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Step-by-step analysis of the condition of the side tunnel for a pylon-type metro station under construction NATM

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Abstract. This scientific research provides a step-by-step analysis of the condition of the side tunnel for a pylon-type metro station with combined lining. An analysis of the algorithm for applying the New Austrian Tunneling Method to the construction of underground structures in hard rocks (as in the Dnipro Metro) has been conducted. It is justified that the analysis of the stress-strain state in the combined lining for the side tunnel of a station should be carried out in accordance with the stages of opening the working and installing the combined lining. A finite element model has been developed to represent the stages of side tunnel construction. This model also reflects the station structure's conditions, its dimensions, and the interaction between the combined lining and the surrounding rock massif. The dependences of horizontal stresses in the rock massif and the bending moment in the combined lining on the stage of construction of the side tunnel have been obtained. The conclusion from the step-by-step analysis in the construction of the side tunnel for a pylon-type metro station, built using the New Austrian Tunneling Method, is that maximum stresses and force factors occur during construction rather than during the operational phase.

1. Introduction

A significant event in the construction of metro systems in Ukraine in 2016 was the change in the approach to constructing the underground facilities, specifically moving from prefabricated to monolithic frames [1]. It is no exaggeration to say that using combined monolithic frames in building the Dnipro metro marked a new beginning in adopting more efficient technologies for constructing deep underground structures. The successful implementation of the New Austrian Tunneling Method (NATM) during the construction of interstation and escalator tunnels, mine shafts, and station complexes demonstrated that the Ukrainian industry has the potential to move away from the concept of prefabricated underground structures or at least not treat it as the main method [1-3].

The use of NATM has been widespread worldwide for about 65 years. In Ukraine, however, this period is much shorter – around 6 years – and the accumulation of experience with this method has been interrupted by the Russian-Ukrainian war. Despite this, hundreds of meters of interstation tunnels, four large-diameter mine shafts, and the beginning of construction on two stations have been successfully completed in a short time [1, 4]. The experience of constructing three-vaulted stations, which are similar to classic pylon-type metro stations [2] but are built using shotcrete, was entirely new for Ukraine.

The essence of this innovation lies in the fact that such station structures are large-section



workings, and the presence of sufficiently strong rock at the Dnipro Metro construction site does not make the construction process easier. The emergence and formation of a stress-strain state occur through a unique interaction between the surrounding massif and the lining, meaning the level of displacements and stresses depends on their stiffness [5]. The situation becomes more complex because, in the NATM concept, the lining is combined and includes anchors, arches, and shotcrete [6-8].

Research on such complex structures interacting with the surrounding massif is currently grounded on numerical analysis, which, for example, can be based on the finite element method [9, 10]. Even when applying a planar formulation, it is numerical analysis provides the most accurate parameters of the stress-strain state for the actual operating conditions of the station structure. A planar formulation at the stage accepted for research (opening and installing combined lining in the side station tunnel) is appropriate since the processes that will release the spatial factor (such as the construction of the middle station tunnel and opening passages between it and the side tunnel) have not yet been involved [10-12]. At the same time, using a planar formulation allows for a more precise application of finite elements, which simulate temporary linings (anchor or arch) [1, 3].

An important methodological step, noted by some authors, is considering the step-by-step approach in the working opening during the numerical analysis [3, 6, 12]. Dividing the face into several stages significantly changes the stress-strain state, unlike the method that involves opening the working to the full face. Thus, other research has already proved that the sequential opening of the calotte and the stross, with their gradual temporary fixation using a combination of anchors, arches, and shotcrete, is the main factor that forms the stress-strain state of the underground structure and the surrounding massif.

Therefore, implementing NATM in particular and monolithic concreting of underground structures in general, i.e., a new technology for constructing underground facilities in Ukraine, requires a scientific rationale with research on the condition of the station structure and the surrounding massif. The research aim is to obtain dependencies of changes of stress and force factors (bending moments), in the finite element model of the side tunnel of the pylon station, and these changes are related to the step-by-step working development and the sequential installation of the lining.

2. Methods

To achieve the set goal in the scientific research, a general finite element model was created in the LIRA computational platform. This model can be transformed and reflects the step-by-step tunnelling and lining of the side tunnel of the metro pylon station. An important difference in the numerical analysis of finite element models is that during the transition from one stage to another, as well as after the installation of temporary lining in the upper part of the working (calotte) and its connection with the temporary lining in the lower part (stross), the stress-strain state of the stage was maintained and transferred to the next stage. Thus, in the numerical analysis conducted, which demonstrates the stages of constructing an underground facility, there is a continuity of the stress-strain state formation, which is a significant advantage of the research.

The construction of the pylon station, in general, and the side tunnel, in particular, in hard rocks, using monolithic concreting – i.e., the basic principle of NATM – is founded on the top bench method. Its core idea involves the staged opening of the large cross-sectional working in parts (into a calotte and a stross), during which the stability of the exposed working is maintained at a high level. For the side tunnel of the pylon-type metro station, two stages of working opening and two stages of its lining with a combined frame are envisaged (figure 1).

Before installing the combined monolithic shotcrete-concrete lining, placing the steel arch, and stretching the mesh, the rock massif with a certain fracturing is reinforced with anchor lining. After completing a cycle of drilling and blasting operations (drilling, placing charges, blasting, ventilation, removal of broken rock), temporary lining is arranged by shotcrete concreting along the installed arches and the stretched mesh.

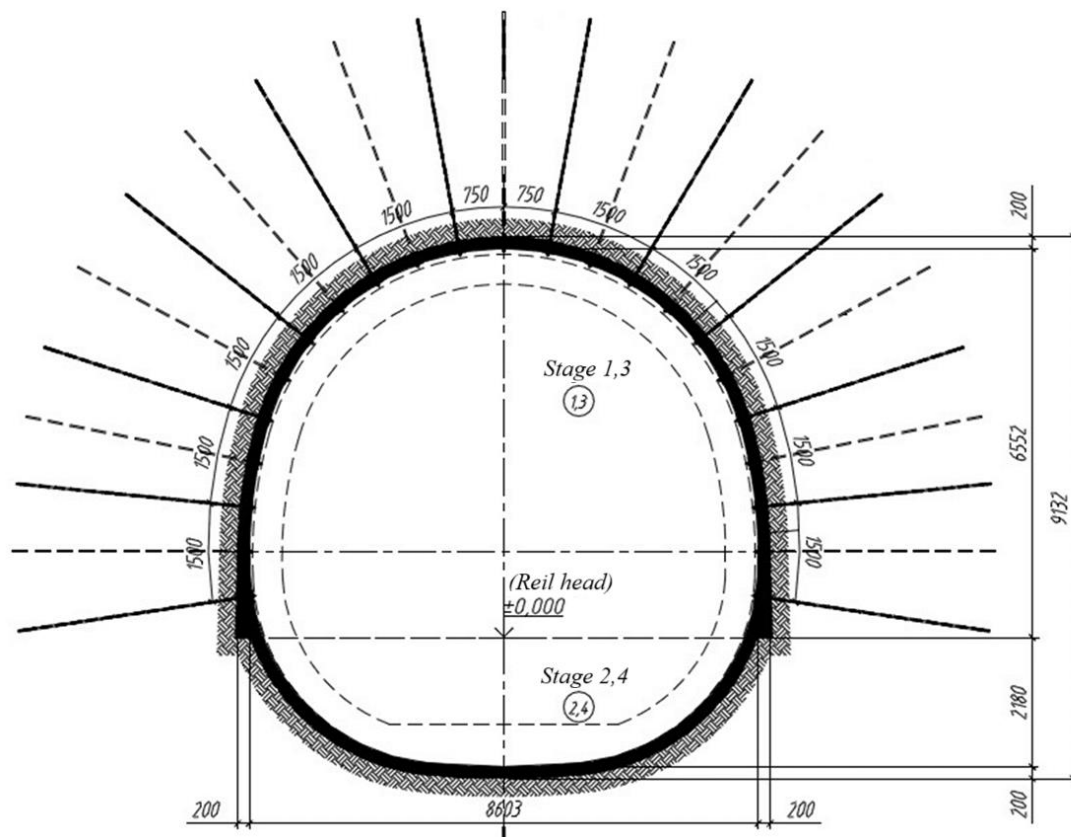


Figure 1. Stages of construction of the side tunnel of the pylon station.

There is still a discrepancy in terminology because the temporary lining in NATM is not truly temporary in the sense that it is still understood in Ukrainian underground construction areas. This temporary lining can be called "temporary permanent" since it will not be removed or refastened. After the complete opening of the working and installing temporary lining, a permanent frame consisting of reinforcement and shotcrete is installed after some time needed for partial unloading of the surrounding massif.

The joint action of the temporary lining with the soil was modelled. For the side tunnel, the total thickness of soil above the tunnel is determined to be 37.0 m. The load from the surrounding soil was calculated as the vertical pressure of the soils lying to a depth of 37.0 m, according to characteristics such as the uniaxial compressive strength and rock mass failure coefficient (D_f) for hard rocks and for all rocks: 1) specific weight (γ); 2) cohesion (C), 3) friction angle (φ); and 4) deformation modulus (E). According to the layers of the thickness determined during geological research, the following characteristics were obtained: Layer 1 (lies from mark 0.00 m) – bulk soil: $\gamma=18$ kN/m³, $C=1$ kPa, $\varphi=22^\circ$, $E=5$ MPa; Layer 2 – dusty heavy loam: $\gamma=19$ kN/m³, $C=25$ kPa, $\varphi=18^\circ$, $E=12$ MPa; Layer 3 – sandy loam: $\gamma=18.8$ kN/m³, $C=25$ kPa, $\varphi=18^\circ$, $E=7$ MPa; Layer 4 – fine sand: $\gamma=18.9$ kN/m³, $C=3$ kPa, $\varphi=26^\circ$, $E=15$ MPa; Layer 5 – mixed-grained sands with pebble inclusions: $\gamma=20.8$ kN/m³, $C=1$ kPa, $\varphi=40^\circ$, $E=41$ MPa; Layer 6 – dispersed zone of weathering crust: $\gamma=22.3$ kN/m³, $C=45$ kPa, $\varphi=34^\circ$, $E=140$ MPa; Layer 7 – plagiogranite, granite, diorite (with a failure coefficient $D_f=0.0$): $\gamma=26$ kN/m³, $C=533$ kPa, $\varphi=59.6^\circ$, $E=5412$ MPa.

Soils are modelled using physically nonlinear quadrilateral and triangular finite elements for plane deformation. Temporary lining is modelled by a 20×100 cm beam, while anchors are modelled with a special physical nonlinear element. Granite is modelled with plate finite elements, which more accurately reflect the behavior of the rock soil and its physical properties. The overall finite element model reflected the complete station structure (figure 2).

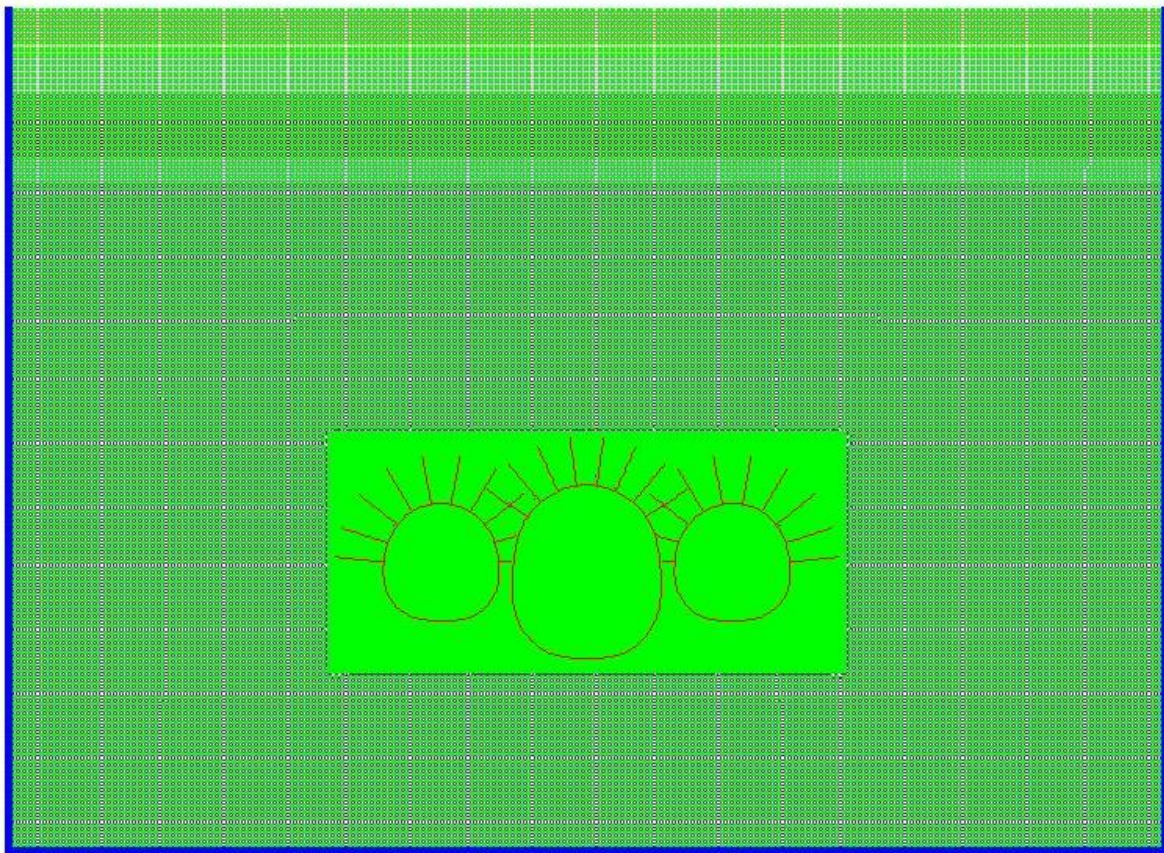


Figure 2. The general finite element model of a metro pylon station.

During the numerical analysis, elements modelling the rock were removed from the overall finite element model, considering the step-by-step opening of the side tunnel working, and its temporary lining. Thus, the working was modelled in the given model; however, to save space, the finite element models reflecting the stages are not presented, only the characteristic patterns of stress formation and displacements for them are provided.

3. Results and discussion

Analysis of underground construction experiences shows that the most critical stresses, deformations, or situations with stability in workings arise at intermediate stages of work after the rock development but before the installation of temporary lining.

Figure 3 shows the stress state (horizontal component) in the soil massif caused by the soil's own weight during the phase when a fully developed calotte (the upper part of the working) is in place, but before the installation of temporary lining. The yellow colour highlights the zone of tensile stresses that arise in the vault before installing arched lining and applying shotcrete.

The stresses arising in the vault do not exceed the strength of granite, but if crushed rocks enter the tension zone, collapses are possible, requiring special lining methods.

Figure 4 shows the moment diagrams at characteristic points of the combined tunnel lining, including a fully developed calotte and installed anchors, an arch, and applied shotcrete.

To save space, the paper does not include further values of horizontal stresses and bending moments in the form of stress state pictures and diagrams. However, they are systematized, analysed, and presented as dependencies on the stages of side tunnel construction (see figure 5). Four stages have been analysed, which are reflected in the general finite element model by removing the finite elements of the surrounding massif and adding finite elements of the lining, namely: stage 1 – opening

of the calotte; stage 2 – opening of the calotte and installing the temporary lining; stage 3 – opening of the stross; stage 4 – opening of the stross and installing the temporary lining. At stage 4, the lining forms a closed circuit in the working, creating a clear interaction with the surrounding massif of hard rocks.

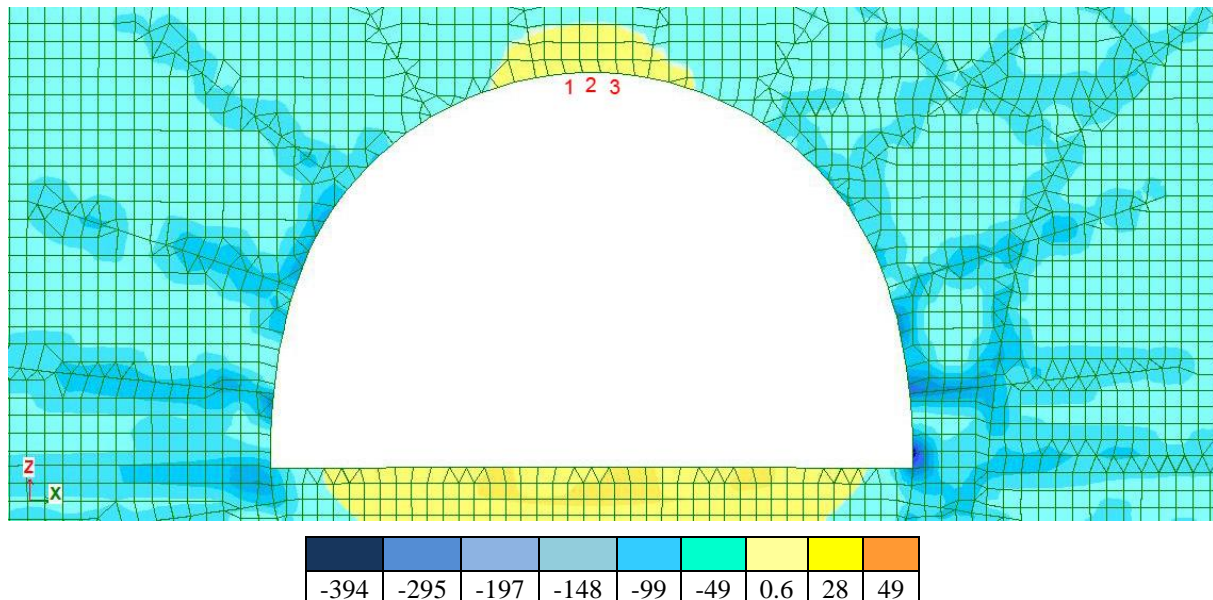


Figure 3. Horizontal stresses (kN/m^2) at characteristic points 1, 2, and 3 of the finite element model (stage 1 – opening of the calotte).

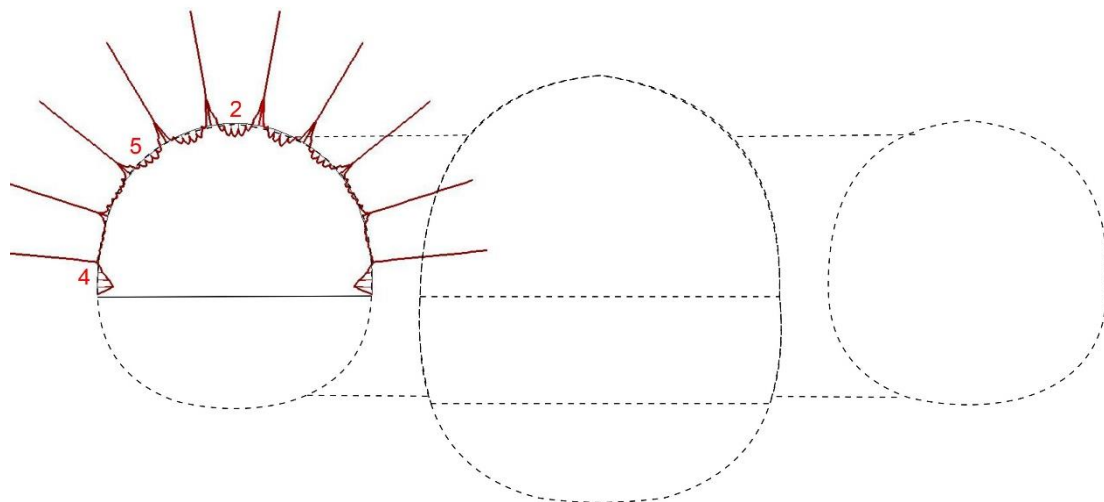


Figure 4. Bending moment diagrams at characteristic points 2, 4 and 5 of the temporary lining (stage 2 – opening of the calotte and installation of the lining).

The obtained dependencies convincingly demonstrate the importance of the step-by-step analysis when constructing a side tunnel for a pylon station. Examining the dependence of horizontal stresses (figure 4, a), one can see a significant leap in this component at stage 3, i.e., during the opening of the stross, which leads to a substantial increase in the cross-section of the working. Even with the lining installed in the calotte, stresses still increase. The magnitude of this increase is 2 to 3 MPa less than at stage 1, meaning that during the opening of the stross, the stresses in the surrounding massif have a level arising during the initial opening, i.e., in the calotte.

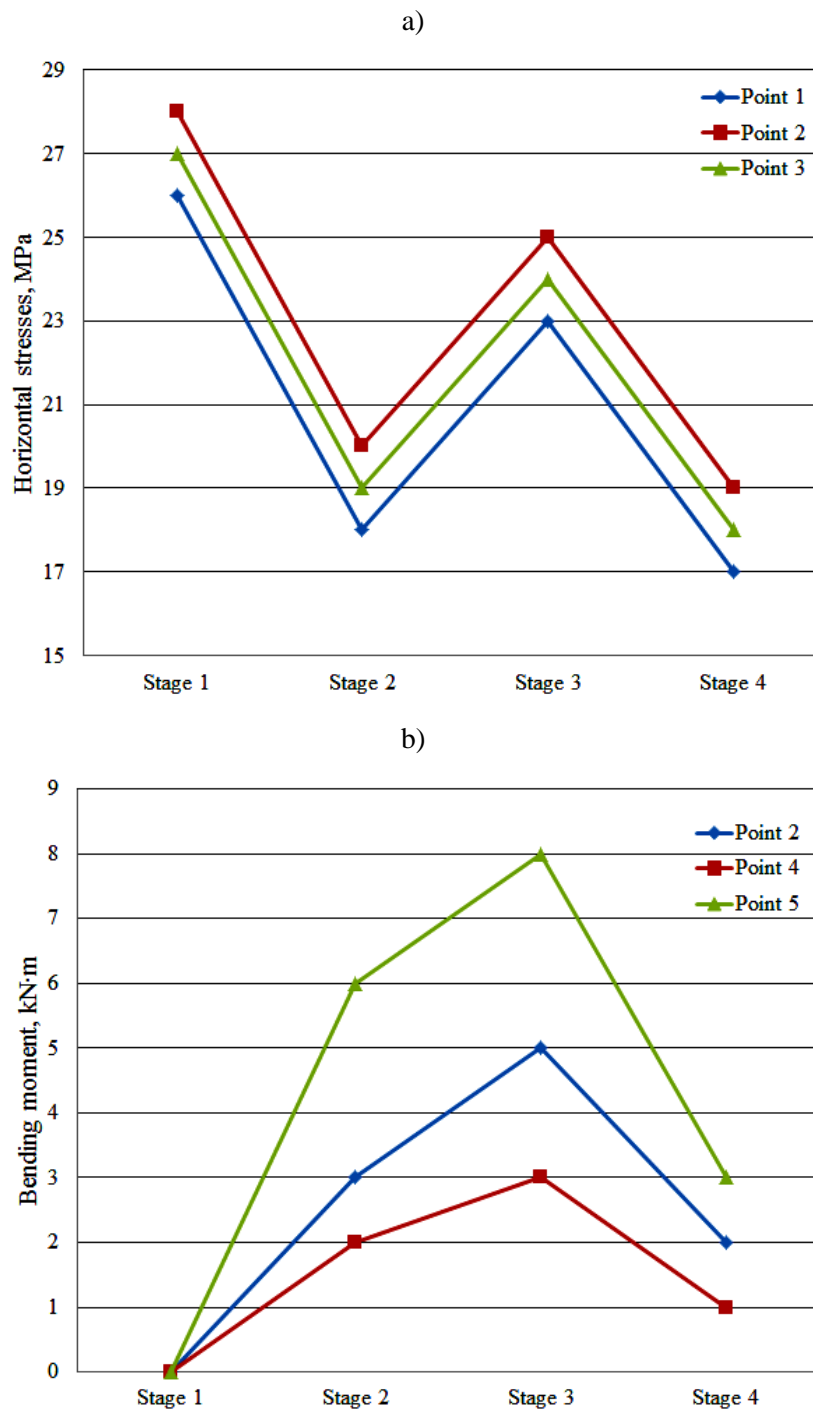


Figure 5. Dependences of horizontal stresses at characteristic points 1, 2 and 3 of the surrounding massif (a) and bending moments at characteristic points 2, 4 and 5 of the temporary lining (b) on the stage of the working construction.

Simultaneously, at stage 3, judging by the graph (figure 4, b), the bending moment is highest at point 2 and will decrease only at stage 4, when the lining is closed. Therefore, calculating the side tunnel of a pylon-type station during the operational stage (stage 4) would not provide the researcher with the maximum values and could distort the calculated situation.

4. Conclusions

Using the developed finite element model of the metro pylon station, which reflects the geometric parameters of the side tunnel, the step-by-step analysis of its construction was performed. The model also represents conditions of the station structure foundation and the interaction between the combined lining system (anchors, arch, and shotcrete) and the rock massif.

The dependences of the horizontal stresses in the rock massif and the bending moment in the combined lining on the construction stage of the side tunnel were obtained. The conclusion of the step-by-step analysis of constructing the side tunnel of the pylon station, which is built using the New Austrian Tunneling Method, is that the maximum stresses and force factors arise during the construction process, not in the operational phase.

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