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МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

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DEPENDENCE OF THE STRESS-STRAIN STATE OF THE METRO RUNNING TUNNEL LINING ON ITS SHAPE

Purpose. The purpose of the scientific article is to conduct a numerical analysis of the metro running tunnel to determine, based on the results, the dependence of the lining's stress-strain state on its shape. To achieve this goal, a modeling of a tunnel with a circular outline and an ovoid shape was performed. **Methodology.** LIRA-CAD is a multifunctional software package for calculation, research and design of structures for various purposes. It is based on the use of the finite element method (FEM), recognized worldwide as the main tool for numerical analysis of the building structures' strength and stability. Calculation of forces, modeling of changes in the stress-strain state of the structure at the stages of its construction and research of the operation of building structures using the finite element method are performed after specifying the materials and properties of the elements. **Findings**. Finite element models of the soil massif and tunnel linings of various shapes (circular outline and ovoid shape) were developed for numerical analysis of the system. An analysis of the results of the stress-strain state of the soil massif and tunnel linings was performed, which allowed to draw a conclusion about the discrepancy of the results for different lining shapes. The analysis was conducted for the stress-strain state of linings of various shapes, taking into account the method of construction and their waterproofing, allowing to conclude that ovoid linings, which are constructed by NATM, have advantages in strength and durability. **Originality**. The originality of the scientific research lies in the analysis of the stress-strain state of the metro running tunnel lining in various engineering and geological conditions, which provides an opportunity to reasonably use calculation methods, the results of which reflect the most reliable operation of the structure for specific engineering and geological conditions. **Practical value.** The practical value lies in the fact that the developed methodology allows for considering underground structures of complex spatial forms, various models of soil behavior, taking into account the technology of tunnel construction.

Keywords: metro; running tunnel; lining; stress-strain state; numerical analysis; New Austrian Tunneling Method

Introduction

During the construction of the first stage of the Dnipro Metro, the erector construction method was used, in which the rock was excavated by drilling and blasting. After the rock removal, the circular lining of reinforced concrete blocks or cast-iron tubings was installed, depending on the geological conditions of the site (Pshynko, Radkevych, Netesa, M., & Netesa, A., 2020).

The Turkish company LIMAK departed from the traditional technology of building the Dnipro Metro. Construction began according to the New Austrian Tunneling Method (NATM) with preliminary excavation of workings and supporting them with temporary lining (Chapman, Metje, & Stärk, 2010; Kuesel, King, & Bickel, 2012). Monolithic reinforced concrete was used as a permanent lining of the ovoid-shaped tunnels.

In addition to changing the shape of the structures of the Dnipro Metro second stage, there was a change in the methods of calculating the stress-strain state of the linings of the tunnels. Current

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state building codes establish that tunnel lining designs must be calculated taking into account their joint work with the surrounding rock massif (Liu, Luo, & Mei, 2000; Li, Jin, Lv, Dong, & Guo, 2016).

The development of methods for calculating tunnel linings from the theory of natural arch of equilibrium to analytical and numerical methods of continuum mechanics, that take into account the joint work of the lining with the surrounding rock massif, has made it possible to consider the technological features of tunnel construction, the phased opening of the excavation for further construction of the lining, and the features of the surrounding rock massif structure.

Existing calculation methods can be divided into four groups: 1) calculation methods based on the theory of natural arch of equilibrium; 2) empirical methods; 3) analytical and 4) numerical methods of continuum mechanics. Insufficient research has been devoted to methods for calculating the stress-strain state of a tunnel by the finite element method to confidently rely on past experience (Kolymbas, 2005; Do, & Dias, 2017; Fumagalli, 2013).

The fundamental drawback of these calculation methods is that they do not fully take into account the physical and mechanical properties of the surrounding massif, as well as the technology of construction of the excavation and its shape, which significantly affects the magnitude of the loads on the tunnel structure.

Calculation methods for various types of influences for circular and non-circular tunnels have been developed, which are based on analytical solutions to the corresponding plane problems of the theory of elasticity, implemented in the form of algorithms and computer programs that allow performing multivariate calculations of underground structures lining. When using the empirical method to determine the loads on the tunnel lining, various classifications are used, which are recommended depending on the engineering and geological conditions and the dimensions of the tunnel, a certain type of lining and formulas for calculating rock pressure. Initially focused on the working, which is excavated in various ways, later empirical methods were modified for tunnels constructed using NATM.

Purpose

The purpose of the scientific article is to conduct a numerical analysis of the metro running tunnel to determine, based on the results, the dependence of the lining's stress-strain state on its shape. To achieve this goal, a modeling of a tunnel with a circular outline and an ovoid shape was performed.

Methodology

The lining for the running tunnel during the construction of the first stage of the Dnipro metro was designed with a circular outline (Fig. 1), and of the second stage, respectively, as a closed prefabricated structure with an ovoid outline (Fig. 2). The inner diameter of the tunnel lining is determined by the dimensions of the clearance profile.

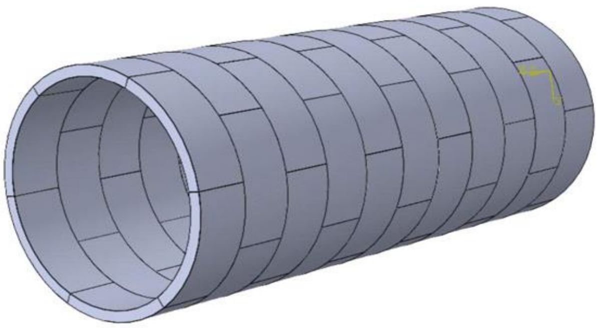

Fig. 1. Circular tunnel lining

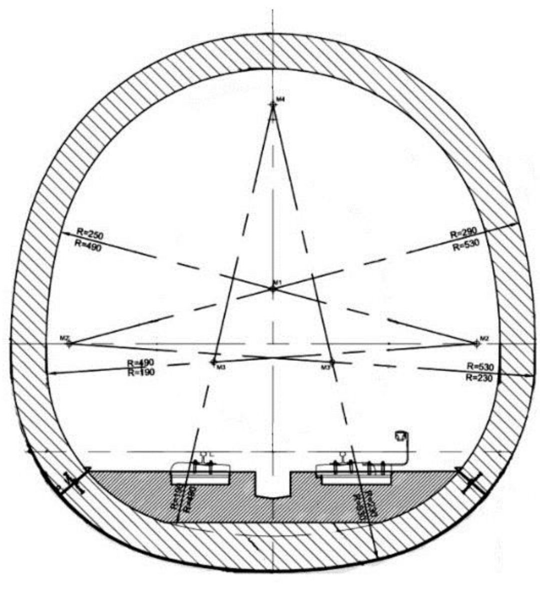

Fig. 2. Ovoid tunnel lining

The two identified variants of the metro tunnel linings were modeled in the LIRA-CAD software package (Fig. 3) (Купрій, Тютькін, & Захарченко, 2017).

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a)

b)

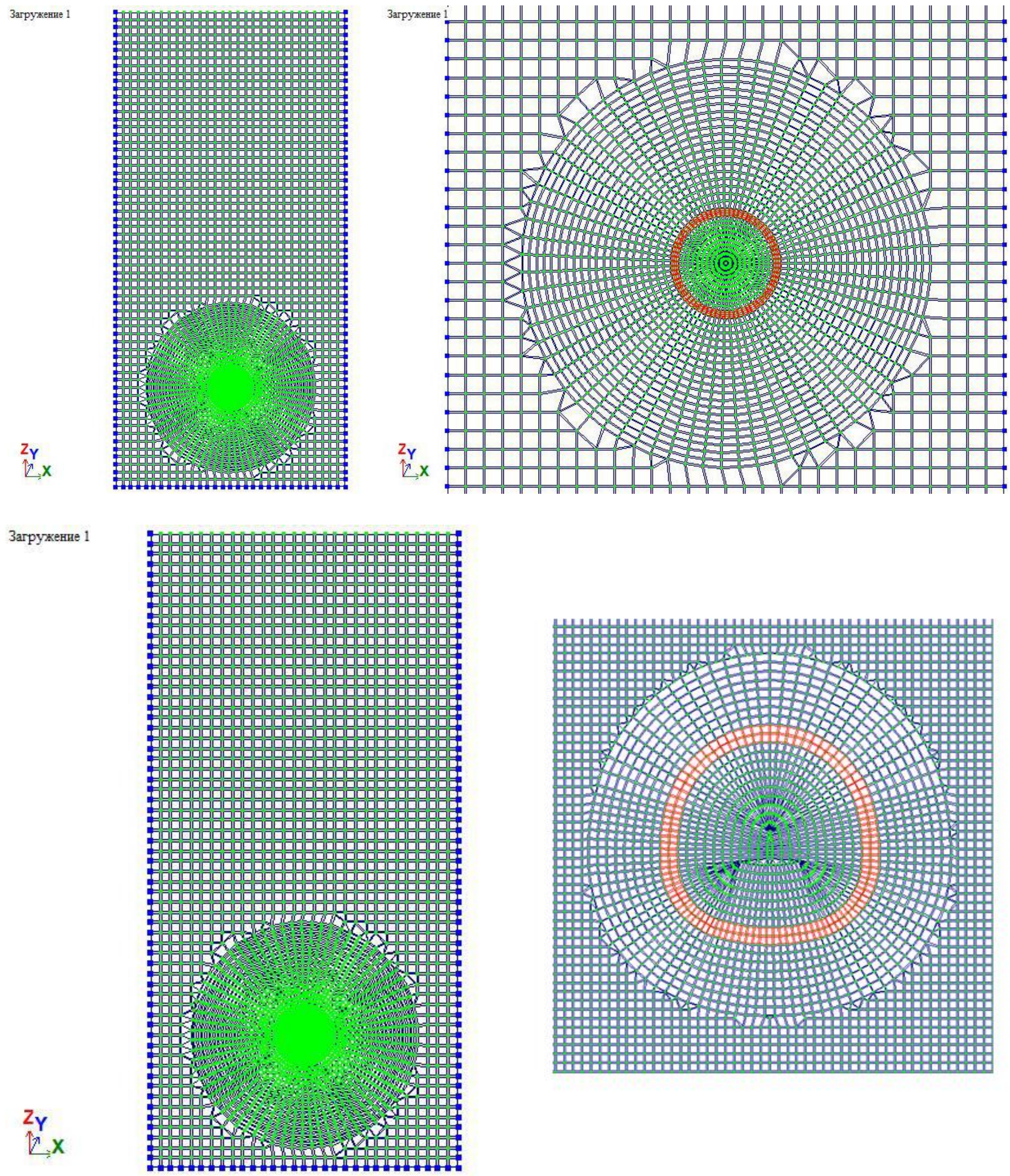

Fig. 3. Finite element model of the soil massif and tunnel lining:
a) circular outline; b) ovoid

LIRA-CAD is a multifunctional software package for calculation, research and design of structures for various purposes. It is based on the use of the finite element method (FEM), recognized worldwide as the main tool for numerical analysis of the building structures' strength and stability (Pande, Beer, & Williams, 1990; Pang, Yong, & Dasari, 2005; Tiutkin, & Bondarenko, 2022).

Calculation of forces, modeling of changes in the stress-strain state of the structure at the stages of its construction and research of the operation of building structures using the finite element method are performed after specifying the materials and properties of the elements.

After forming the geometric scheme of the structure, the next stage is the assignment of external loads. Solving the problem of determining the most dangerous combinations of loads provides an interrelation between the results of the calculation of the structure for various loads and the design of its elements. The software package provides for automated formation of calculated combinations of forces in accordance with design codes for construction objects.

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The calculation stages are as follows:

1. Initial (self-weight + soil mass).
2. Clearing displacements.
3. Modeling of soil excavation and installation of the lining.

Analysis and interpretation of the calculation results are as follows:

1. Visualization of the calculation results.
2. Analysis of the results.
3. Verification of the adequacy of the obtained results.

Using graphical capabilities, one can easily assess the reliability of the stress-strain state of the scheme from each load or their combination, the correctness of the constrains and stiffnesses assignment, and obtain numerical information for each node or element.

Findings

LIRA-CAD provides a graphic visualization of the following results with the ability to fragment, scale, and rotate. Fig. 4 and 5 show the vertical component of the stress-strain state for the circular and ovoid metro tunnel variants.

a)

b)

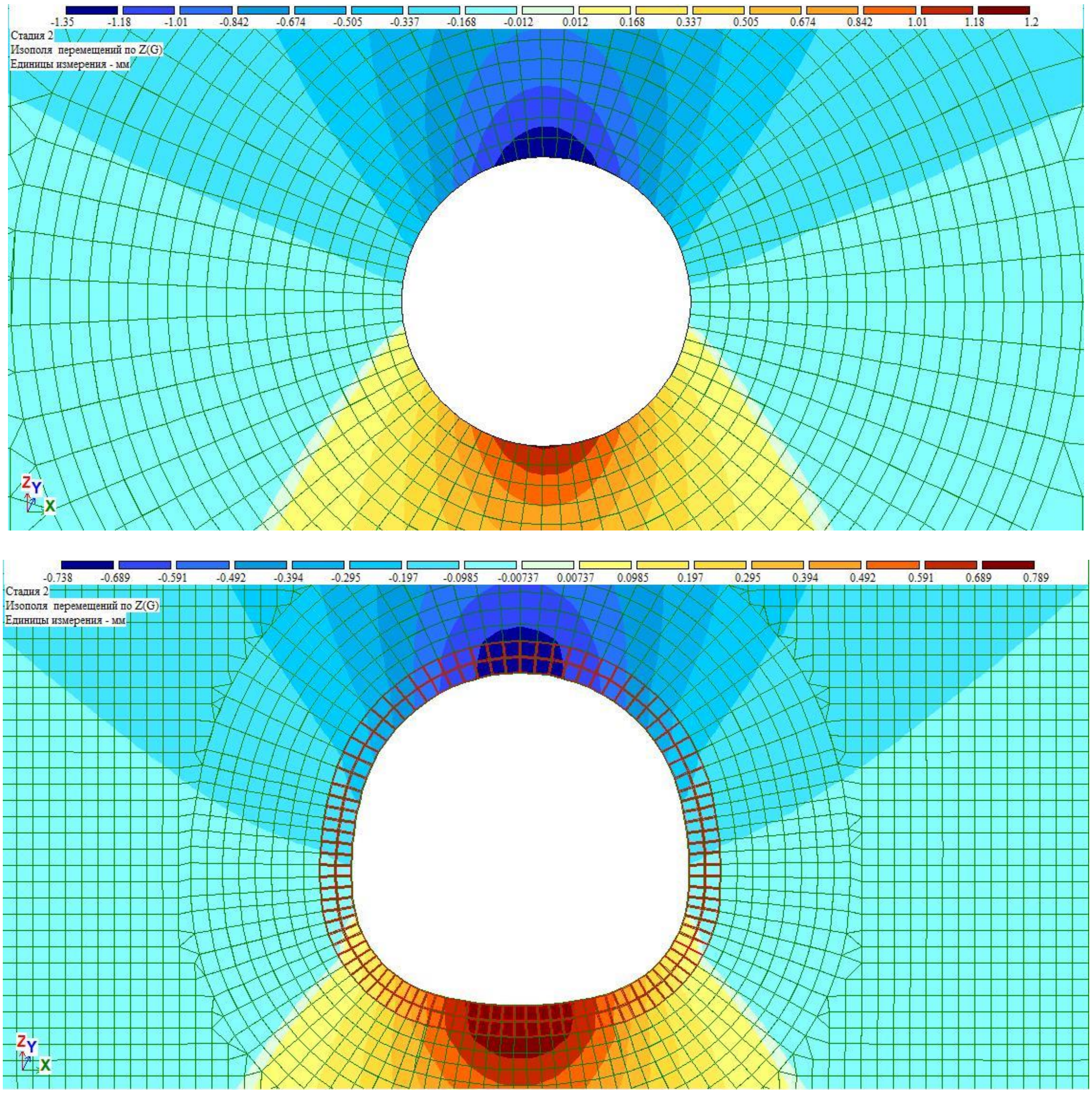

Fig. 4. Vertical displacements of the soil massif after soil excavation and installation of the tunnel lining:
a) circular outline; b) ovoid shape

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a)

b)

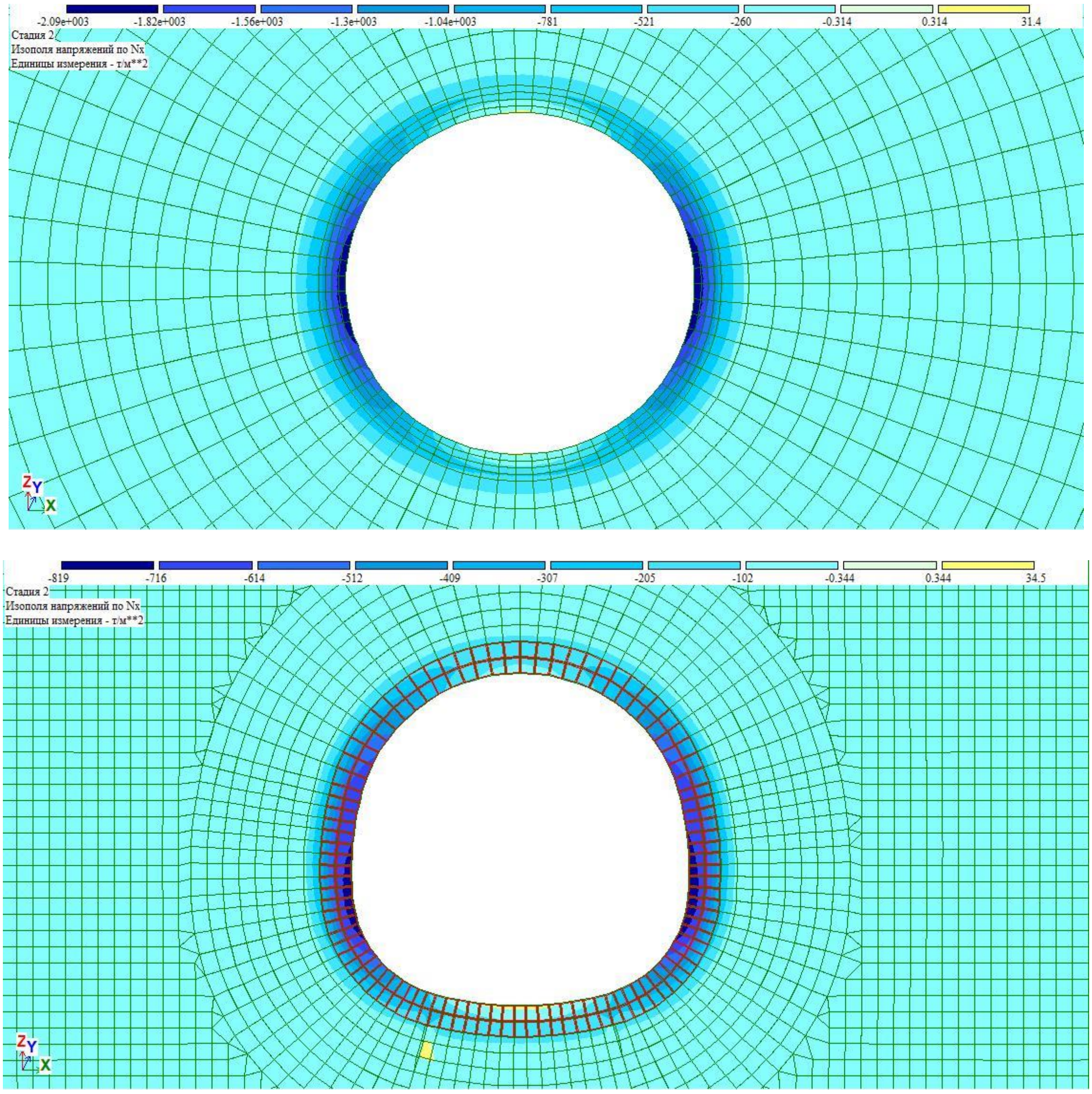

Fig. 5. Vertical stresses in the soil massif after soil excavation and tunnel lining installation:
a) circular outline; b) ovoid shape

Analysis of the stress-strain state results shows that the value of maximum deformations (vertical displacements) in the circular lining is greater than those in the ovoid lining. The value of tensile stresses at the upper point of the linings vault is the same, and the value of compressive stresses is greater in the circular lining, but the zone of maximum stresses changes; in the ovoid lining it moves to the bottom of the lining, to the connection point.

Since the lining in the finite element model was displayed in the form of finite elements, and the stress-strain state in the form of isofields, an additional analysis of force factors (bending moment and normal force; for this purpose, the lining is represented as bar elements, and the results are obtained in the form of diagrams) was also performed, which are necessary for calculating the strength of critical cross-sections, in accordance with current standards. The value of these factors is an indicator of the influence of the shape on the distribution of parameters in the lining, as well as the dependence of strength on it (Fig. 6).

Analysis of force factors proves that changing the shape of the lining affects not only the magnitude of the forces in the lining, but also changes their distribution across the lining.

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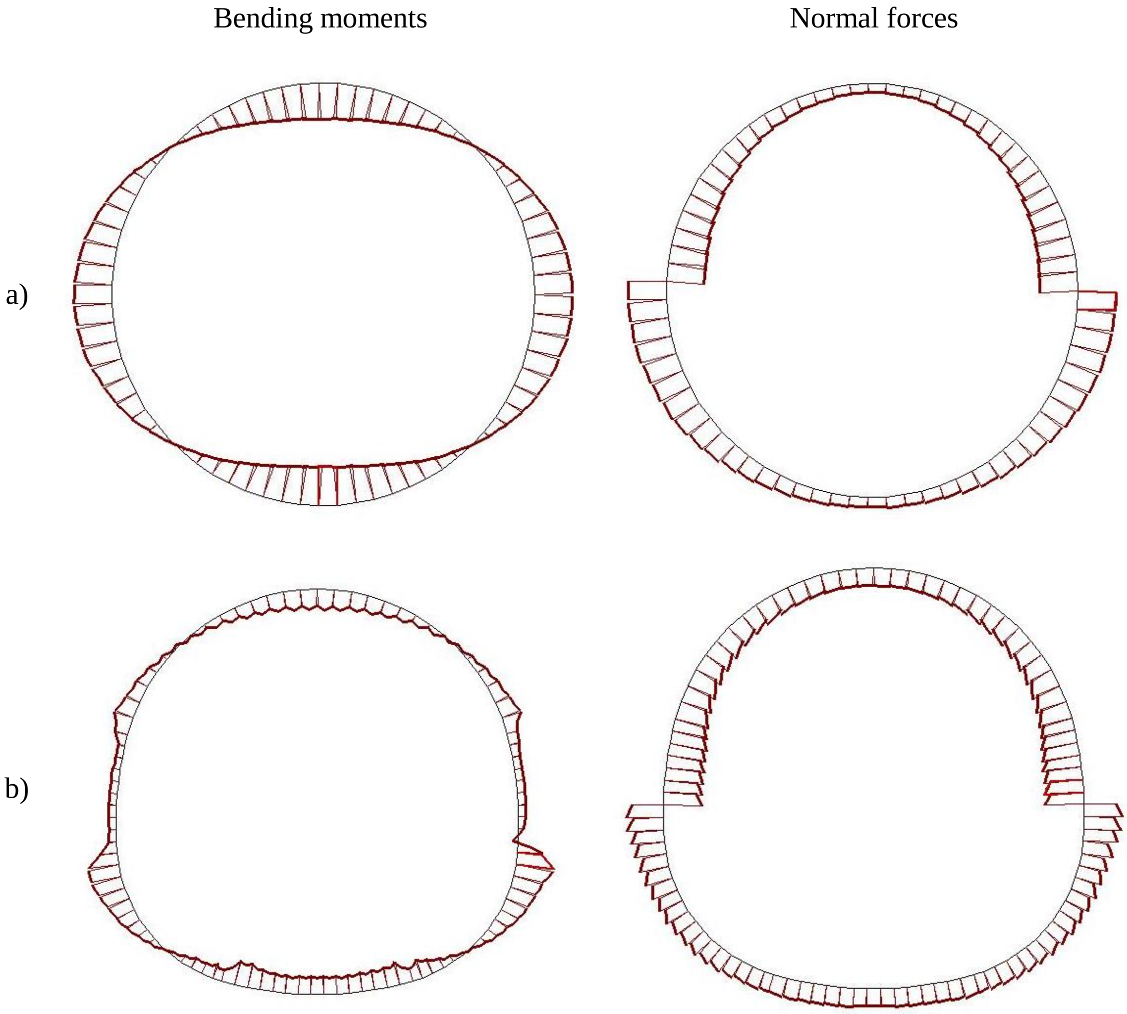

Fig. 6. Diagrams of force factors: a) circular outline; b) ovoid shape

Thus, the influence of the lining shape on the complex of stress-strain state and force factors has been determined.

Originality and practical value

The originality of the scientific research lies in the analysis of the stress-strain state of the metro running tunnel lining in various engineering and geological conditions, which provides an opportunity to reasonably use calculation methods, the results of which reflect the most reliable operation of the structure for specific engineering and geological conditions.

The practical value lies in the fact that the developed methodology allows for considering underground structures of complex spatial forms, various models of soil behavior, taking into account the technology of tunnel construction.

Conclusions

Finite element models of the soil massif and tunnel linings of various shapes (circular outline and ovoid shape) were developed for numerical analysis of the system.

An analysis of the stress-strain state results of the soil massif and tunnel linings was performed, which allowed to obtain a conclusion about the discrepancy of the results for different shapes of linings.

The analysis of the stress-strain state for linings of various shapes, taking into account the method of construction and their waterproofing, allows to conclude that ovoid linings, that are constructed by NATM, have advantages in strength and durability.

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ЗАЛЕЖНІСТЬ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ОПРАВИ ПЕРЕГІННОГО ТУНЕЛЮ МЕТРОПОЛІТЕНУ ВІД ЇЇ ФОРМИ

Мета. Метою наукової статті є проведення чисельного аналізу перегінного тунелю метрополітену із визначенням на основі результатів залежності напружено-деформованого стану оправи від її форми. Для досягнення поставленої мети виконане моделювання перегінного тунелю колового окреслення й еліпсоподібної форми. **Методика.** ЛІРА-САПР є багатофункціональним програмним комплексом для розрахунку, дослідження і проектування конструкцій різного призначення. Він заснований на використанні методу скінченних елементів (МСЕ), признаного в світі основним інструментом чисельного аналізу міцності та стійкості будівельних конструкцій. Розрахунок зусиль, моделювання зміни напружено-деформованого стану конструкції на етапах її спорудження та дослідження роботи будівельних конструкцій методом скінченних елементів виконується після завдання матеріалів та властивостей елементів. **Результати.** Розроблено скінченно-елементні моделі ґрунтового масиву і тунельних оправ різної форми (колове окреслення й еліпсоподібна форма) для чисельного аналізу системи. Виконано аналіз результатів напружено-деформованого стану ґрунтового масиву і тунельних оправ, який надав змогу отримати висновок про розбіжність результатів для різних форм оправ. Проведений аналіз напружено-деформованого стану оправ різної форми з урахуванням способу спорудження і їх гідроізоляції дає змогу зробити висновок, що оправи еліптичної форми, які споруджуються NATM, мають переваги у міцності і довговічності. **Наукова новизна.** Наукова новизна наукового дослідження полягає в аналізі напружено-деформованого стану оправи перегінного тунелю у різних інженерно-геологічних умовах, що надає можливість обґрунтовано використовувати методи розрахунку, результати яких відображають максимально достовірну роботу конструкції для конкретних інженерно-геологічних умов. **Практична значимість.** Практична значимість полягає в тому, що розроблена методика дозволяє розглядати підземні споруди складних просторових форм, різні моделі поведінки ґрунтів, враховуючи технологію будівництва тунелів.

Ключові слова: метрополітен; перегінний тунель; оправа; напружено-деформований стан; чисельний аналіз; Новоавстрійський спосіб будівництва тунелів

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