway tunnels are not presented in the regulatory literature.

2. Materials and methods
The excess excavation ratio is the ratio of the area of the soil removed during driving to the cross-sectional area of the working. The design features of TBM machine affect the value of this coefficient. This is due to the fact that the cutting diameter exceeds the diameter of the tail of TBM machine. It is also connected with the technological sequence of pumping the cement mixture behind the lining and engineering and geological conditions. Thorough control of technological parameters: pressure of the weight, volumes of excavated soil etc. affects the excess excavation ratio. This is necessary to avoid downtime of TBM machine and emergency situations [16-17]. Additional vertical deformations of buildings depend on the rigidity of their structures, layout solutions, the type of foundation and the position of buildings relative to the tunnel axis [18].

Previously the choice of the calculated excess excavation ratio in numerical modeling was made on the basis of table Zh.1 SP 249.1325800.2016. However the analysis of many data of geodesic monitoring showed that the real deformations of buildings are much less than the deformations obtained by numerical calculation. Thus taking into account the excess excavation ratio according to [4] leads to an increase in the cost of construction due to the use of various protective measures for the foundations of buildings and communications. In addition, this regulatory document is applicable only to microtunnels for communications [19]. At present the choice of the excess excavation ratio is determined based on the experience of designing construction organizations.

To determine the actual excess excavation ratio for correct modeling of the deformation of buildings and structures it is necessary to carry out a backward calculation. It is produced by the method of numerical modeling by selecting such the excess excavation ratio that will allow obtaining settlements close to the actual p settlements obtained from geodesic monitoring data. The numerical calculation was carried out in two-dimensional and three-dimensional formulation in the geotechnical software PLAXIS 2D and PLAXIS 3D. The excess excavation ratio was determined at the construction site of the running tunnel in Moscow from the Stakhanovskaya Ulitsa station to the Nizhegorodskaya Ulitsa station, stage 11.4 from PK 131.00 to PK 137.00. Seven existing buildings fell into the estimated zone of influence.

The distance from the elevation of the bottom of the foundations to the elevation of the roof sheath varies from 13.8 m to 21.4 m. The diameter of line tunnel under construction is 10.3 m. The lining thickness is 450 mm. Tunneling is carried out by a Herrenknecht TBM machine with a cutting diameter of Ø10.69 m. In this type of shield grouting is injected in the tail part of the tunnel machine. In the face there are mainly fine and silty water-saturated sands. According to regulatory documents the excess excavation ratio is 3.5%. However, taking into account the tendency with overestimation of
the calculated deformations a coefficient of 2.5% was adopted in the project. Figure 1 shows an engineering-geological section with a line tunnel landing on it.

Figure 1. Engineering-geological section with a tunnel landing.

Figure 2 shows that the pre-testing zone of influence (purple color) of the tunnel under construction in the considered section includes 6 buildings of the surrounding development. The location the calculated sections in a two-dimensional formulation is indicated on the plan. Figure 3 shows one of the calculated schemes of the problem modeled in PLAXIS 2D. The scheme shows the tunnel under construction and the building located at Ryazansky Prospekt, d2s27.

Figure 2. Plan of the location of the line of the tunnel (red) in relation to the existing buildings of the surrounding development (blue).
Figure 3. Calculation scheme of 2D model (section 6-6).

The calculated deformed scheme №1 in a three-dimensional formulation is shown in figure 4. This scheme considered the section of line tunnel from PK 131.00 to PK 134.00 and three buildings located at the address: Ryazanskiy prospect, d4As2; Ryazansky prospect, d4As3 and Ryazansky prospect, d4As8.

Figure 4. Deformed scheme №1 3D model.

Figure 5 shows the calculated deformed scheme №2 of the section of the running tunnel from PK 134.00 to PK 137.00 and three buildings located at Ryazansky Prospekt, d4; Ryazansky prospect, d2s27 and Ryazansky prospect, d2s26.
3. Results

By the iteration method backward calculation was used to obtain the actual excess excavation ratio at the stage of completion of the construction of line tunnel. The results of numerical modeling and geodetic monitoring data are presented in table 1. The obtained settlements in a two-dimensional formulation exceed the actual excess excavation ratio by 3-25 times and in a three-dimensional formulation - by 2-25 times. The additional settlement of buildings at the project excess excavation ratio in a two-dimensional formulation is significantly higher than in a three-dimensional formulation. In the case of backward calculation with approximately the same vertical deformations of buildings the excess excavation ratio in PLAXIS 3D turned out to be higher than the coefficients in PLAXIS 2D. The obtained values of the actual excess excavation ratio are consistent with the results described in [11, 20].

The analysis of the results presented in table 1 shows that the actual settlement of all considered buildings does not exceed the maximum permissible values which are taken in accordance with table K.1. Using the excess excavation ratio of 2.5% six buildings in a two-dimensional formulation received additional displacements that exceeded the allowable limits. In a three-dimensional formulation two buildings received additional displacements. Incorrectly selected the excess excavation ratio leads to the need to develop additional protective measures for buildings. Consequently, the construction cost increases.
Table 1. Vertical actual and calculated deformations of buildings.

| Name of buildings                     | PLAXIS 2D                      | PLAXIS 3D                      | Actual settlement, mm |
|---------------------------------------|--------------------------------|--------------------------------|-----------------------|
|                                       | Project | Backward calculation | Project | Backward calculation | Project | Backward calculation | Project | Backward calculation |
|                                       | The excess excavation ratio, % | Settlement, mm | The excess excavation ratio, % | Settlement, mm | The excess excavation ratio, % | Settlement, mm | The excess excavation ratio, % | Settlement, mm | The excess excavation ratio, % | Settlement, mm |
| Ryazansky prospect, d4A c2 (section 2)| 2.5     | 73.5             | 0.5     | 2.9                 | 2.5     | 30.0             | 0.6     | 2.4                 | 2.9     | |
| Ryazansky prospect, d4A c2 (section 3)| 2.5     | 54.8             | 0.7     | 13.3                | 2.5     | 30.0             | 1.2     | 12.5                | 13.0                | |
| Ryazansky prospect, d4A c3 (section 3)| 2.5     | 46.6             | 0.3     | 3.8                 | 2.5     | 16.8             | 0.7     | 3.1                 | 3.0     | |
| Ryazansky prospect, d4A c2 (section 4)| 2.5     | 38.3             | 0.2     | 6.1                 | 2.5     | 30.0             | 0.8     | 5.6                 | 5.9     | |
| Ryazansky prospect, d4A c8 (section 4)| 2.5     | 22.8             | 0.3     | 2.2                 | 2.5     | 16.0             | 0.6     | 2.0                 | 2.4     | |
| Ryazansky prospect, d4 (section 5)    | 2.5     | 32.8             | 0.1     | 3.0                 | 2.5     | 27.5             | 0.1     | 4.3                 | 3.4     | |
| Ryazansky prospect, d2 s27 (section 6)| 2.5     | 35.4             | 0.1     | 4.5                 | 2.5     | 33.8             | 0.1     | 5.5                 | 3.0     | |
| Ryazansky prospect, d2 c26 (section 7)| 2.5     | 34.4             | 0.7     | 5.5                 | 2.5     | 14.8             | 0.7     | 5.5                 | 5.4     | |

Figure 6 shows a fragment of the A-A * section of a three-dimensional model with isofields of vertical displacements of the soil mass at the stage of completion of the tunnel construction. The sections are similar in other areas.
Figure 6. Fragment of section A-A* isofields of vertical displacements of the soil mass after tunneling.

4. Conclusion and discussion

1. Analysis of geodesic monitoring data and the results of numerical calculations shows the excess of additional vertical displacements of the foundations of existing buildings by several times in comparison with the actual vertical displacements.

2. The actual excess excavation ratio obtained by the iteration method backward calculation is significantly less than the calculated excess excavation ratio accepted in accordance with Russian standards. Based on the results of numerical simulations it can be concluded that the actual excess excavation ratio varies in the range from 0.1% to 1.2%.

3. In a two-dimensional formulation 6 out of 7 buildings received additional precipitation that exceeded the maximum permissible values in numerical modeling taking into account the normative excess excavation ratio. In a 3D formulation only 2 buildings received additional precipitation. But the real settlements of buildings does not exceed the maximum permissible values. Consequently using the project excess excavation ratio it becomes necessary to apply protective measures for the foundations of buildings. This leads to a rise the cost of construction and an increase the construction time of line tunnel.

4. An analysis of a similar study to determine the actual excess excavation ratio at another construction site confirms that the project excess excavation ratio is several times higher than the actual ratio. This leads to an overestimated settlement of the foundations of the buildings of the surrounding development.

5. The optimal choice of the excess excavation ratio at a specific construction site is a ratio adopted on the basis of backward calculation for an already traversed section with similar engineering and
geological conditions, with the same type of TBM machine and the diameter of the tunnel. However, it is necessary to analyze more numerical calculations and compare them with geodetic monitoring data. This will make it possible to determine and assign the average standard the excess excavation ratio during the construction of tunnels using the shield method.

6. The results of numerical modeling have shown the effect of the stress-strain state on the amount of settlement in a two-dimensional and a three-dimensional formulations. This requires further study and an informed choice of 2D or 3D calculations.

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