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The comparative analysis of the stress-strain state of the support of the escalator tunnel constructed in weak soils by the NATM

Anatolii Radkevych[1], Oleksii Tiutkin[1,2], Volodymyr Kuprii[1] and Sofiia Bielikova[1]

[1]Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryan Str., 2, Dnipro, 49010, Ukraine

[2]Corresponding author: alexeytutkin@gmail.com

Abstract. The construction of underground objects of the subway is always associated with building of structures connecting the surface. For subways, such structures are escalator tunnels. During the construction of the Dnipro Metro, these underground structures are built using a new technology that forms a multilayered support. This technology is the New Austrian tunneling method. A special feature of its application under the conditions of the Dnipro city is the existence of weak rocks in the upper part of the escalator tunnel. To ensure their stability, various special operational techniques are used that impact the rock massif. The basic techniques include artificial freezing, which was the dominant strengthening technology, and chemical strengthening (cementation), which is more consistent with the New Austrian tunneling method. To elucidate the effectiveness of the two strengthening techniques, a finite-element model of the Dnipro Metro escalator tunnel has been built. The numerical calculation of two variants for the strengthening of weak soils yielded results for a comparative analysis of the stress-strain state. The result of the comparative analysis is the conclusion of greater cementation efficiency when strengthening weak soils of the massif in which the escalator tunnel is constructed using New Austrian tunneling method.

1. Introduction

The transport issue related to the growth of the population leads to the active development of public transport; such systems as subway and railway transport make it possible to solve it more effectively. When constructing underground subway facilities in Ukraine, new technologies are constantly being implemented to correct or completely change the concept of underground construction. There is a steady interest and the relevance in the use of such methods of building infrastructure projects in underground space as the New Austrian tunneling method (NATM) [1–2].

NATM has been developed by Professor Rabcewicz [3] and has been actively used in the Austrian Alps, and subsequently around the world [1, 4, 5]. At present, the scope of its implementation is growing worldwide, in particular in Turkey where NATM is the most popular technique to build transport tunnels [5, 6]. The city's longest road tunnel with a length of 2.5 km is being built in Izmir; tunnels for high-speed trains are constructed in the direction of Istanbul–Ankara, as well as many other projects throughout that country. While implementing NATM under difficult engineering and geological conditions, engineers apply various techniques of additional soil strengthening, which make it possible to freely apply this method in weak soils.

The technology is actively developed in Ukraine in recent years. A railroad two-track Beskydskyi tunnel was built in the Carpathians in the rocks of medium strength (whose strength is $f = 3…4.5$ according to M. M. Protodyakonov). In Dnipro, the construction of underground subway facilities is currently underway: Turkish company Limak builds three stations, running and inclined escalator tunnels, using NATM.

Features of engineering and geological conditions in the construction zone are that the massif is characterized by considerable heterogeneity. A section of the escalator tunnel, located in strong rocks, does not require additional protection; under such conditions, the minimum temporary strengthening is able to perceive all loads. However, in the weak and water-saturated upper layers of the soil, tunneling requires the use of additional methods for strengthening the surrounding massif.

In the specified cases, such special techniques as artificial freezing of the soil [7–8], chemical strengthening (cementation) [9] are used, as well as the use of temporary strengthening in the form of screens of Umbrella type [7]. Under complicated engineering and geological conditions, each of these methods has proven its effectiveness. For example, at significant water inflows, the freezing method is more effective, in very weak soils (whose strength is $f < 0.6$ according to M. M. Protodyakonov) – the Umbrella-type screens, while cementation was established as a more universal technique for a wide range of engineering and geological conditions. The purpose of this work is to perform a comparative analysis of the stress-strain state (SSS) of the strengthening of an escalator tunnel constructed in weak soils using NATM [10, 11], the results of which would determine the most effective technique for strengthening the massif under the conditions of the Dnipro Metro.

2. Methods

A technique of artificial freezing can significantly improve the physical and mechanical properties [8]. Such manipulations with water-saturated soils form an ice-soil fence, which acts as a waterproof temporary strengthening structure and provides conditions for tunneling works. In the process of freezing, the strength (soil strength at compression) and deformation (the elastic modulus) characteristics of the soil improve. A significant disadvantage of artificial freezing is the short duration of rock massif strengthening, which requires significant material and financial costs.

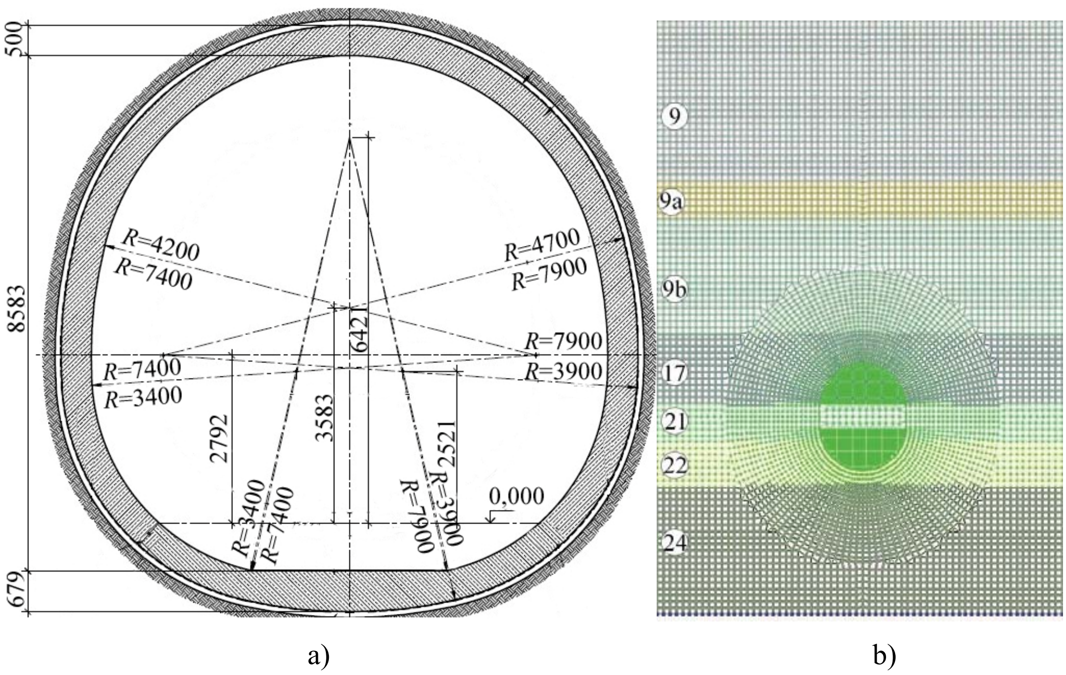


Figure 1. Escalator tunnel geometry: a) cross-section; b) a finite-element model indicating soil layers.

The method of soil cementation is based on the creation of a soil-cement mixture with increased strength indicators [9]. Cementation is the primary stage, without which the tunnelling of workings of large cross-sections, for example, escalator tunnels in weak soils, is impossible. To elucidate the effectiveness of both operational techniques involving NATM, a finite-element model was developed, which reflected the geometric features of the escalator tunnel of the Dnipro Metro and the layered massif in which it is constructed (figure 1).

The finite-element model is implemented in the 79th LIRA computational package (license No. 1d/2063); the soil is assigned by the universal finite element CE 30, designed to solve the flat problem of elasticity theory, and has the properties of the layers of an actual soil massif, given in table 1.

Table 1. Properties of the soil massif layers.

Soil number and type	Specific density γ, kN/m^3	Specific cohesion C, kPa	Inner friction angle φ, degree	Elastic modulus E, kPa
9 – sandy loam, loess sandy loam	17	7	25	12000
9a – loess sandy loam	18	5	26	15000
9b – loess loam	18	9	26	22000
17 – red brown clay	23	75	15	25000
19 – fine sand	20	6	34	38000
21 – dispersed zone of weathering crust	18	45	34	20000
24 – plagiogranite, granite	26	365	52	1330000

In the finite-element model, a multilayer strengthening structure with its actual properties is displayed. The first layer is sprayed concrete of variable thickness, the second layer is an I-beam arch with parallel faces of the type B shelves (I-beam 20B1). The third layer is the strengthening rock massif of weak soil; two variants have been considered: variant 1 – freezing, variant 2 – cementation.

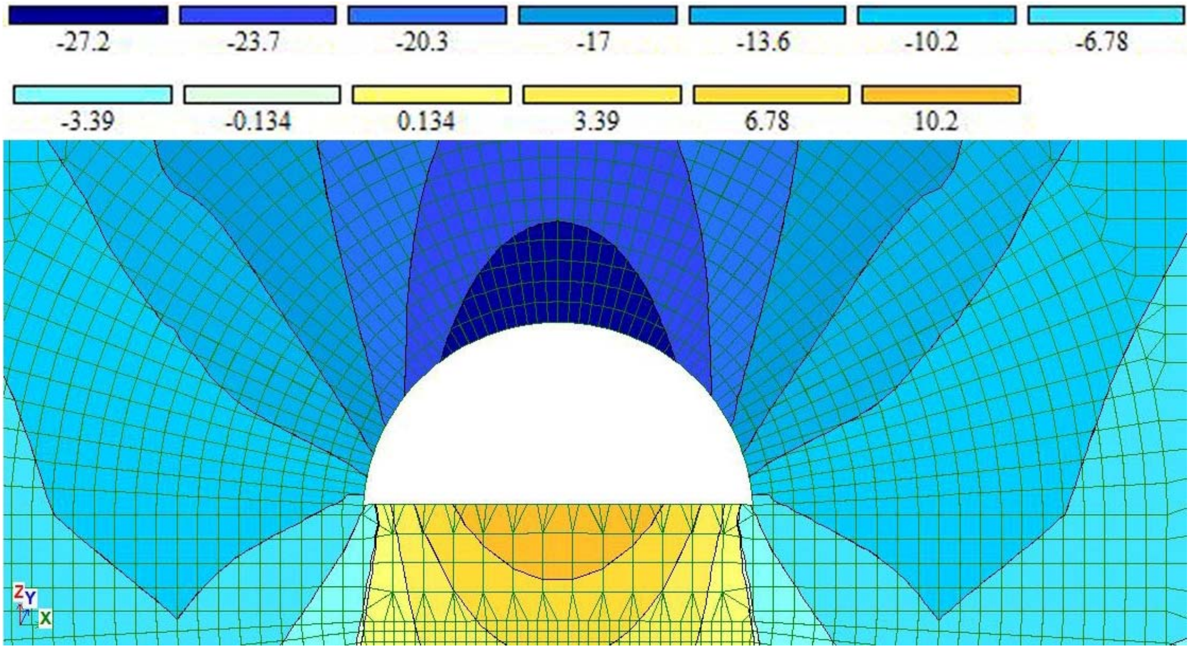
Accordingly, the deformation characteristics in the variants were changed: soil cementation; elastic modulus, $E = 600$ MPa; freezing; elastic modulus, $E = 120$ MPa. Upon altering the deformation characteristics of two variants for strengthening weak soils, a numerical calculation was carried out, its results were used for comparative analysis in order to determine which strengthening technology has a greater impact on SSS.

3. Results and discussion

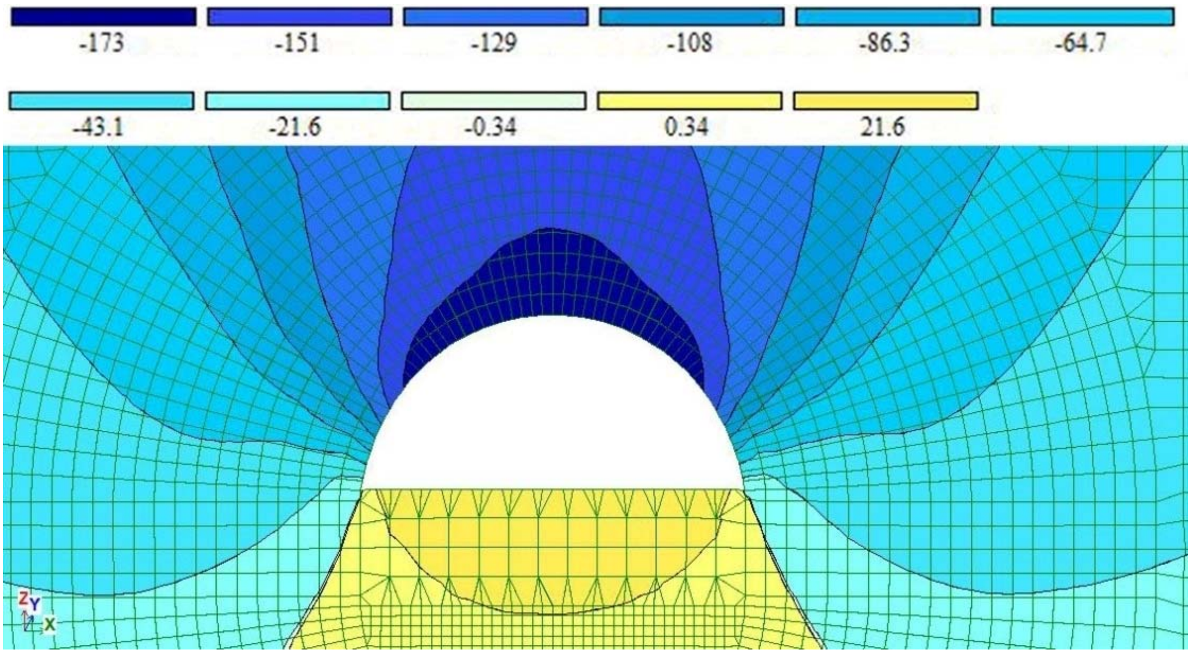
Figures 2–3 show the vertical displacements z (mm) in the finite-element models, depending on the strengthening technique for the surrounding weak massif. In addition to two variants of strengthening considered (cementation technology and freezing technology), the finite-element model reflects the technological feature of tunnel construction, namely, opening the working by parts. The working arrangement includes two stages: Stage 1 implies excavating the soil of the upper part (calotte) and a temporary strengthening, Stage 2 involves the additional working out of the cross-section and the excavation of the lower part (stros), after which the temporary strengthening is closed.

Qualitative analysis of the two strengthening variants makes it possible to conclude that both reduce the vertical displacements z (mm) of the model for the two stages of construction, and their distribution is quite similar. However, it should be noted that in the case of freezing, during stage 1 (figure 2, a), the zone of maximum vertical displacements is much larger in its area, which could cause a local inrush. The calculation of the non-strengthening massif has revealed a complete roof collapse if the massif is not strengthening by freezing or cementation; and qualitative analysis proves that at Stage 1 cementation is more active at reducing the massif displacement than freezing.

The analysis of Stage 2 indicates the occurrence of a heterogeneous displacement field for the case of freezing (figure 3, b), which also negatively characterizes this technique of strengthening the weak surrounding massif. Qualitative analysis of the cementation variant for two Stages (figure 2, a, and figure 3, a) proves that, in this case, there is only an increase in the zone of active deformation, which is logical in the case of increasing the area of the cross-section when opening a stros.

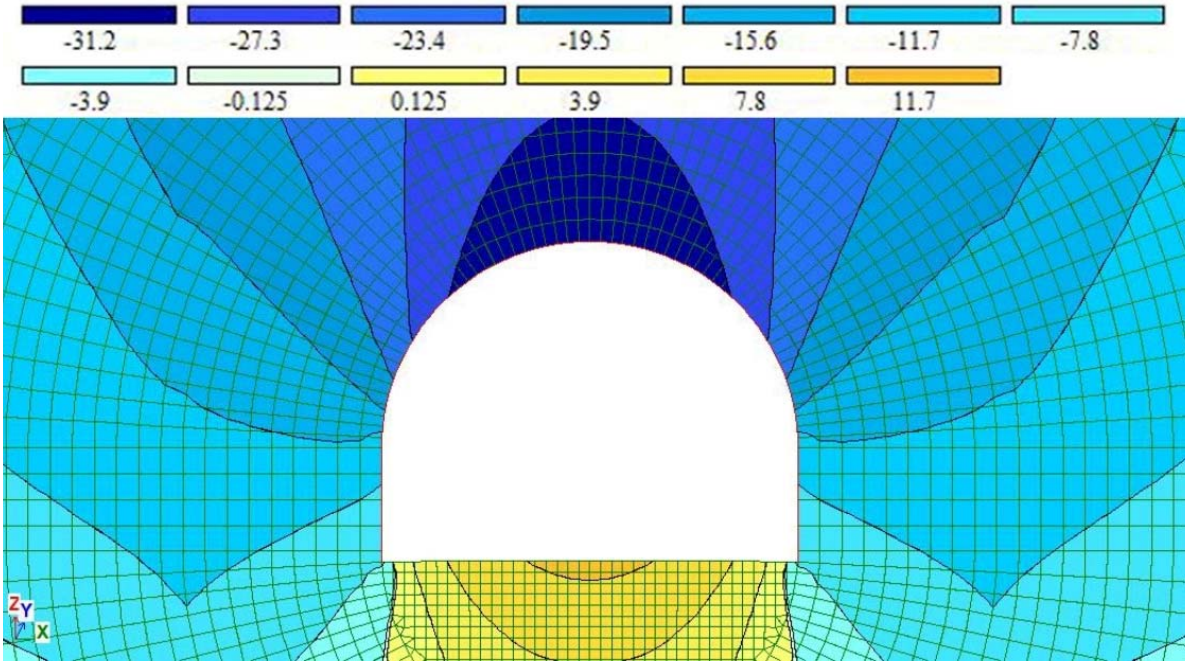


a)

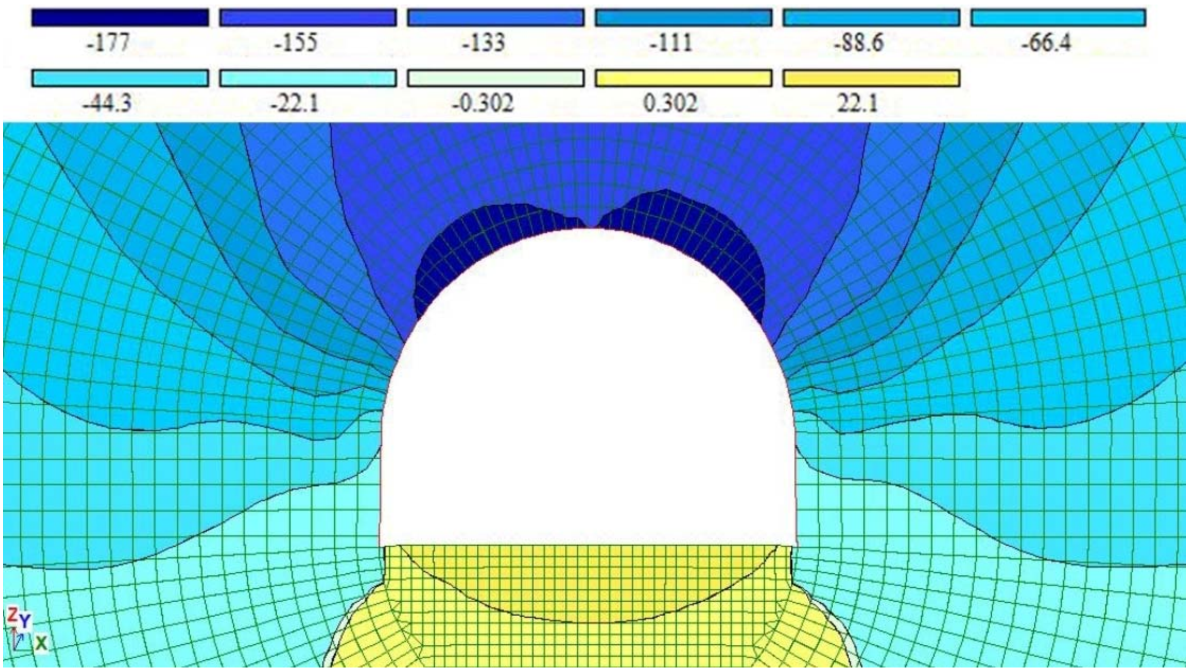


b)

Figure 2. Isolines and isofields of vertical displacements z (mm) of the model reflecting Stage 1 (calotte opening): a) cementation; b) freezing.



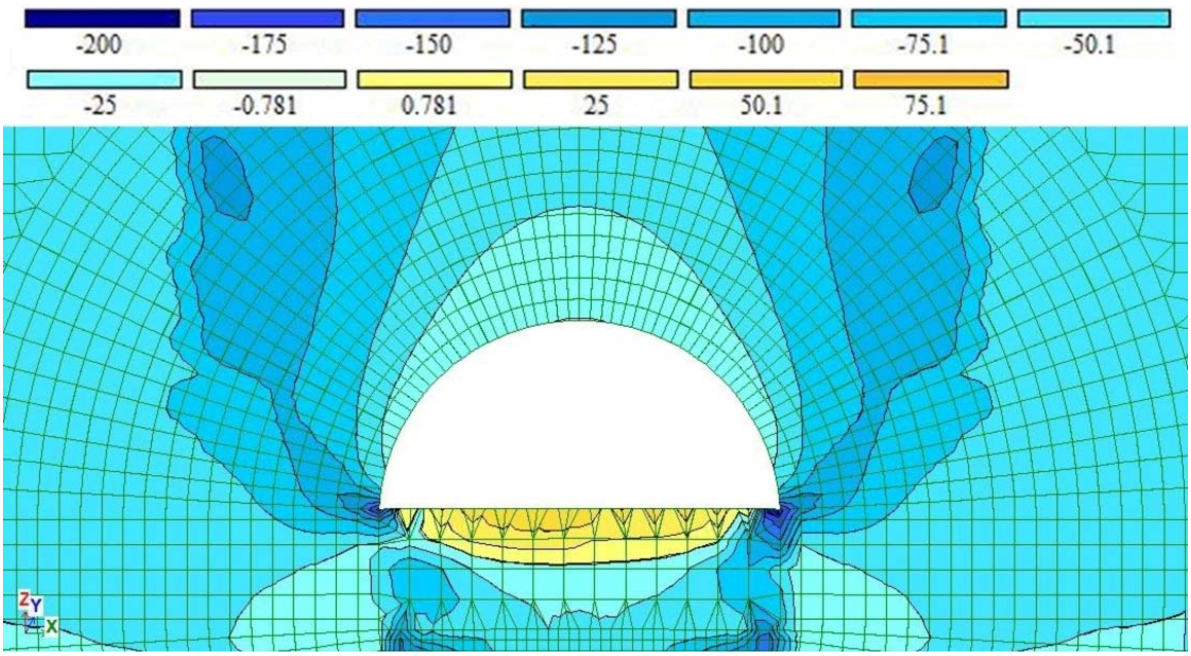
a)



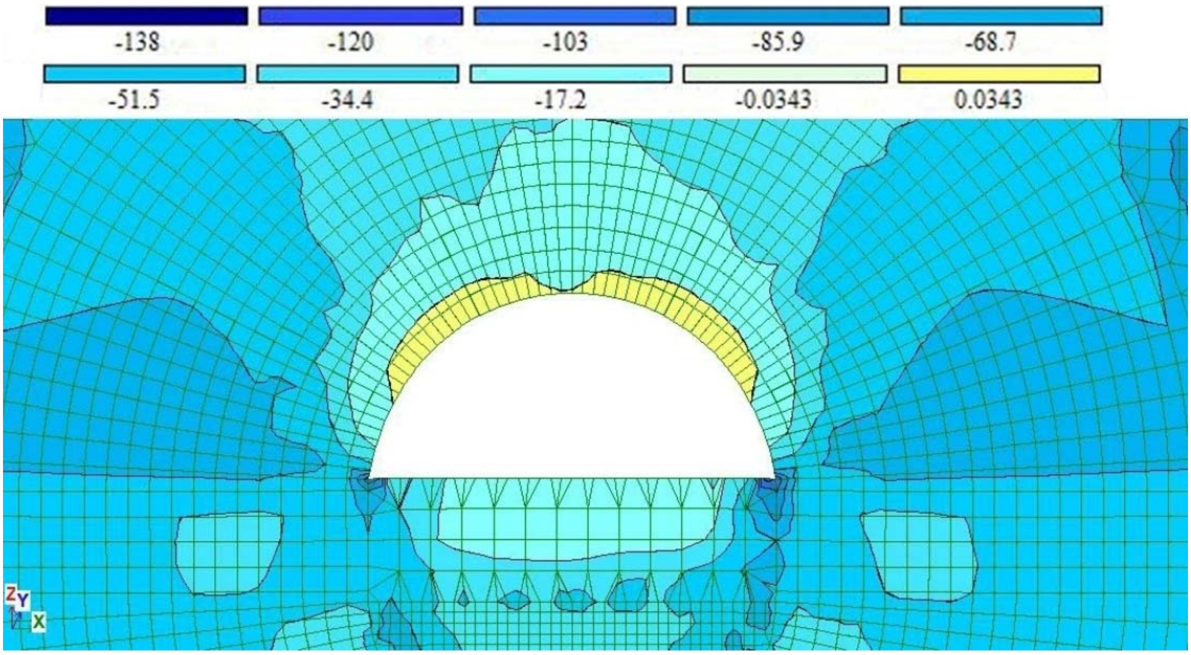
b)

Figure 3. Isolines and isofields of the vertical displacements z (mm) of the model reflecting Stage 2 (stros opening): a) cementation; b) freezing.

Following the qualitative analysis of the deformed state, a similar stress analysis was carried out. Figures 4–5 show the vertical stresses in the finite-element models, depending on the technique for strengthening the surrounding weak massif. At stage 1, the cementation variant demonstrates a greater uniformity of the stress state (figure 4, a), but, at stage 2, the freezing variant yields more homogeneous vertical stresses (figure 5, b).



a)

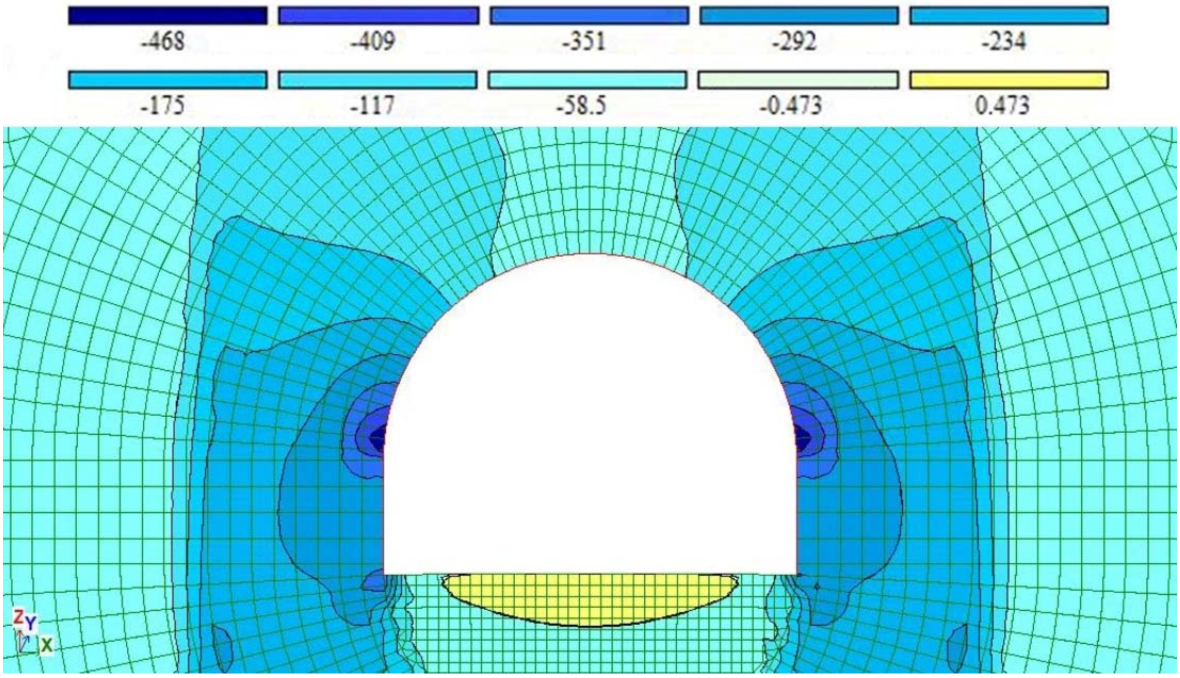


b)

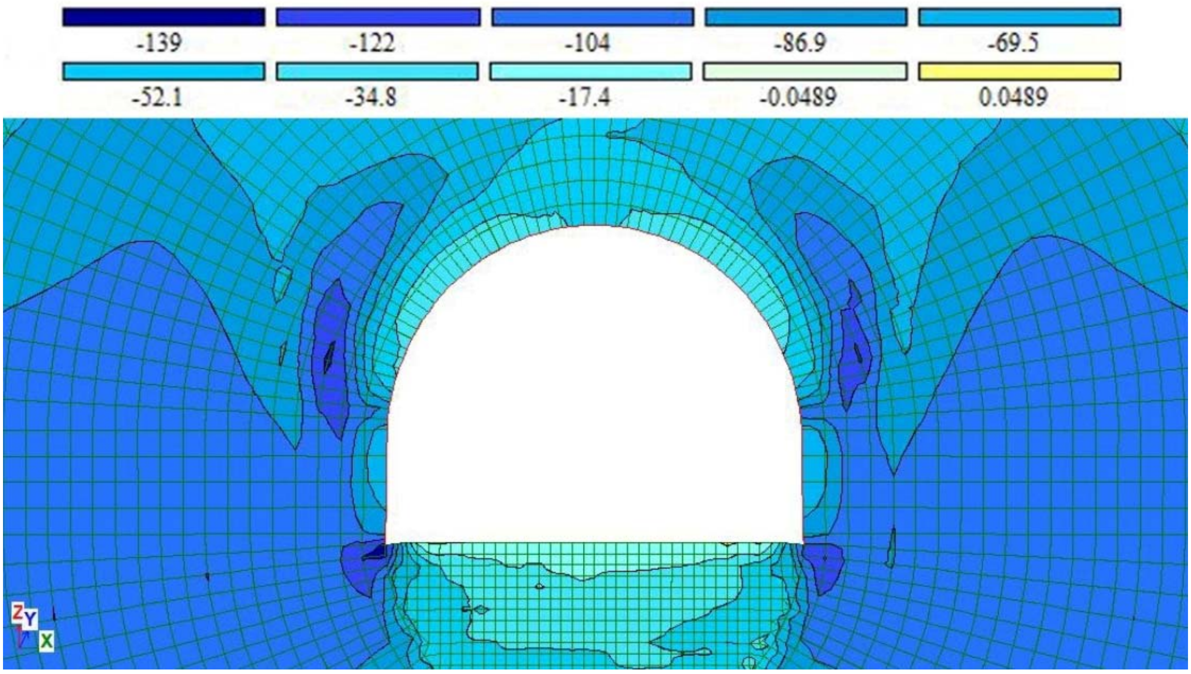
Figure 4. Isolines and isofields of the vertical stresses Nz (kPa) of the model reflecting Stage 1 (calotte opening): a) cementation; b) freezing.

Quantitative analysis of the maximum vertical displacements *z* (mm) of the vertical stresses (kPa) depending on the technique for strengthening the surrounding weak massif is effectively carried out using the growth dependences of this parameter. Cementation, unlike freezing, demonstrates the indisputable effectiveness of reducing the deformed state, since in both stages the vertical maximum displacements are less by 6.36 times (stage 1) and 5.67 times (stage 2) (figure 6). However, freezing, unlike cementation, demonstrates an active decrease in maximum vertical stresses, which are less by

1.45 times (stage 1) and 3.37 times (stage 2) (figure 7). However, the level of maximum stresses at stage 2 in the cementation variant, which was −409...−468 kPa, is about 2.0...2.5 times less than the strength limit of the strengthening rock at compression, which indicates a sufficient margin of safety.



a)



b)

Figure 5. Isolines and isofields of the vertical stresses (kPa) of the model reflecting Stage 2 (stros opening): a) cementation; b) freezing.

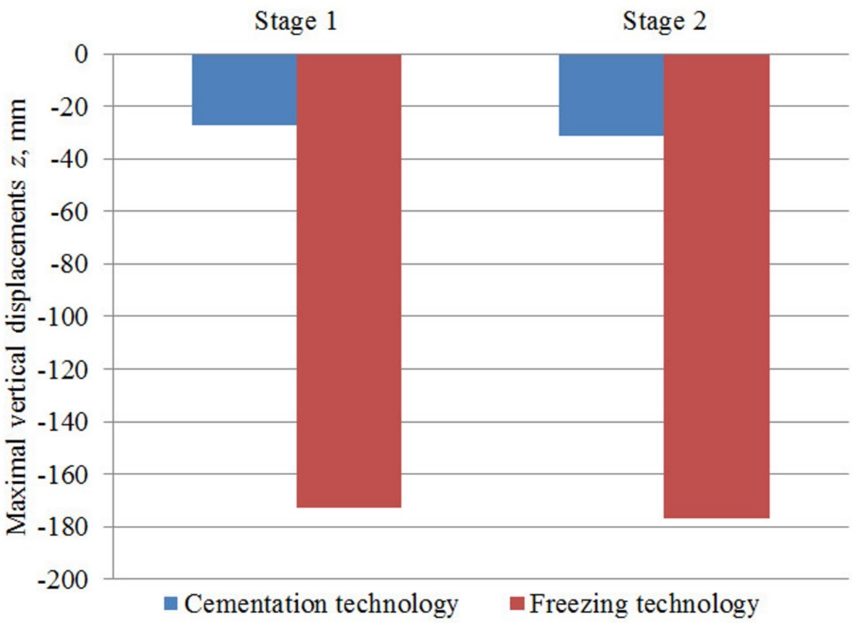


Figure 6. The pattern of maximum vertical displacements z (mm) depending on the technique for strengthening the surrounding weak massif.

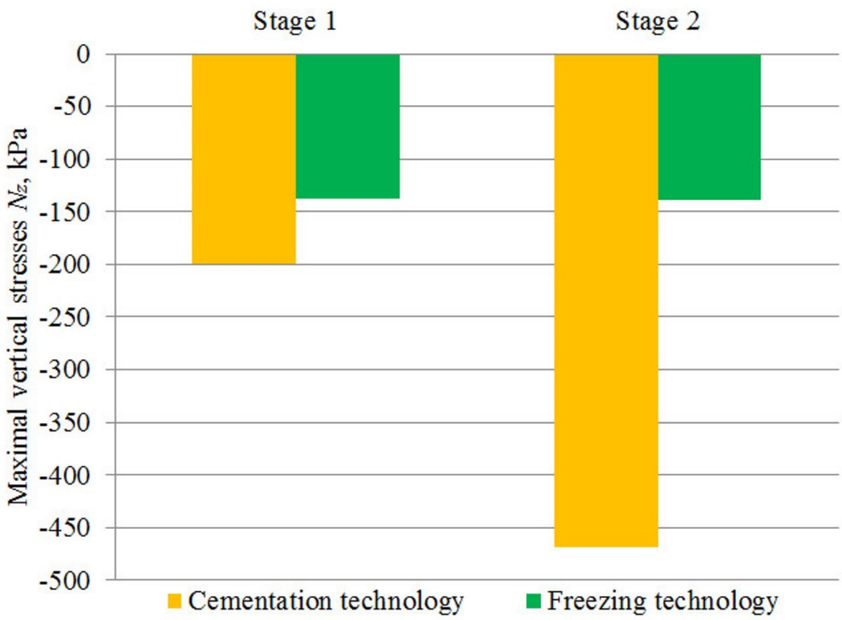


Figure 7. The pattern of maximum vertical stresses (kPa) depending on the technique for strengthening the surrounding weak massif.

It should also be emphasized that the layer of the weak surrounding massif, strengthening by cementation, would remain as an additional fastener throughout the entire service life of this underground structure. The frozen rock layer will disappear after the construction of the escalator tunnel in some time while the strength of the weak soil would remain at the level before its strengthening. This allows us to conclude that the use of cementation is more justified in the construction of an escalator tunnel in a weak massif when using NATM.

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4. Conclusions

A decision to apply a specific type of strengthening to the surrounding massif, composed of weak soils, is based on the qualitative and quantitative analyses of the underground structure's SSS. For the case of the escalator tunnel, a numerical calculation of two variants for strengthening weak soils was carried out, taking into consideration the stage nature of the construction of the underground structure.

Qualitative analysis has shown a greater uniformity of vertical displacements and stresses in the case of cementation. Quantitative analysis has shown that for the same variant of strengthening, the vertical maximum displacements are less by 6.36 times (Stage 1) and 5.67 times (Stage 2). The result of the comparative analysis is the conclusion about greater cementation efficiency when strengthening weak soils of the massif in which the escalator tunnel is constructed using NATM.

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