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МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

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ANALYSIS OF THE IMPACT OF THE CONSTRUCTION TECHNOLOGY OF A COLUMN-TYPE METRO STATION ON THE STRESS-STRAIN STATE OF ITS STRUCTURE

Purpose. The purpose of the scientific research is to analyze the influence of the construction technology of the metro column station on the stress-strain state of its structure. The achievement of this goal is based on the numerical analysis of the metro column station, during which the construction stages of the underground facility are taken into account. **Methodology.** To calculate the stress-strain state of the column-type station structure at different stages of the station lining construction, the modern LIRA-CAD calculation complex was used. Eight stages of the station construction were considered, for which finite element models were developed. After creating finite element models for the eight stages of the column station construction, a numerical analysis was performed. **Findings**. The main results of the work demonstrate that the correctly selected construction technology is critically important for ensuring the stability of the station structures and minimizing the risks of deformations in the soil. The study considers the stages modeling of the station construction using the LIRA-CAD software package. Thanks to this, accurate data on the structural performance of the structure at different stages of construction were obtained. The results obtained allow to state that the proposed construction technology provides high reliability and durability of the column station, and also minimizes the negative impact on the rock massif. This is confirmed by low settlement values and uniform stress distribution in the structure. Moreover, the proposed safety measures and recommendations for monitoring the condition of structures can be used to increase the efficiency of the station operation in the future. **Originality**. The originality lies in the fact that the analysis of the results showed that the greatest stresses occur in the connection zones of the central and side tunnels, which requires special attention to the design and construction of columns and lining of the station. **Practical value.** The practical value lies in the fact that the developed recommendations for strengthening stressed zones allow to significantly increase the safety of operation.

Keywords: metro; column-type station; stress-strain state; construction process; numerical analysis

Introduction

The structures of the column-type metro stations, that are constructed by a closed method with the sequential construction of individual station tunnels (Kolymbas, 2005; Chapman, Metje, & Stärk, 2010), should be verified according to the calculation schemes that provide for different of the stress-strain state (SSS) stages of the structure and its individual parts during the construction process as well as that of the rock massif (Kuesel, King, & Bickel, 2012).

The structural scheme of the column station (Fig. 1) involves combining the track tunnels and the distribution hall into a single structure.

Thanks to this approach, unlike pylon stations (Банніков, Купрій, & Вотченко, 2021), the design of column stations allows for efficient use of space and materials due to the close arrangement of tunnels (Liberati, Marques, Leonel, Almeida, &

Trautwein, 2019). It should be noted that the load from rock pressure on the side station tunnels of the column station changes during its construction (Liu, Luo, & Mei, 2000).

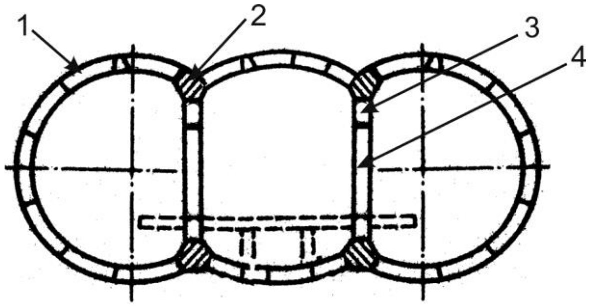

Fig. 1. Scheme of the column station:
1 – lining of the station tunnel; 2 – shaped blocks;
3 – lintel beam; 4 – column

During the construction of the side station tunnels, in addition to normal blocks, shaped blocks are placed in the lining, on which the vault of the lining of the central station tunnel rests. Thus, at the stage of the central station tunnel construction, the entire load from rock pressure on the station lining is transmitted through them to the lintel beam and to the columns.

For a long time, the force method was used to calculate tunnel structures, in which the structure was loaded with a design load, which replaced the action of the rock mass. Most often, the structure was calculated already at the operation stage, not taking into account the construction stages, at which the structures are subjected to greater loads than at the operation stage. Also, tunnel lining calculations involve many assumptions that simplify the calculations and, as it is believed, reduce their accuracy.

The use of the finite element method (FEM) allows for tunnels to be calculated taking into account their interaction with the surrounding rock massif (Pande, Beer, & Williams, 1990; Pang, Yong, & Dasari, 2005; Deb, 2012).

Purpose

The purpose of the scientific research is to analyze the influence of the construction technology of the metro column station on the stress-strain state of its structure. The achievement of this goal is based on the numerical analysis of the metro column station, during which the construction stages of the underground facility are taken into account.

Methodology

To calculate the stress-strain state of the column station structure at different stages of the station lining construction, the modern LIRA-CAD calculation complex was used (Петренко, В. І., Петренко, В. Д., & Тютькін, 2004; Kolymbas, 2005; Chapman, Metje, & Stärk, 2010; Купрій, Тютькін, & Захарченко, 2017). The SSS results are presented further in the form of isofields of stresses and strains (Kuesel, King, & Bickel, 2012; Sun, Dias, Guo, & Li, 2019; Zhou, Mei, Ke, Liu, & Xu, 2024).

For the successful solution of the problem of calculating the column station structures SSS at different stages of construction, the type of calculation scheme adopted and the degree of idealization of the actual station structure are of great importance. The developed finite element model of the soil massif has dimensions of 44×64 meters (Fig. 2).

Eight stages of the station construction were considered, for which finite element models were developed:

Stage 1. The initial state of the soil massif is calculated without any construction intervention.

Stage 2. The soil in the area of the left station tunnel is excavated and the lining is installed.

Stage 3. Columns and lintel beams are installed.

Stage 4. The soil is being excavated in the area of the right station tunnel and the lining is installed.

Stage 5. The columns and the lintel beam are installed.

Stage 6. The soil of the upper ledge in the central tunnel is excavated. The lining of the upper vault is installed.

Stage 7. The soil of the middle ledge in the central tunnel is excavated. Parts of the lining blocks that extend beyond the columns into the central tunnel are removed from the side tunnels.

Stage 8. The soil of the lower ledge in the central tunnel is excavated. The invert of the lining is installed.

Below are the finite element models according to the stages of construction. Stage 1. The finite element model of the column station and the soil mass is calculated without any construction intervention. The developed finite element model of the soil mass is verified under the self-weight load.

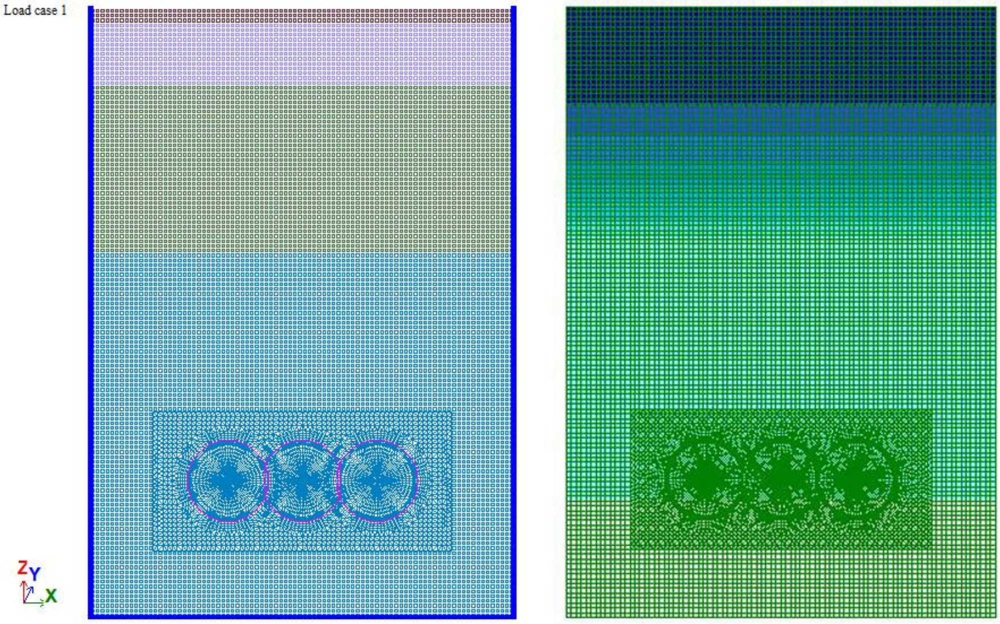

Fig. 2. Finite element model of a column station and soil massif

Stages 2 and 3. The soil is excavated in the area of the left station tunnel with the installation of the lining and columns with a lintel beam. A fragment of the finite element model in the second stage of the model calculation is shown (Fig. 3).

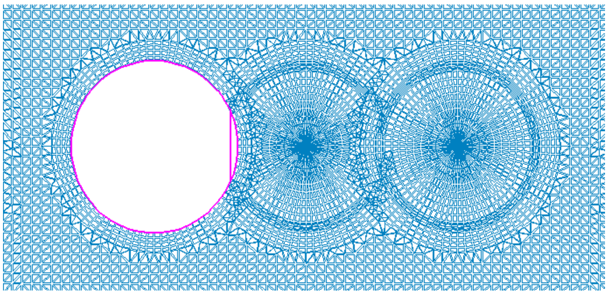

Fig. 3. Finite element model for stage 3

Stages 4 and 5. At the design distance from the left station tunnel, the soil is excavated in the area of the right station tunnel and the lining with columns and a lintel beam is installed (Fig. 4).

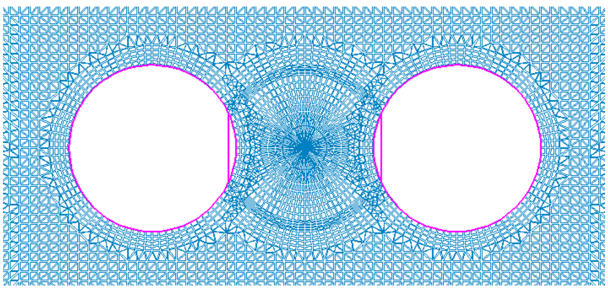

Fig. 4. Finite element model for stage 5

Stage 6. After the installation of the lining in the side station tunnels and the installation of the columns with lintel beams, the soil of the upper ledge in the central tunnel is excavated. The upper vault lining is installed. A fragment of the finite element model of the sixth stage is shown (Fig. 5).

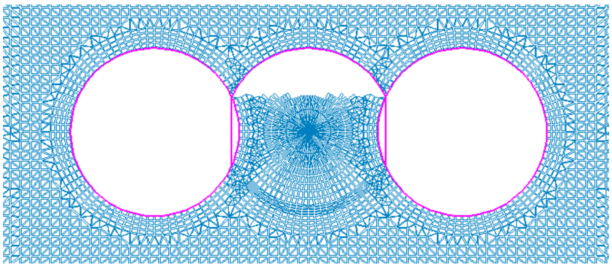

Fig. 5. Finite element model for stage 6

Stage 7. The soil of the middle ledge in the central tunnel is excavated. From the side of the side tunnels lining, part of the lining blocks that extend beyond the columns into the central tunnel at the passage point are dismantled.

During the passage of the middle ledge of the central station tunnel, the elements of the temporary filling of the side station tunnels at the passageways are dismantled, but only after the installation of the upper vault. At this stage, all the load from the linings is transferred to the supporting shaped elements, and through them to the lintel beam and columns. Fig. 6 shows a fragment of the finite element model for the seventh stage of model calculation.

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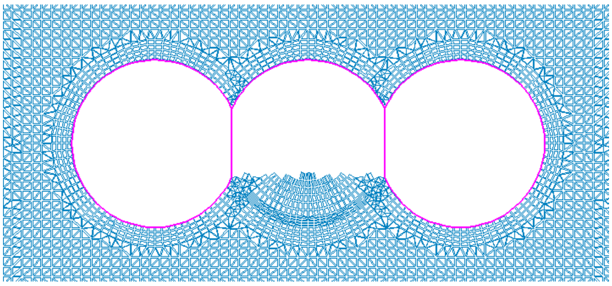

Fig. 6. Finite element model for stage 7

Stage 8. The soil of the lower ledge in the central tunnel is excavated and the lining invert is installed. Fig. 7 shows a fragment of the finite element model for the eighth stage of model calculation.

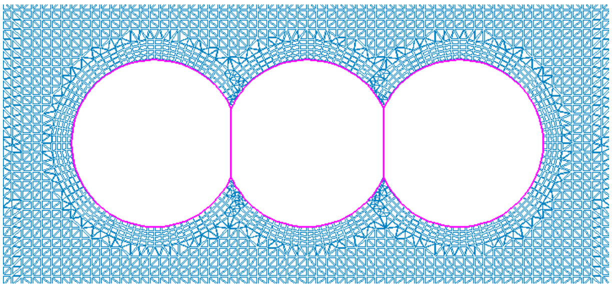

Fig. 7. Finite element model for stage 8

After creating finite element models for the eight stages of the column station construction, a numerical analysis was performed.

Findings

At the first stages of the side station tunnels construction, the influence of technology is insignificant. The main increase in SSS in the station elements starts with the development of the central station tunnel (the sixth stage, i.e. the development of the upper ledge of the central tunnel). The analysis shows, that the forces increase asymmetrically in the linings of the side station tunnels (Fig. 8). Part of the load through the shaped tubing elements is transferred to the columns, in which the compressive forces increase by two times.

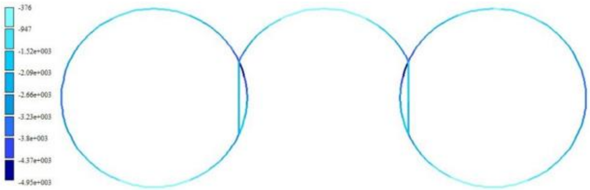

Fig. 8. Force isofields in the lining (stage 6)

A significant increase in SSS in the station elements occurs during the excavation of the middle ledge of the central station tunnel and the dismantling of the lining parts of the side station tunnels at stage seven. In this case, the entire load, both from the side linings and from the vault of the central tunnel lining, is transferred through the shaped tubing elements to the columns, in which the compressive forces increase several times (Fig. 9).

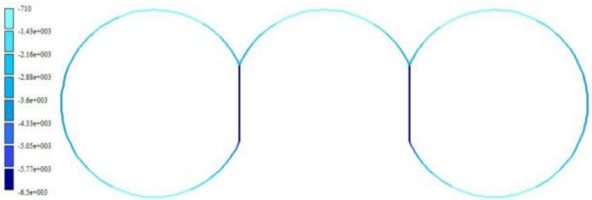

Fig. 9. Force isofields in the lining (stage 7)

Fig. 10 shows a mosaic of the normal forces values in the lining and columns of the station at stages 6 and 7 of construction.

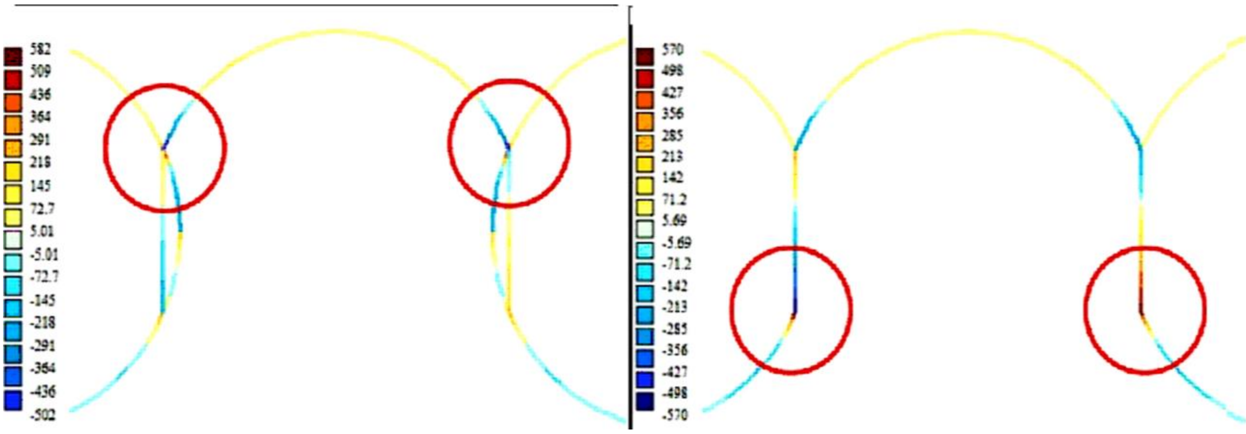

Fig. 10. Mosaic of normal forces values in lining and columns of the station
at the sixth (left) and seventh (right) stages of construction

At this stage, the greatest forces occur in the column. The same forces are transmitted to the lintel beam from each open ring of the side and central tunnels in the passage openings. An important condition of the construction technology is also the simultaneous inclusion in the operation of both columns located in one cross-section of the station.

Fig. 11 shows the scheme of loads impact on the lintel beams above the passage opening and the stress state in it at the stage of the central station tunnel excavation. Forces are transmitted to the lintel beam from the shaped supporting elements, which are part of the station lining vaults.

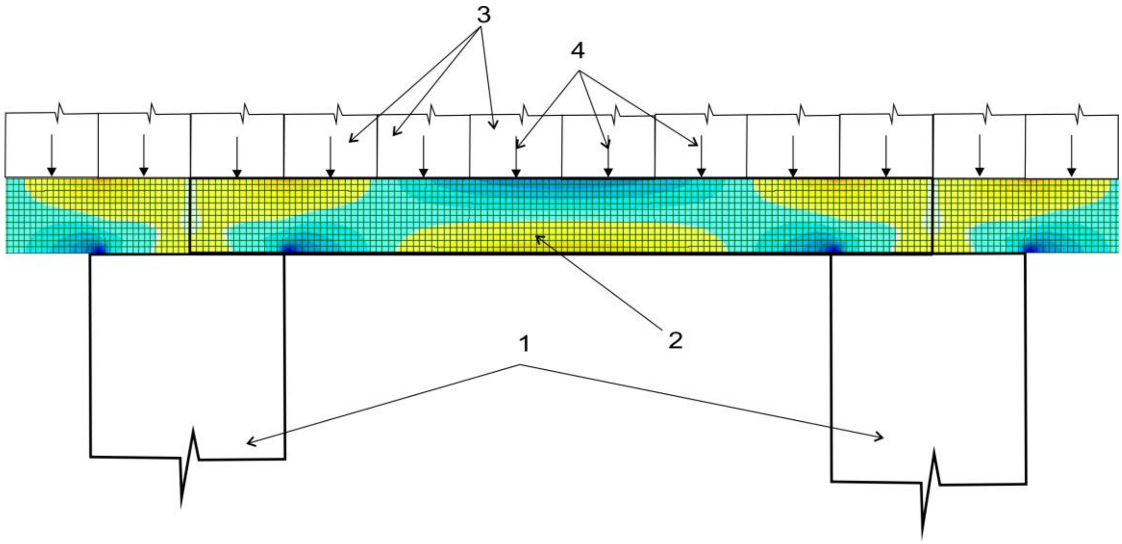

Fig. 11. Scheme of a column station at the passageways with a lintel beam:
1 – column; 2 – lintel beam; 3 – normal forces; 4 – shaped elements

According to the obtained calculation results of all stages, it is possible to analyze the history of changes in forces in each tunnel lining and each column. The graphs of Fig. 12-13 present the change in normal forces and bending moments, respectively, which allows to analyze the increase in SSS in the station structures and clearly see the transition of forces from the station linings to the columns during the excavation of the central tunnel.

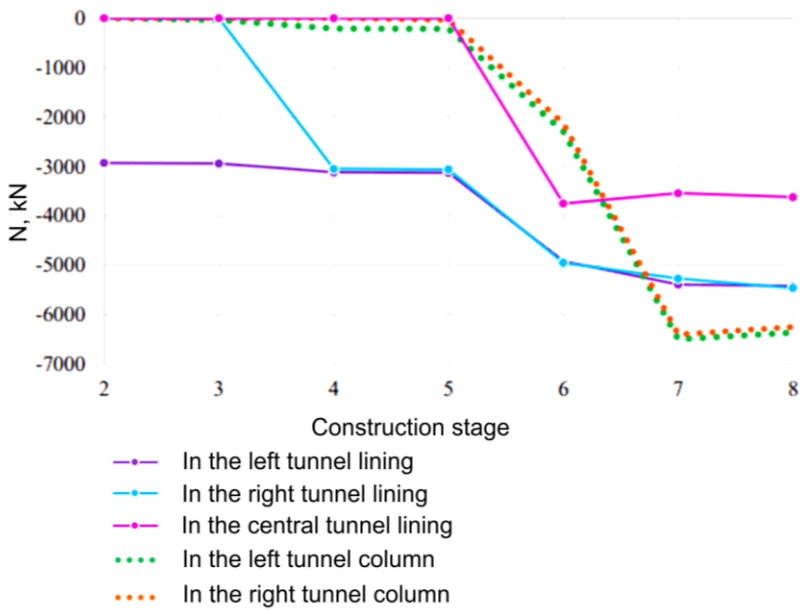

Fig. 12. Graph of changes in the largest normal forces in linings and columns

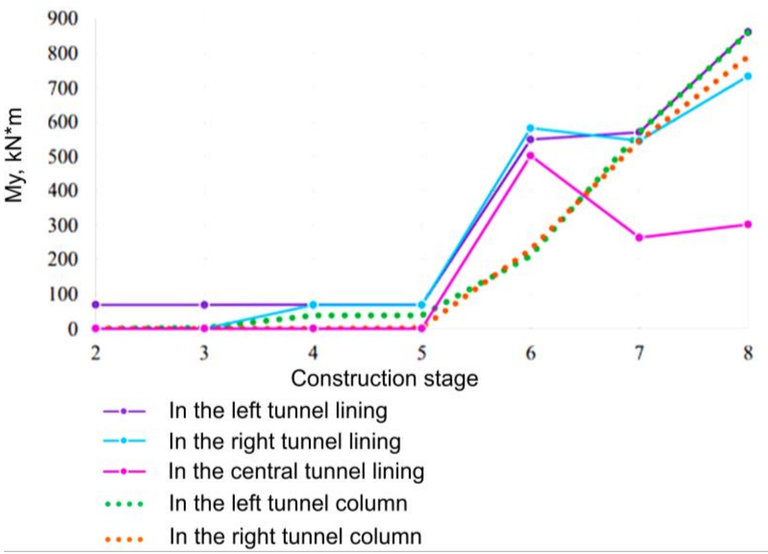

Fig. 13. Graph of changes in the largest bending moments in linings and columns

SSS analysis of the column station structure and the surrounding soil massif at different stages of construction allows to determine the maximum forces and to change the technology of station structures constructing depending on the stresses and deformations occurring in them.

Originality and practical value

The originality lies in the fact that the analysis of the results showed that the greatest stresses occur in the connection zones of the central and side tunnels, which requires special attention to the design and construction of columns and lining of the station. The practical value lies in the fact that the developed recommendations for strengthening stressed zones allow to significantly increase the safety of operation.

Conclusions

The main results of the work demonstrate that the correctly selected construction technology is critically important for ensuring the stability of the station structures and minimizing the risks of deformations in the soil. The study considers the modeling of the station construction stages using the LIRA-CAD software package. Thanks to this, accurate data on the SSS of the structure at different stages of construction were obtained.

The results obtained allow to state that the proposed construction technology provides high reliability and durability of the column station, and also minimizes the negative impact on the rock massif. This is confirmed by low settlement values and uniform stress distribution in the structure. Moreover, the proposed safety measures and recommendations for monitoring the condition of structures can be used to increase the efficiency of the station operation in the future.

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АНАЛІЗ ВПЛИВУ ТЕХНОЛОГІЇ СПОРУДЖЕННЯ КОЛОННОЇ СТАНЦІЇ МЕТРОПОЛІТЕНУ НА НАПРУЖЕНО-ДЕФОРМОВАНИЙ СТАН ЇЇ КОНСТРУКЦІЇ

Мета. Метою наукового дослідження є аналіз впливу технології спорудження колонної станції метрополітену на напружено-деформований стан її конструкції. Досягнення цієї мети ґрунтується на проведенні чисельного аналізу колонної станції метрополітену, під час якого враховано стадії спорудження підземного об’єкту. **Методика.** Для розрахунку напружено-деформованого стану конструкції колонної станції на різних стадіях спорудження станційних оправ використовувався сучасний розрахунковий комплекс ЛІРА-САПР. Було розглянуто вісім стадій будівництва станції, для яких розроблялися скінченно-елементні моделі. Після створення скінченно-елементних моделей для восьми стадій будівництва колонної станції був проведений чисельний аналіз. **Результати.** Основні результати роботи демонструють, що правильно обрана технологія спорудження є критично важливою для забезпечення стійкості конструкцій станції та мінімізації ризиків деформацій у ґрунті. У роботі розглянуто моделювання стадій будівництва станції за допомогою програмного комплексу ЛІРА-САПР. Завдяки цьому було отримано точні дані про НДС конструкції на різних етапах спорудження. Отримані результати дозволяють стверджувати, що запропонована технологія будівництва забезпечує високу надійність і довговічність колонної станції, а також мінімізує негативний вплив на гірський масив. Це підтверджується низькими значеннями просідання та рівномірним розподілом напружень у конструкції. Крім того, запропоновані заходи безпеки та рекомендації щодо моніторингу стану конструкцій можуть бути використані для підвищення ефективності експлуатації станцій у майбутньому. **Наукова новизна.** Наукова новизна полягає в тому, що аналіз результатів показав, що найбільші напруження виникають у зонах сполучення центрального та бокових тунелів, що вимагає особливої уваги до проєктування та монтажу колон і оправ станції. **Практична значимість.** Практична значимість полягає в тому, що розроблені рекомендації щодо посилення напружених зон дозволяють суттєво підвищити безпеку експлуатації.

Ключові слова: метрополітен; станція колонного типу; напружено-деформований стан; процес будівництва; чисельний аналіз

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