Study results of a stress-strain state of a pylon station construction from monolithic reinforced concrete in the engineering and geological conditions of St. Petersburg

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Abstract. In recent years, structures made from monolithic reinforced concrete have been increasingly developed in the field of underground construction. This has been made possible by the development of modern tunneling technologies such as NATM and ADECO&RS, which have proven themselves abroad. Being low-sedimentation methods of underground structures construction, they have found wide application not only in mountain transport tunneling but also in construction in an urban environment, where precipitation and negative impact on the surrounding infrastructure has a decisive role in the choice of one or another technology. Foreign experience of construction in the same physical and mechanical characteristics of soils gives reason to assert the possibility of using new technologies in our country. However, this task requires a comprehensive approach to its solution. This article presents an experimental and theoretical substantiation of a pylon station lining made from monolithic reinforced concrete in the engineering and geological conditions of St. Petersburg on the example of the planned St. Petersburg Metro station "Chernigovskaya" of the "Krasnoselsko-Kalininskaya" line being built from "Obvodniy Kanal-2" station to "Yugo-Zapadnaya" station. **Keywords**: pylon station construction, monolithic reinforced concrete, tunnel, NATM, SEM, ADECO&RS

1 Introduction

Experimental and theoretical justification of the outcomes of this or that work has always been of great importance in the practice of engineering. It is especially relevant in the field of tunneling, where any new technology before being implemented, should be verified by field data. The outcomes of field studies allow obtaining the real nature of the dependence of the studied values and, if necessary, to promptly make the appropriate changes in the technology.

In the previous article "Feasibility of a Pylon Station Construction from Monolithic Reinforced Concrete in the Engineering and Geological Conditions of St. Petersburg" [1]

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based on the outcomes of physical and mathematical modeling, the following data were obtained:

- precipitation of the day surface;
- deformation of the station from the design loads, as well as loads exceeding the design loads;
- analysis of the outcomes and conclusions.

To theoretically justify the data of mathematical and physical modeling, it became necessary to compare them with the data of day surface settlements and deformations at the St. Petersburg Metro facilities under construction. For this purpose, sections were selected at three stations under construction in the area of large cross-section excavations from monolithic reinforced concrete lining. An important criterion was that the lining had to be constructed using a technology similar to that adopted for the "Chernigovskaya" station.

Thus, this work involves solving the following series of problems:

- give the outcomes of physical and mathematical modeling of the typical platform section of the station "Chernigovskaya";
- give the outcomes of field studies at the facilities under construction in the St. Petersburg Metro;
- analyze the day surface settlements and deformations of the tunnel lining obtained by experimental and in-situ methods; based on the outcomes of the analysis of the data to draw appropriate conclusions and recommendations.

2 The outcomes of physical modeling of the typical platform section of "Chernigovskaya" station

Physical modeling of the "Chernigovskaya" station structure and the surrounding ground massif (Proterozoic clay) by the method of equivalent materials was performed on a special hydraulic stand installed in the tunnel modeling laboratory at the "Tunnels and Underground Railways" Department of PGUPS. The scale of modeling was accepted as 1:20.

The following outcomes were obtained in the course of physical modeling:

- displacements of characteristic points of the station model lining;
- vertical deformations of the station model;
- the groundmass model settlement;
- a picture of the destruction of the station from loads exceeding the design loads.

Thus, the displacements of characteristic points of the station model lining were determined based on the readings of displacement sensors and plastic beacons. The outcomes obtained are shown on a conditional scale in Fig. 1.

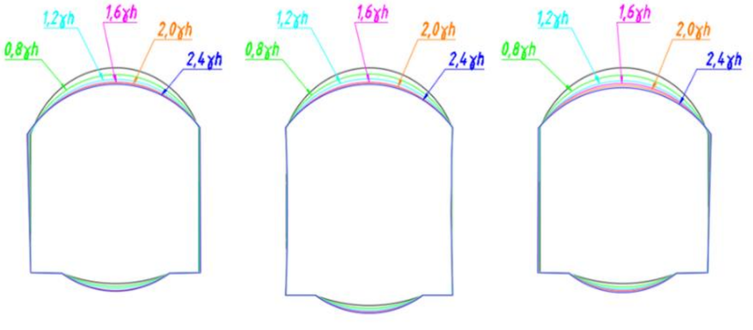

Fig. 1. Station tunnel lining displacements.

The deformations of the station model representing the difference between upper and lower vault displacements for each of the tunnels separately were determined using the obtained values of displacements (see Table 1). The data for in-situ conditions obtained by multiplying the actual values by the modeling scale are also presented here.

Table 1. Vertical deformations of the station model.

Loading number	**Left side station tunnel**		**Middle station tunnel**		**Right side station tunnel**	
	Vertical deformations, mm					
	In the model	In-kind	In the model	In-kind	In the model	In-kind
Stage I-load 0,8γh	0.017	0.34	0.199	3.98	0.019	0.38
Stage II-load 1,2γh	0.09	1.8	0.29	5.8	0.101	2.02
Stage III-load 1,6γh	0.228	4.56	0.588	11.76	0.255	5.1
Stage IV-load 2,0γh	0.288	5.76	0.659	13.18	0.323	6.46
Stage V-load 2,4γh	0.754	15.08	0.93	18.6	0.843	16.86

Based on the outcomes of the photo fixation, an epicure of the daytime surface settlement of the soil mass, which contains the station tunnels, was built. It also shows the general displacement of the station tunnels relative to their original position (see Fig. 2).

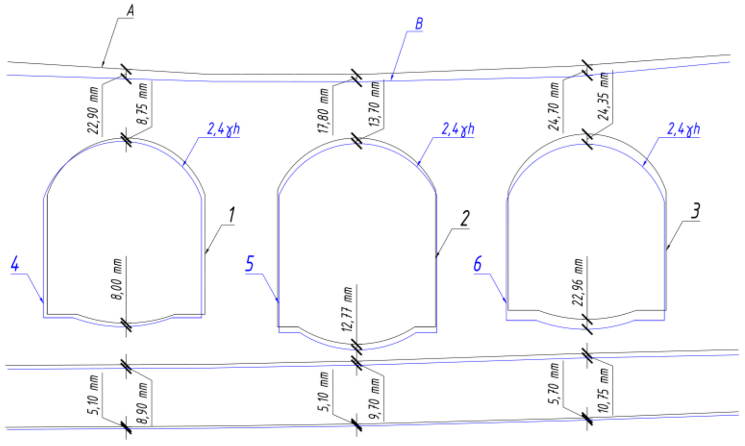

Fig. 2. Diagram of the ground massif settlement. Final displacements of the station tunnels relative to their original position.

A-Ground model level before the test; B-Ground model level after test; 1-contour of the left side tunnel before the test; 2-contour of the middle tunnel before the test; 3-contour of the right-side tunnel before the test; 4-contour of the left side tunnel after the test; 5-contour of the middle tunnel after the test; 6- contour of the right-side tunnel after the test

Testing the physical model of the station against design loads, as well as loads exceeding design loads, allowed us to determine the failure pattern of the station model. The general view of the physical model of the station with cracks and defects applied is shown in Fig. 3.

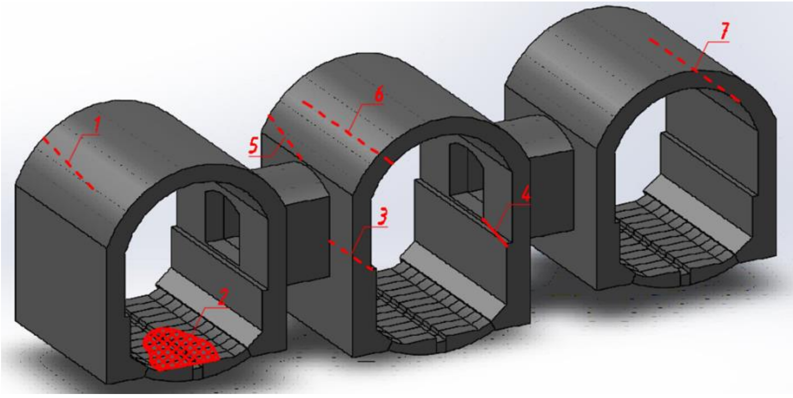

Fig. 3. General view of the physical model of the station with applied cracks and defects (characteristic places of defects are marked by numbers).

Based on the outcomes of physical modeling, the following conclusions were made:

– The design of the "Chernigovskaya" station turned out to be sufficiently rigid, which is confirmed by the deformability pattern of the station model, as well as the deformation values obtained in the course of staged modeling.

– The presence and character of cracks and defects in the station model lining indicate insufficient elaboration of its design solutions. For example, the horseshoe-shaped cross-section of the station tunnels forms characteristic stress concentration zones in the places of a sharp break in the shape of the neutral axis, and the large thickness of the tunnel lining leads to increased rigidity of its construction.

– The vertical deformations of the station tunnels from the design load γh were 7 and 5 mm for the side and middle tunnels, respectively. At the same time, the day surface settlements reached an average of 25 mm.

– Staged loading of the station model allowed us to obtain a displacement of the station tunnels relative to their original position, which averaged 15 mm.

– Taking into account the modeling of the tunneling stages, the total precipitation of the day surface reached an average of 35-40 mm.

3 Outcomes of mathematical modeling of the typical platform section of "Chernigovskaya" station

The need for mathematical modeling of the station "Chernigovskaya" consisted in the fact that physical modeling does not provide a complete picture of the deformation of its structure, in particular, it is not possible to determine the internal forces arising in the elements of the lining, as well as the characteristic zones of stress concentration. It is important to note that a prerequisite for mathematical modeling was the accurate reproduction of the deformed state of the station structure at the stage of physical modeling.

Thus, the calculation was performed in the Solid works software package by the finite element method. The soil mass was modeled in full accordance with the real engineering and geological conditions of the station construction. The nonlinear Coulomb-More model was adopted as a model of the soil massif.

The calculation scheme of the mathematical model is shown in Fig. 4.

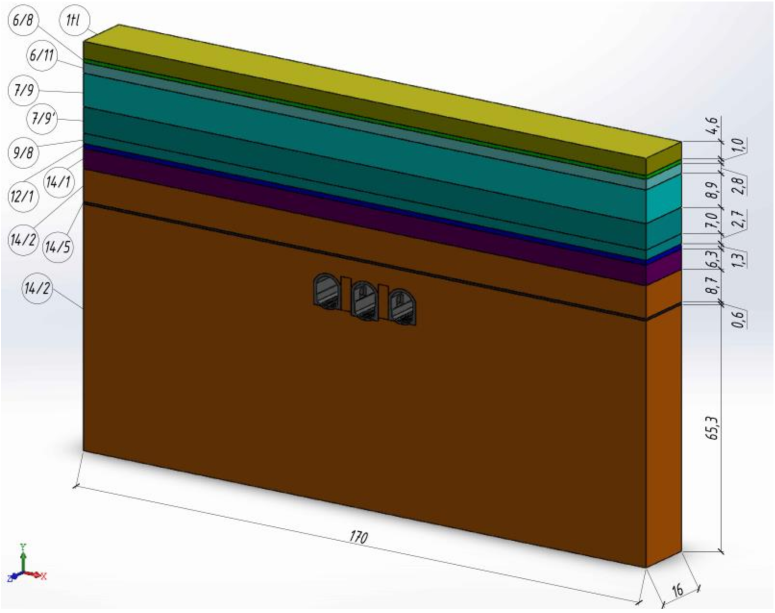

Fig. 4. Calculation scheme of the mathematical model of the station "Chernigovskaya" (boundary conditions, as well as the load from its weight of the soil mass, are not shown; the dimensions are given in meters).

1tl-technogenic layer of bulk soils (sandy-sandy material with construction debris); 6/8- dusty loam with interlayers of sand and loam of plastic consistency; 6/11-light dusty loam, loamy, layered of soft plastic consistency; 7/9-light dusty loam with gravel and pebbles 5-15%, with boulders of soft plastic consistency; 7/9'-light dusty loam with gravel and pebbles 5-15%, with boulders of tight plastic consistency; 9/8-light dusty loam with gravel and 5-15% pebbles, with boulders of firm consistence; 12/1-clay shifted with fragments of sandstone, gravel, pebbles, boulders of firm consistence; 14/1-dislocated clay with fragments of sandstone of firm consistence; 14/2-layered argillite-like clay of firm consistence; 14/5-quartz sandstone of medium strength.

As an outcome of the calculation, the values of stresses, displacements, and deformations in the station structure were obtained. Some calculation outcomes are presented below.

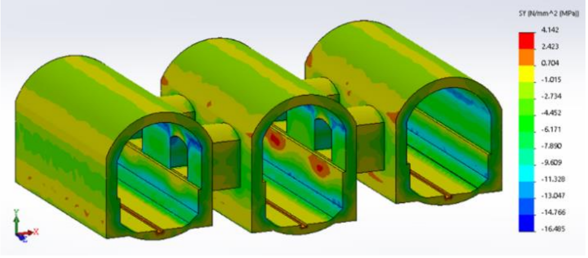

Fig. 5. Stresses σ_y, MPa in the station structure relative to the vertical axis OY.

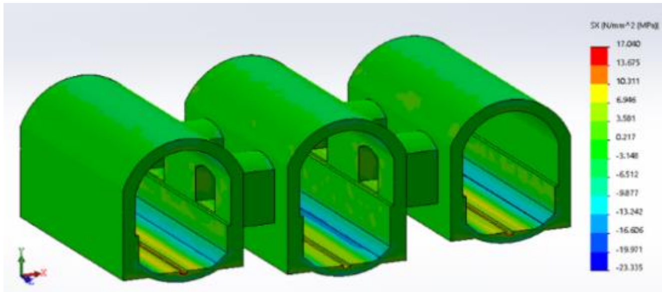

Fig. 6. Stresses σ_x, MPa in the station structure relative to the horizontal axis OX.

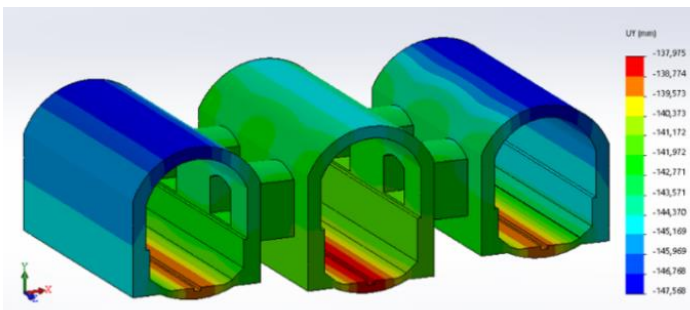

Fig. 7. Vertical movements U_y, mm in the station structure.

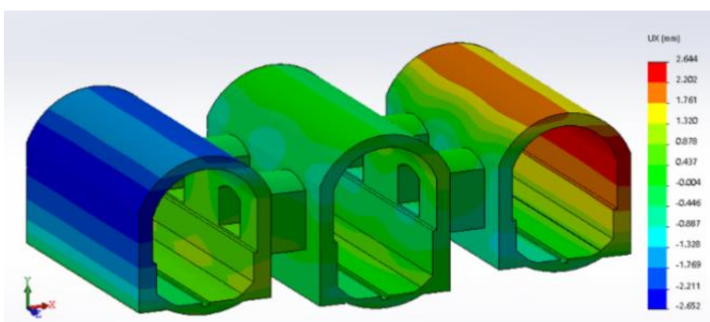

Fig. 8. Horizontal movements U_x, mm in the station structure.

Mathematical modeling showed that "Chernigovskaya" station structure can be considered sufficiently rigid. In this case, the character of stress distribution in all three station tunnels is almost identical.

Thus, the design of the station works mainly in compression, which is facilitated by the correct outline of the tunnel vaults. The upper vaults are subjected to predominantly compressive forces – only minor tensile stresses occur on their inner contour. Also, small tensile stresses occur at the locations where the upper vaults rest on the walls on the outer contour of the lining, as well as at the heels of the walls. Tensile stresses are also present in the wall sections at the opening points of the side aisles. As expected, the tensile stresses reach their highest values on the inner contour of the reverse vault.

The greatest compressive stresses occur at the locations where the back-arch rests on the heels of the tunnel walls. This area of concentration of compressive stresses, which significantly exceeds the design resistance of concrete to axial compression, can lead to a brittle resolution of the lining concrete in these places.

Based on the pattern of vertical and horizontal displacements of all three station tunnels, the following conclusion can be made: the side station tunnels are subject to the greatest displacements and, hence, deformations. In this case, vertical displacements in them reach the value of about 9 mm. Under the action of the load, the walls of the side tunnels move aside the outer walls by about 2 mm towards the ground massif, and the inner walls by 1 mm towards the middle station tunnel. As the height of the station increases, the horizontal displacements of the outer walls decrease and the inner walls increase, while the relative horizontal deformations also decrease.

The vertical displacements of the middle station tunnel are slightly less than the side displacements and equal to 7 mm-this is explained by the location of the middle station tunnel between the two side tunnels, which absorb a significant part of the load and transfer it to the surrounding soil mass. In this case, the side aisles limit the horizontal movements of the walls of the middle station tunnel, increasing the rigidity of the whole station and preventing the development of significant vertical movements. It is important to note that in contrast to the side tunnels, the walls of the middle tunnel move inside the station structure. However, due to the high rigidity of the side aisles, these movements are not so great and reach values of the order of 0.5 mm in the level of the upper and lower vaults of the middle tunnel, as well as 0.6 mm in the level of the side aisles themselves.

The character of the deformability of the typical platform section of "Chernigovskaya" station is presented in Table 2.

Table 2. Vertical deformations of the station model.

Title	Left side station tunnel	Average station tunnel	Right side station tunnel	Side aisles
Vertical deformations. mm				
	9	7	9	2
Horizontal deformations in the level. mm:				
upper vault stains	3	1	3	-
middle of the wall height	2.5	1.2	2.5	-
wall stains	1	1	1	-

4 The outcomes of field studies at the facilities under construction in the St. Petersburg Metro

When introducing the technology of deep subway station construction made from monolithic reinforced concrete in the conditions of St. Petersburg, in addition to several tasks considered in this work, it is worth mentioning another one, which consists of verification of the outcomes obtained in field studies. Thus, the values of deformations of station tunnels as well as day surface settlements obtained in the course of physical modeling by the method of equivalent materials should be compared with field data on objects of similar shape and size, depth, and engineering and geological conditions of the surrounding soil massif.

Thus, there was a task to search for analogs among already existing and newly built stations of the St. Petersburg subway. The analysis showed that the constructions of tension chambers of modern metro stations under construction were completely similar to the given selection criteria. Tension chambers are a part of deep-flowing metro station construction, connecting the central hall of the station, or downstairs or intermediate vestibule with the inclined tunnel. Modern constructions of tension chambers are horseshoe-shaped excavations, vaults, and walls made from monolithic reinforced concrete, and the reverse vault from precast elements. As in the case of the planned metro station "Chernigovskaya", the prefabricated inverted vault design includes Freycinet jacks – this accelerates the process of its inclusion in the static operation of the entire station structure and reduces the possibility of sliding the walls into the excavation. An example of the design of one of these stations is shown in Fig. 9.

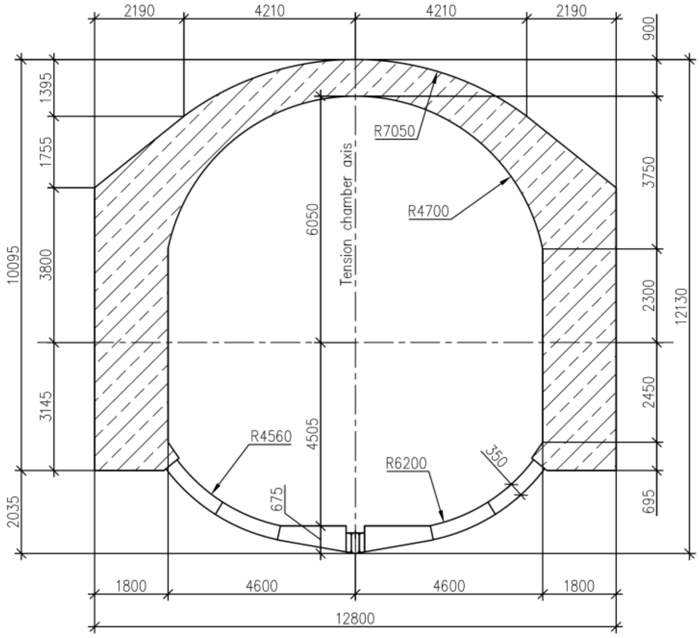

Fig. 9. Construction of the tension chamber of one of the deep-flowing metro stations under construction in St. Petersburg.

Thus, three object-analogs were selected, and adopted for further consideration and comparison of outcomes.

The values taken as comparable outcomes are as follows:

- vertical deformations of the station structures;
- precipitation of the day surface.

For the analog objects, day surface settlements were taken according to the reports of observation stations for the entire design observation period. An important feature is the fact that the construction technology adopted in the project works for the subway analogs is very close to the sequence of works in the construction of the "Chernigovskaya" station, which indicates the necessary correlation of the compared values.

A comparison of the obtained deformations is presented in Table 3.

Table 3. Vertical deformations of the station model and analog objects.

Design name	Vertical deformation. mm
Middle station tunnel of "Chernigovskaya" station (outcomes of physical modeling scaled to full-scale values)	5.0
Tension chamber of station 1 (according to the observation station)	2.6
Tension chamber of station No. 2 (according to the observation station)	9.0
Tension chamber of station No. 3 (according to the observation station)	14.5

A graphical representation of the obtained deformations on a conditional scale is shown in Fig. 10.

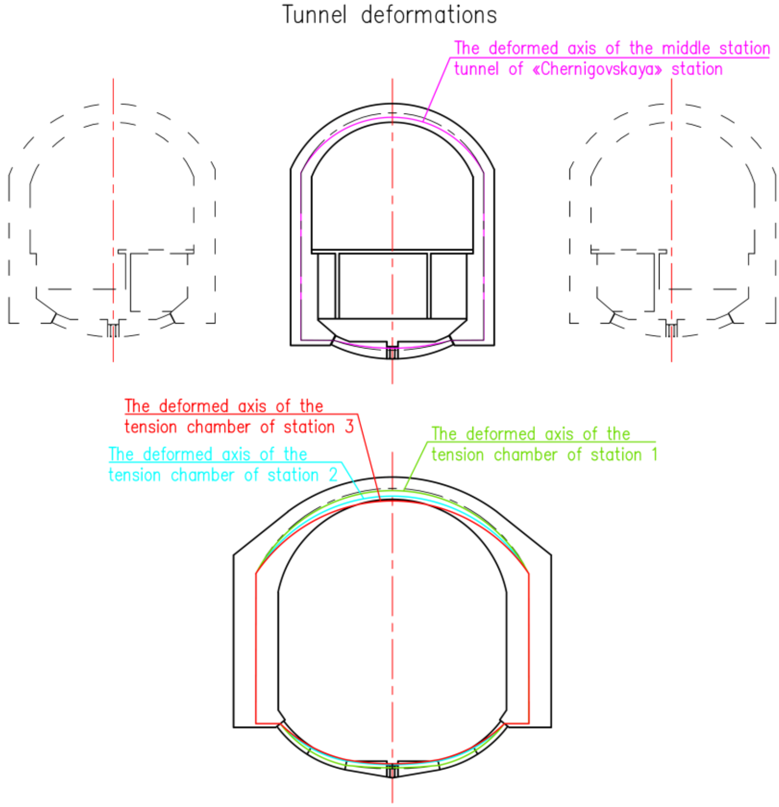

Fig. 10. Graphical representation of the deformations of the middle station tunnel of the "Chernigovskaya" station and the tension chambers of the analog objects (scale is notional).

For the object-analogs, the day surface sediments are taken in the transverse direction in the tension station alignment. A comparison of the outcomes of the day surface sediments is shown in Fig. 11.

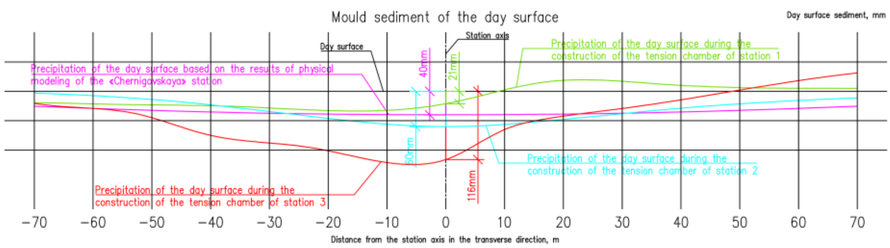

Fig. 11. Comparison of day surface settlements during the construction of the middle station tunnel of "Chernigovskaya" station and the tension chambers of analog objects.

For the convenience of analysis, the outcomes of field studies are related to the outcomes of physical modeling as a percentage. The outcomes are presented in Table 4.

Table 4. Summary comparison table.

Title	Vertical deformations. mm		Precipitation of the day surface. mm	
	Actual value	**%**	**Actual value**	**%**
Middle station tunnel of "Chernigovskaya" station (outcomes of physical modeling scaled to full-scale values)	5.0	100.0	40	100.0
Tension chamber of station 1 (according to the observation station)	2.6	52.0	21	52.5
Tension chamber of station No. 2 (according to the observation station)	9.0	180.0	60	150.0
Tension chamber of station No. 3 (according to observation station)	14.5	290.0	116	290.0

The table shows that the full-scale data vary greatly, which is due to the difference in the shape and size of the tension chamber structures, their depth, as well as the engineering and geological conditions of the construction site. Having averaged the outcomes of field studies, we obtain that the difference between the compared outcomes is of the order of:

- for vertical deformations–74 %;
- for day surface sediments–64 %.

In this case, if we discard the outcomes for the object-analog №3, as it is strongly out of the total data sample, we get the following differences in the outcomes:

- for vertical deformations–16 %;
- for day surface sediments–1,2 %.

Thus, as the number of analog objects increases, the values of deformation and settlement differences will fall, approaching the outcomes of physical modeling. It follows that other things being equal, the outcomes obtained during physical modeling and multiplied by the scale of modeling will repeat the in-situ outcomes for the same construction conditions.

5 Conclusions

The outcomes of physical and mathematical modeling showed that "Chernigovskaya" station is sufficiently rigid with a high reserve of bearing capacity.

The transition from a horseshoe-shaped cross-section of the station to a smooth outline of all three station tunnels will reduce the material intensity of the tunnel lining, and the absence of sharp breaks in the neutral axis will reduce the characteristic zones of stress concentration.

Comparison of the day surface settlements and deformations of the tunnel lining, obtained by physical modeling using the method of equivalent materials with the data of field studies at the analog objects, showed a high degree of convergence. Thus, for vertical deformations, the error of the outcomes was about 16%, and for day surface settlements-1.2%. The obtained outcomes allow us to speak about the successful verification of physical modeling data based on field studies of really existing object analogs.

Nevertheless, in conditions of dense urban development and proximity to utilities, the requirement to reduce day surface precipitations plays a key role in the choice of particular construction technology. Thus, modern low-sediment methods of underground structures construction, such as NATM and ADECO&RS, allow significantly reduce the effect of underground structures on the existing urban infrastructure, and the malleability of temporary support reduces the loads on the structures, reducing their material intensity and, consequently, the cost.

On the issue of implementation of the technology of pylon stations construction from monolithic reinforced concrete in engineering and geological conditions of St. Petersburg on the example of the planned station "Chernigovskaya" the following directions of research and improvement can be distinguished:

1. A transition should be made from the horseshoe-shaped cross-section of station tunnels to their smooth outline using modern Austrian technology, including the replacement of the traditional monolithic tunnel lining with a multilayer one made of composite materials and sprayed concrete with fiber, which will significantly improve the static operation of the station structure and also increase its load-bearing capacity;
2. The key problem of day surface sedimentation in dense urban development should be solved by operational geotechnical monitoring using modern laser scanning systems;
3. The existing methods of calculating underground structures with the help of software packages based on FEM (finite element method) do not provide a complete picture of the nature of the "lining-soil massif" system. Moreover, it is not possible to see the picture of the surrounding soil's mass destruction. The transition from FEM to DEM (discrete element method) will solve these problems. Thus, it will become possible to bring the soil mass to visual destruction, which will allow to quickly change the construction technology if necessary, increasing the efficiency and safety of labor.

Thus, the outcomes obtained during the experimental and theoretical justification of the pylon station lining made from monolithic reinforced concrete and confirmed by the data of full-scale studies at the analog objects, allowed to get a real character of the station operation in the engineering and geological conditions of St. Petersburg, as well as determine the further direction of development and research in this area.

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