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# Regularities of the stress state of the rock massif around the single-vault station under construction by NATM

Anatolii Radkevych<sup>1</sup>, Oleksii Tiutkin<sup>1,3</sup>, Volodymyr Kuprii<sup>1</sup> and Taisiia Tkach<sup>2</sup>

<sup>1</sup>Ukrainian State University of Science and Technologies, Lazaryan Str., 2, Dnipro, 49010, Ukraine

<sup>2</sup>State Higher Educational Institution "Prydniprovsk State Academy of Civil Engineering and Architecture", Chernyshevskiy Str., 24-a, Dnipro, 49600, Ukraine

<sup>3</sup>Corresponding author: alexeytutkin@gmail.com

**Abstract.** Subway stations are underground facilities of high responsibility. The use of new construction technologies requires their scientific justification. The single-vault station "Teatralna" of the Dnipro Metro is designed as one that is under construction by the New Austrian tunneling method. Since this type of station is a working of a large cross-section, it is necessary to determine the stress state of the rock massif, which affects the temporary fastening. The finite-element model is developed, which shows the stages of cross-section opening. The developed model reproduces the layout of the subway station in the rock massif and the characteristics of the temporary fastening. The numerical analysis for six stages of station construction is carried out. The distributive features of horizontal stresses and the asymmetry of the stress state of the rock massif are clarified. For the first time, the regularities of the rock massif around the single-vault station under construction by the New Austrian tunneling method are obtained. It is established that the maximum of horizontal stresses appears at the stage of opening the lower left part of the cross-section.

## 1. Introduction

Starting in 2016, the Dnipro Metro is being built on the basis of NATM (New Austrian tunneling method). Moreover, all workings of any orientation in space (vertical, horizontal, and inclined) are built according to the basic principles of this method (opening the cross-section of the mine working in parts, use of temporary flexible fastening, construction of a permanent monolithic frame) [1, 2]. It is important to note that the station complexes of the subway (stations of the single-vault and three-vault types) are also decided to be built in parts with the use of multilayer fastening, a characteristic of NATM.

Such a decision is not unique to Ukraine, as a double-track railway tunnel in the Carpathians (The Beskydy Tunnel) has already been built on the basis of the NATM strategy, which is currently being successfully operated. This experience in constructing an underground working of a large cross-section was evaluated positively, but the implementation of NATM principles required a revision of the building concept for the Dnipro Metro. This can be seen as a precedent since the cross-section of the single-vault station "Teatralna" is larger than the cross-section of a double-track tunnel, as The Beskydy Tunnel is, and also has a different shape (the station is more horizontally elongated than a railway tunnel which tends toward a circular outline).

It is known that the main feature of the NATM application is that significant displacements of the



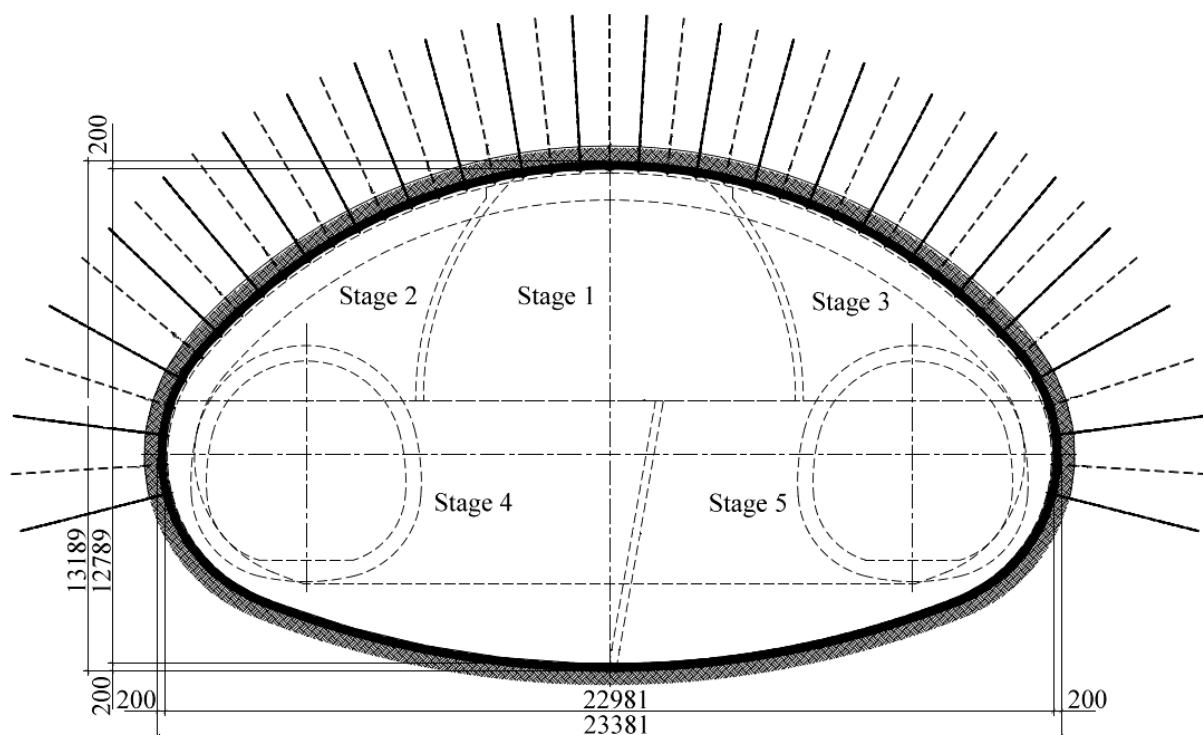
working contour are accepted during the building, thereby providing the rock massif destressing [3, 4]. At the same time, shotcrete and anchors are used as a temporary fastening in stable soils, and the arch lining is used in less stable ones. The permanent frame is installed at the moment when the bearing capacity of the temporary fastening is almost exhausted. As a result, the frame operates into a load that is significantly less than if it had been installed before the massif destressing and therefore may have a smaller thickness.

However, this fact raises a number of questions, the main of which is ensuring the strength of the rock massif around the underground structure, since even for classified hard rocks there is a risk of cracks in the massif and shotcrete [5, 6], especially during drilling-and-blasting operations [7]. According to the construction project of the "Teatralna" metro station, the temporary fastening is provided precisely in the form of shotcrete reinforced with steel mesh mat and anchor lining, and monolithic reinforced concrete as a permanent frame [8, 9].

Thus, the purpose of the scientific research is to obtain the regularities of the stress state of the rock massif around the single-vault station under construction by NATM. Such regularities make it possible to evaluate the risk of stress concentrations in the course of construction and substantiate design solutions developed for temporary fastening.

## 2. Methods

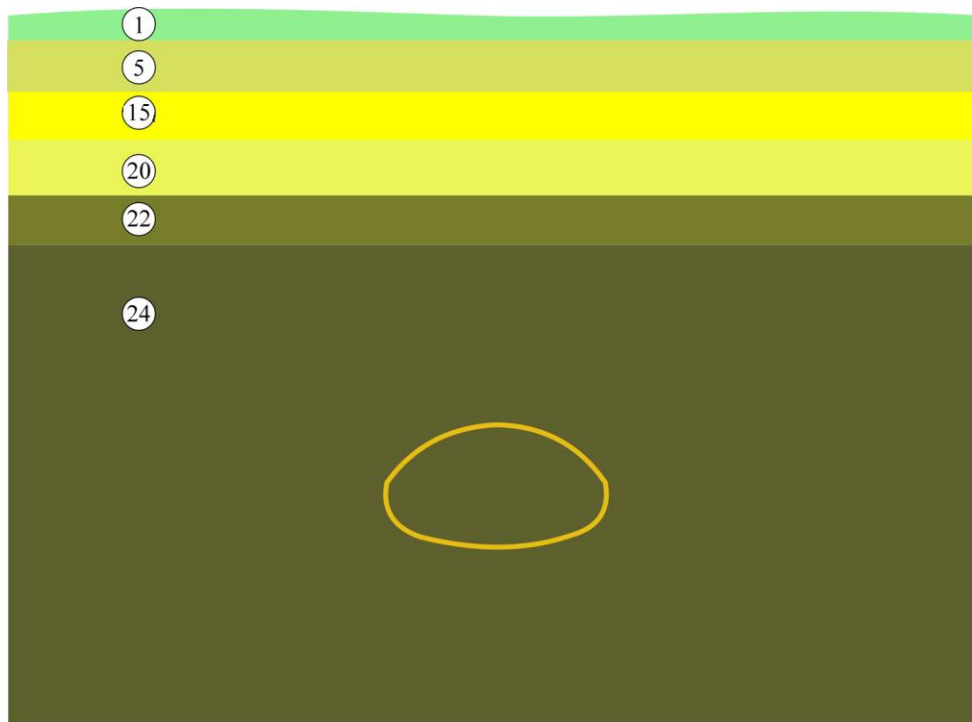
The research on the stress state of the rock massif around the single-vault "Teatralna" station is carried out according to the stages in the opening of the workings (figure 1).



**Figure 1.** The cross-section cut of a single-vault station with indicating stages of cross-section opening.

Analyzing the phasing of the opening, one should immediately note the asymmetry in the forms of workings that are being formed during operations at stages 2, 4 and 5. It can be predicted that such asymmetry of the workings will lead to the asymmetry of the stress state.

For a specific segment in the installation of a single-vault station, the total thickness of soils above the tunnel is determined to be 42.0 m and consists of six rock layers (figure 2).



**Figure 2.** The location scheme of a single-vault station in a rock massif indicating numbers of layers.

Load from the surrounding soil is calculated as the vertical pressure of soils embedding to a depth of 42 m, in conformity with laboratory-defined characteristics (table 1).

**Table 1.** Properties of the soil massif layers.

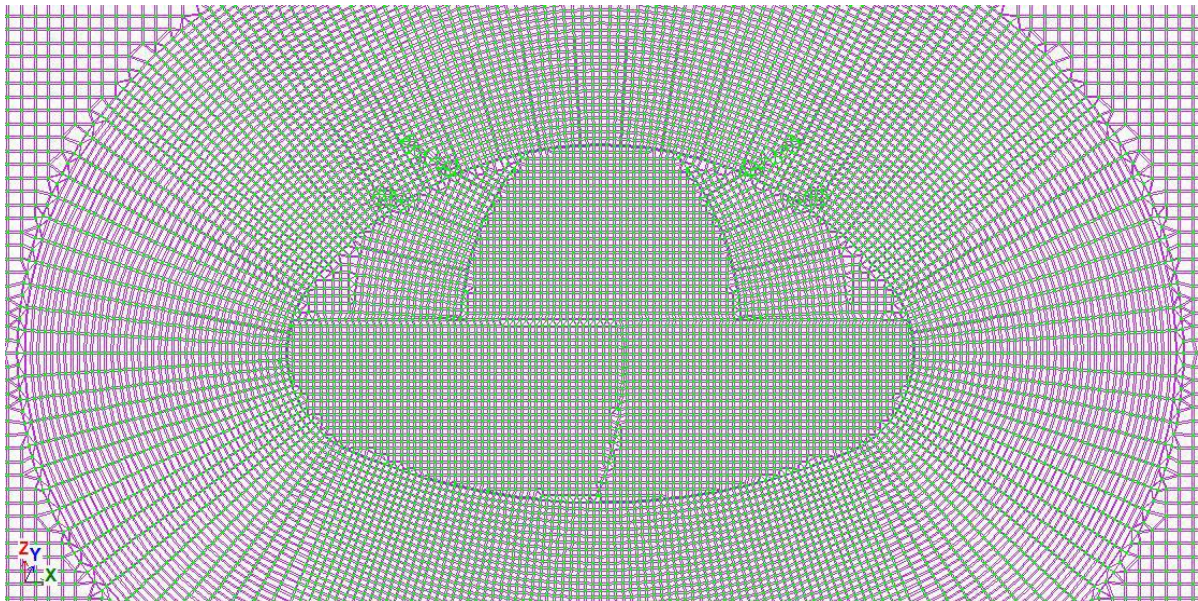
Soil number and type	Layer thickness, m	Specific density $\gamma$ , kN/m <sup>3</sup>	Specific cohesion $C$ , kPa	Inner friction angle $\varphi$ , degree	Elastic modulus $E$ , kPa
1 – bulk soil	2.0	18	1	22	5000
5 – fine sands	6.2	17	2	31	22000
15 – uneven-grained sands	4.4	21	1	40	41000
20 – grained sand	4.6	20	2	35	35000
23 – dispersed zone of the weathering crust	2.6	23	45	34	40000
24 – plagiogranite, granite, diorite	22.2	26	343	57.5	2565000

The characteristics of temporary fastening are as follows:

- shotcrete (thickness 20 cm, concrete grade C20/25);
- steel fabric ( $2 \times \varnothing 8/150$  mm, two-layer, grade A400C);
- lattice beams (P115-20-25/2.00 m, grade A400C);
- anchors installed in the radial and horizontal directions, respectively (A400C,  $1.50 \times 2.00$  m, length 4.00 m,  $\varnothing 25$  mm, hole diameter 42 mm).

Simulating the stress-strain state of the temporary fastening of the workings together with the rock massif is carried out in line with the stages of cross-section opening (figure 1). The phasing of the

construction in the course of numerical analysis in the specialized LIRA complex (License No. 1d/2063) is taken into consideration. Research of six stages has been performed, the results for five are presented below since Stage 0 is the primary and characterizes the stress state before the cross-section opening of a single-vault metro station. The complexity of simulating should be emphasized, since, for example, while displaying Stage 3 (opening the upper right part of the cross-section), in Stages 1 and 2, the temporary fastening has already been simulated. All stages are displayed in one model, which enables us to show the step-by-step cross-section opening and their gradual fastening (figure 3).



**Figure 3.** The fragment of the finite-element model reproduces the phasing of construction of a single-vault station.

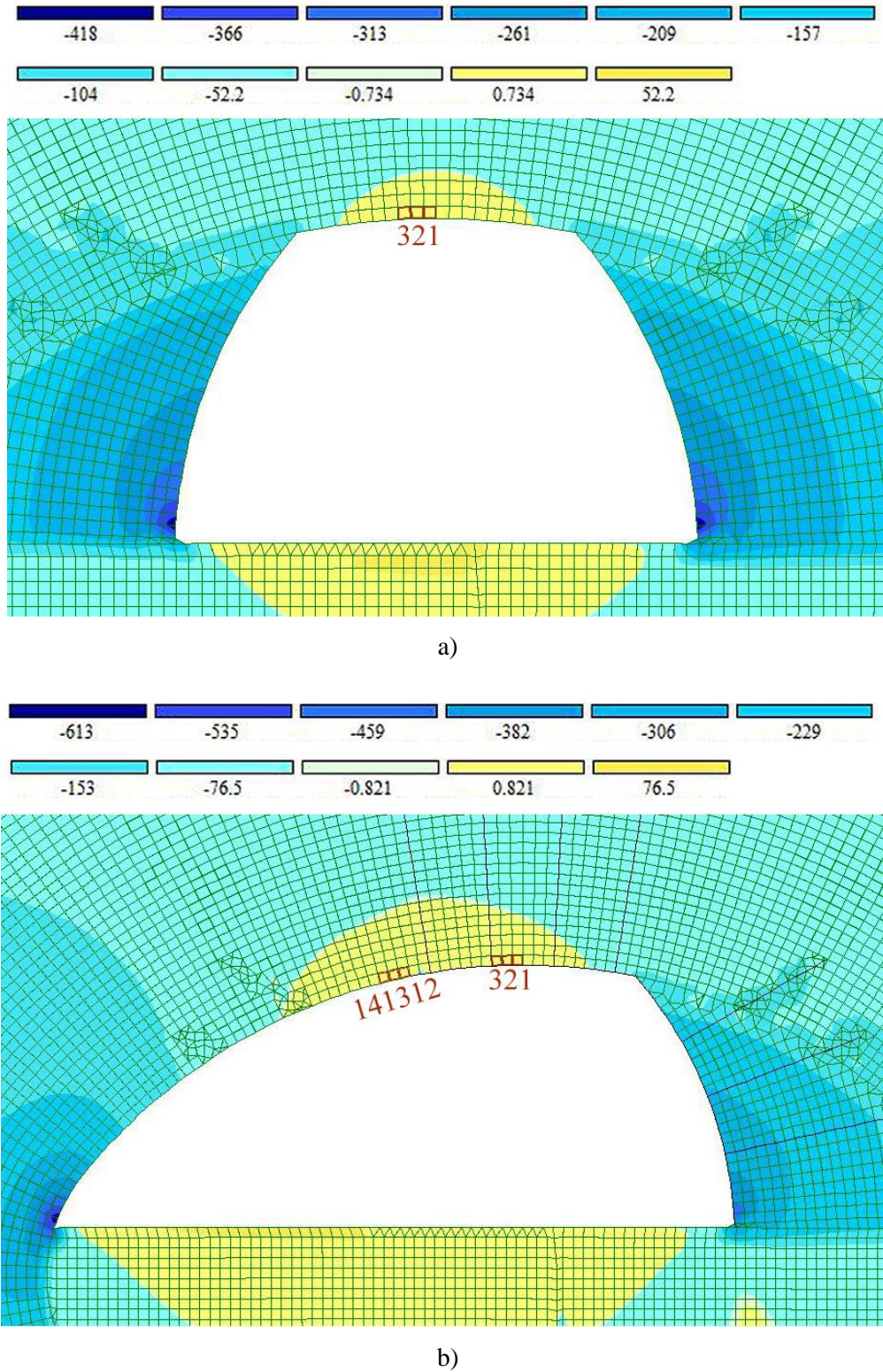
Soils are simulated in the specialized LIRA complex by physically nonlinear quadrilateral and triangular finite elements of flat soil deformation (CE 281, 282, 284), temporary fastening is simulated with a beam of 20×100 cm (CE 10), anchors are CE 208 (special physically nonlinear). Rock layer 24 (granite) is simulated by plate finite elements (CE 30), which more accurately reflect the work of rocky soil.

### 3. Results and discussion

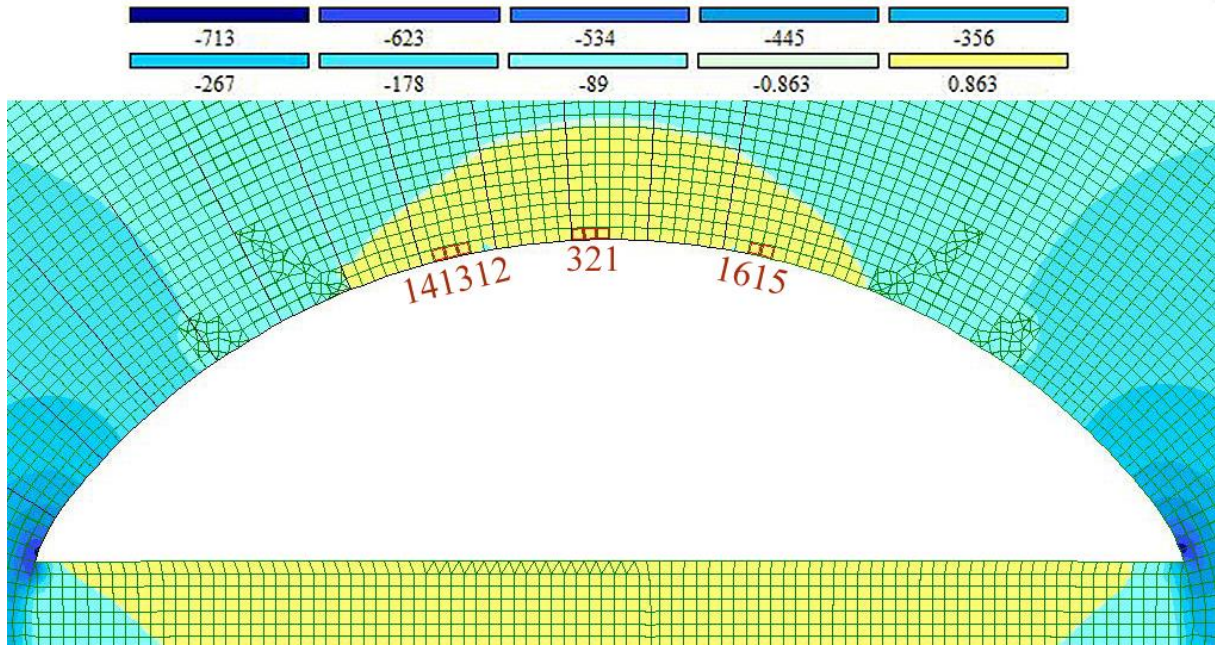
According to the stages of cross-section opening of the single-vault station and installing temporary fastening in the workings, six calculations are made that fully reflect the state of the construction. The analysis of the world experience in the construction of underground workings shows that the most critical stresses can occur at the intermediate stages of conducting operations on the heading of the station tunnel [9]. Figures 4-6 show characteristic patterns in the distribution of horizontal stresses (the characteristic finite elements of the model are in red, where the concentration of the stress state is observed). Exactly values of the horizontal stresses are the largest ones, and it is this component of the stress state that is responsible for the destruction of the rock, characterizing compression or tension in a single finite element.

Horizontal stresses have been analyzed. On their basis, the regularities of the stress state of the rock massif have been obtained (figure 7). As already predicted above, its asymmetry is observed, which is most evident in Stages 2 and 4 (figures 4b and 5b). Adverse stages of work on the cross-section opening of a single-vault station, where concentrations of the stress state of the unfastened part of the working and temporary fastening arise are Stages 1, 2 and 3. Analyzing the regularities of the stress state, it can be concluded that at Stages 3, 4, and 5 the stress in the massif almost stabilizes. This is

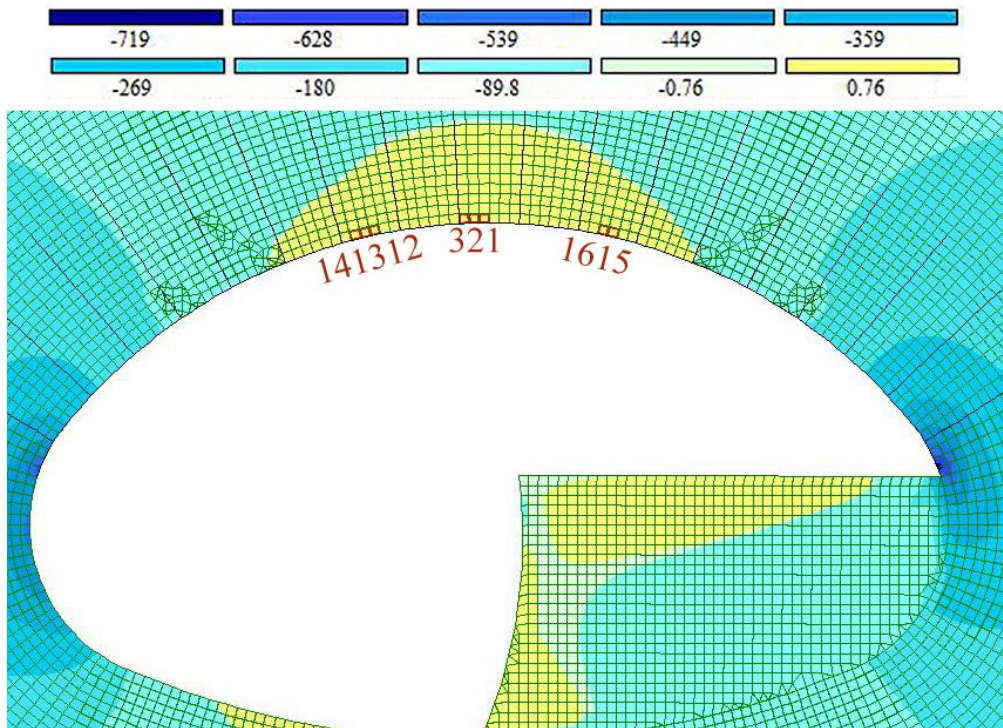
explained by the fact that after the development of the upper part of the single-vault station and its fastening with shotcrete and anchors, the destressing of the massif begins, which is the task of NATM.



**Figure 4.** Isolines and isofields of horizontal stresses (kPa): a) Stage 1; b) Stage 2.

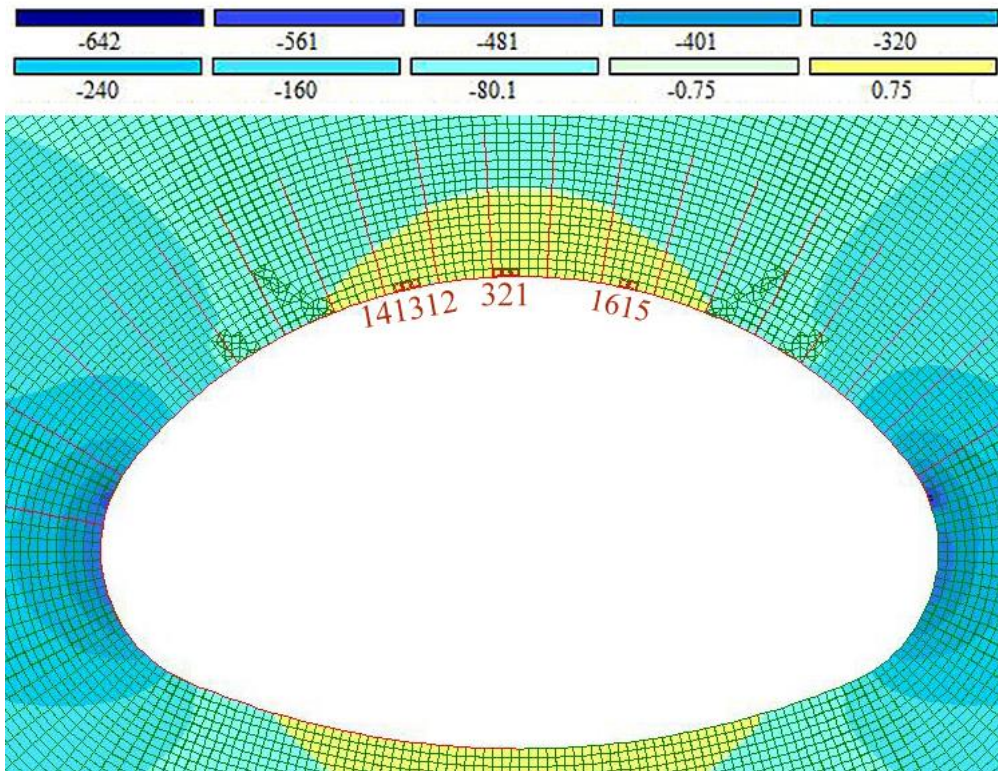


a)

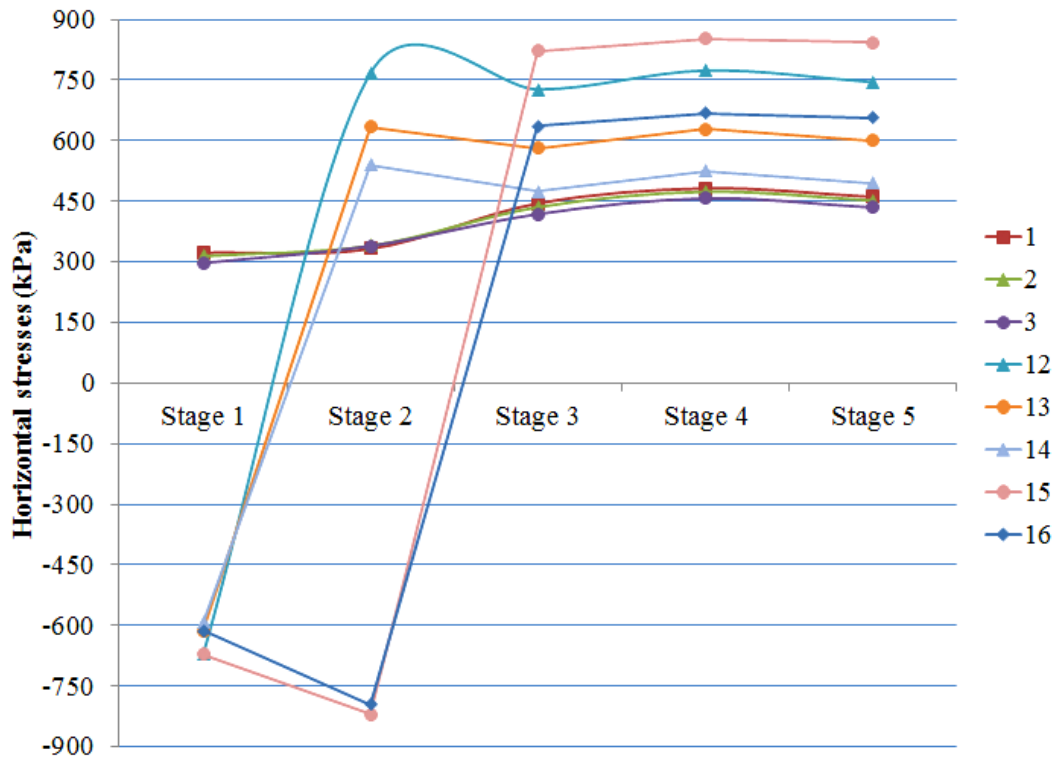


b)

**Figure 5.** Isolines and isofields of horizontal stresses (kPa): a) Stage 3; b) Stage 4.



**Figure 6.** Isolines and isofields of horizontal stresses (kPa) (Stage 5).



**Figure 7.** Graphs of changes of horizontal stresses (kPa) in characteristic finite elements of the model.

It is also important to note a significant stress jump at Stages 1 and 2 (figure 7) what is more, the horizontal component changes sign. This is logical, since the stresses in the rock massif in which the working has not been passed, are compressive stresses that change drastically at Stage 1 in elements 1, 2 and 3, in which tension appears. However, compression retains in yet-to-be-opened elements 12-16, which leads to an asymmetric stress state of the rock massif around the single-vault station, which becomes more homogeneous in Stage 3.

Exactly in element 15 (figure 7) the maximum stresses are observed, increasing to values of 822.6 ... 852.9 kPa, and the maximum is noted at Stage 4, on which the opening of the lower left part of the working has the greatest effect on the stress state.

In compliance with the obtained stress values of the rock massif around the single-vault station, the temporary fastening in the form of reinforcement with reinforcing steel of class A400C with a diameter of 8 mm, and a cell of 150 mm in two layers is checked and approved. However, in view of the analyzed stress state, it is noted that the most critical stresses may emerge in the zones of highly-fractured hard rocks before the installation of temporary fastening. In this case, in order to prevent inrushes, it is recommended to conduct a heading with the help of a protective shield made of reinforcing bars.

#### 4. Conclusions

The single-vault station "Teatralna" of the Dnipro Metro is designed as being built by NATM, which means a change in the construction concept. The research has been conducted on the rock massif around the single-vault station, which is a responsible part of the overall system and has the risk of overstressing and cracking.

The finite-element model of a single-vault station under construction by NATM has been developed. The important conceptual move is taking into consideration phasing in the working opening in the model. For the first time, the regularities of the stress state of the rock massif around the single-vault station have been obtained. Calculations of the strength of the temporary fastening carried out based on the maximum stress values confirm the designed parameters of the reinforcement.

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