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МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

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NUMERICAL ANALYSIS OF A SINGLE-VAULTED METRO STATION OPTIONS

Purpose. The purpose of the study is a numerical analysis of a single-vaulted metro station options, the performing of which allows determining which of the options passes the strength check. The results of the numerical analysis using the finite element method, which allows to determine the strength of the station structure, are the values of the stress-strain state, as well as equivalent stresses. **Methodology.** An analysis of the lining stress-strain state for variating structural solutions was carried out, for which the model reproduced half of the single-vault station structure with the addition of a second invert. The single-vault station models were built based on real geometric dimensions using the professional calculation software Structure CAD for Windows, version 7.29 R.3 (SCAD). **Findings**. In recent years, the single-vaulted metro station has become the underground structure most often used during construction. The design options for the single-vaulted station proposed by designers necessarily require scientific substantiation. As part of the study, the results of which are presented in the article, a numerical analysis of the single-vaulted station, which has two design options, was performed. The created finite element models reflect the features of the developed options in a spatial setting. The numerical analysis performed for dead weight and moving load allowed for finding out the parameters of the stress-strain state. Based on the determined parameters, the overall strength and stability of the single-vaulted station were evaluated and recommendations for their increase were provided. **Originality**. The originality of the study consists of the obtained results of numerical analysis for a single-vaulted metro station options, which allowed to find out which of the options passed the strength check. **Practical value.** The practical value lies in obtaining the results of the calculation using the finite element method, which allowed to find the strength of the station structure and reasonably choose the metro station option.

Keywords: metro; single-vault station; stress-strain state; numerical analysis; design change

Introduction

The calculation of a single-vault station based on the finite element method is aimed at determining the stress-strain state with subsequent evaluation of strength and stability (Pande, Beer, & Williams, 1990; Kuesel, King, & Bickel, 2012). It is known that the behavior of such a structure is more determinate than that of pylon and column-type stations. The calculation scheme of a single-vault station made of monolithic reinforced concrete can be presented in the form of a flat bar system in an elastic medium.

When calculating single-vault stations made of precast reinforced concrete, the calculation scheme must take into account the presence of structural hinges at the junctions of adjacent blocks.

In the presence of massive supports in the structure of a single-vault station, they should be replaced in the calculation scheme by bars of corresponding stiffness. The supports of a single-vault station can be calculated in the same way as rigid retaining walls that are under the influence of forces transmitted from the heels of the arches, the support's own weight, loads from rock pressure and elastic soil resistance. The design scheme of the station in this case is a system of rigid curved blocks on an elastic base, interconnected by hinges, and massive supports (Петренко, В. Д., Тютькін, & Петренко, В. І., 2012). The calculation of such a structure is reduced to determining the stress state of two multi-hinged structures of the upper and lower arches on an elastic base, characterized by soil resistance reactions beyond the lining blocks (Chapman, Metje, & Stärk, 2010; Hunar Farid Hama Ali, 2013; Sun, Dias, Guo, & Li, 2019).

The forces in the arches are determined from the equilibrium conditions of their nodes, while considering the nodes sequentially, starting from the keystone. Assuming that the bending moments at the joints equal zero, the normal and transverse forces, soil resistance reactions, and moments in the blocks are determined.

The linings of stations constructed be an open method, operate, as a rule, in the mode of specified loads and are characterized by a simpler and more defined calculation scheme.

There is a structural form of a single-vaulted station lining made of monolithic reinforced concrete, that is a shallow arch of variable thickness, monolithically connected with vertical walls (Radkevych, Tiutkin, Kuprii, & Tkach, 2023). The principles of constructing the internal contour of the lining are the same as for single-vaulted stations constructed in a closed way. The basis for determining the dimensions of the cross-section of the station is the calculated width of the platform and the buildings clearance size.

The cross-section of the vault can be taken as constant along the length of the station or ribbed. Ribs of different configurations, made with different steps along the length of the station, emphasize the individuality of the structure and add architectural expressiveness to the station. The walls are rigidly connected to a reinforced concrete floor slab, the thickness of which is adopted considering the strength characteristics of the soils at the base of the station. If the base of the station has weak water-saturated soils and hydrostatic pressure, the floor part of the station is constructed as an invert.

This solution is advisable when constructing a station in dense cohesive soils capable of resisting wall displacements from the expansion of a shallow vault. Weak, poorly cohesive soils are unable to limit these deformations, so the reinforced concrete walls and vaults in the lining structure of the station operate under the influence of significant bending moments. As a result, the junction of the vault and walls becomes more complicated, their thickness must be increased, and the consumption of reinforcement increases, also the crack resistance and water tightness of the structure decreases (Більченко, & Смолянюк, 2021; Смолянюк, & Більченко, 2024).

Unlike a monolithic one, a station with a precast reinforced concrete lining has several advantages: the lining is constructed following the excavation of the core and immediately engages it's operation, there is the possibility of using high-performance block-laying equipment, which allows to increase the pace of construction and installation work and reduce their cost.

The platform section of the station complex is designed as a single-span with an island platform 10 meters wide. The platform length is adopted for a five-car train: 102 meters, if the ladders are located in the lobby spaces and 114 meters, if the ladders are placed on the platform.

Purpose

The purpose of the study is a numerical analysis of a single-vaulted metro station options, the performing of which allows determining which of the options passes the strength check. The results of the numerical analysis using the finite element method, which allows to determine the strength of the station structure, are the values of the stress-strain state, as well as equivalent stresses.

Methodology

An analysis of the stress-strain state of the lining for variation in its structural solutions was carried out, for that the model reproduced half of the single-vault station structure with the addition of a second invert (Тютькін, 2020; Смолянюк, & Більченко, 2024). The single-vault station models were built based on real geometric dimensions using the professional calculation software Structure CAD for Windows, version 7.29 R.3 (SCAD) (Fig. 1) (Карпиловский, В. С., Криксунов, Перельмутер, & al., 2000; Tiutkin, & Bondarenko, 2022; Radkevych, Tiutkin, Kuprii, & Tkach, 2023).

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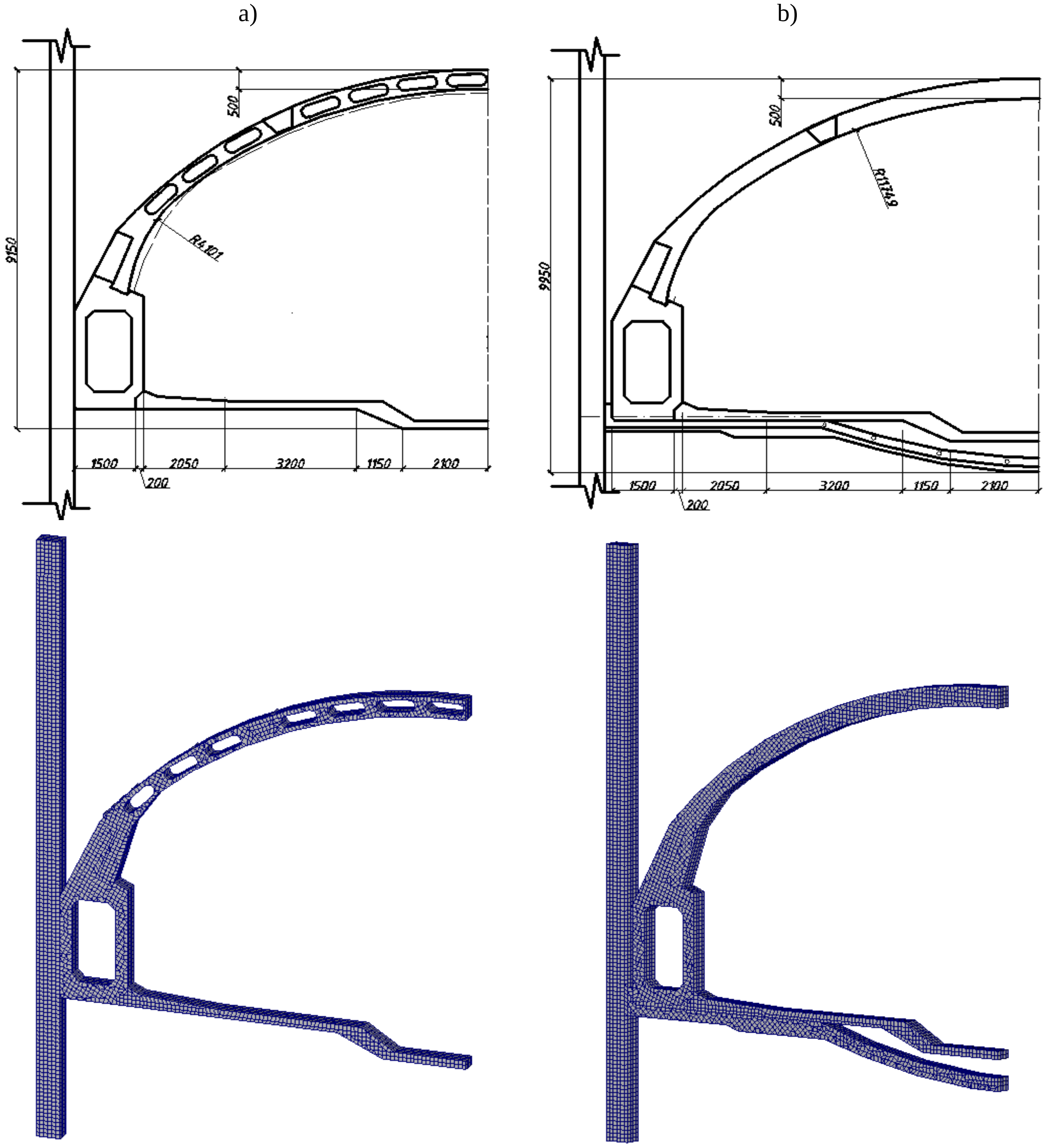


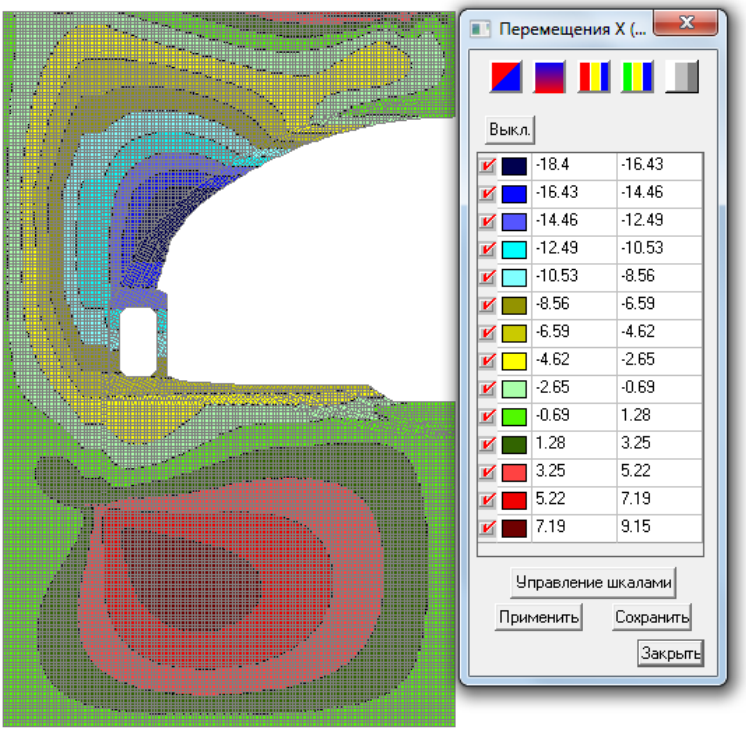
Fig. 1. Schemes and fragments of the FEM-model – station structures with a "slurry wall":
a) standard; b) with implemented design solutions

When developing the model, its adjacency to the "slurry wall" structure was taken into account, as well as the features of the floor part, which is present in the second version of the single-vault station (Fig. 1, b). The number of volumetric finite elements is 119,116, and number of nodes is 113,720; the problem is of medium size.

Findings

The parameters of the stress-strain state of the model are presented in Fig. 2. The maximum displacements along the vertical axis are about 167.74 mm, and the horizontal displacements are 0.69 mm.

a)



b)

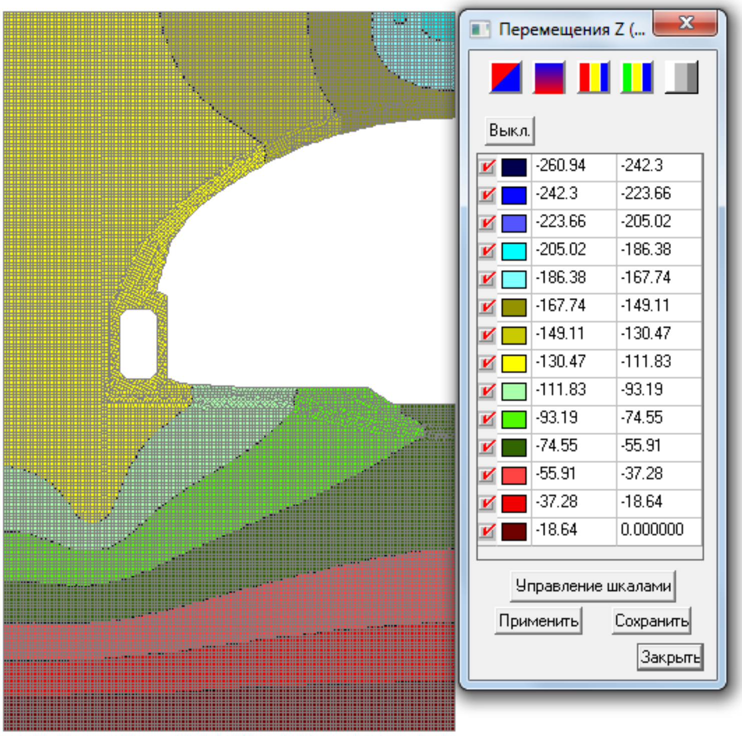


Fig. 2. Isofields and isolines of horizontal (a) and vertical (b) displacements in the model from its own weight and moving load of NK-80

The nature of the development of the stressed state is analyzed at several characteristic stress concentration points (Fig. 3), and the main stresses of the model are also presented (Fig. 4).

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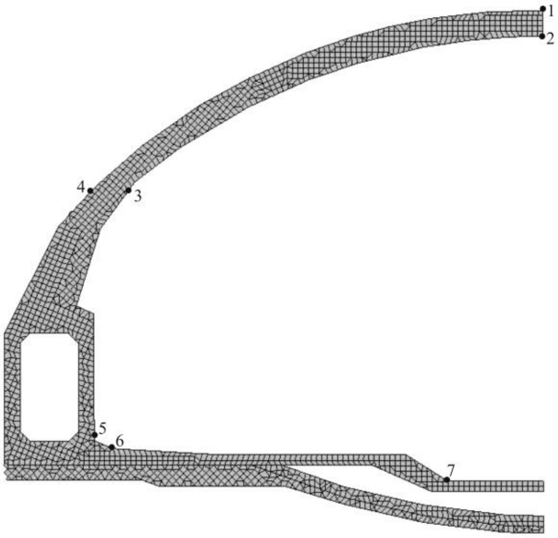


Fig. 3. Diagram of stress concentration points

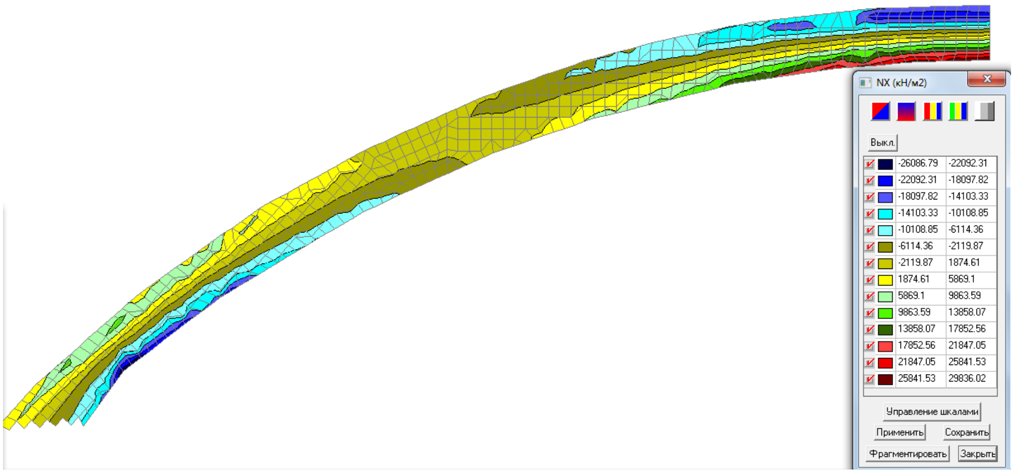
For further for strength verification of the structure, which will be carried out only on concrete, that is, for crack resistance, let's apply the formula of the fourth theory of strength (by energy), the expression for which is:

$$\sqrt{\sigma_x^2 + \sigma_x \sigma_z + \sigma_z^2 + 3\tau_{xz}^2} \leq [\sigma],$$

where σ_x and σ_z are the components of normal stresses along the global axes X and Z; τ_{xz} – the tangential component in the XZ plane; $[\sigma]$ – the ultimate strength of the material, the design resistance value for concrete B30 – $[\sigma]$ = 21.0 MPa.

The calculation was carried out using equivalent stresses (Table 1).

a)



b)

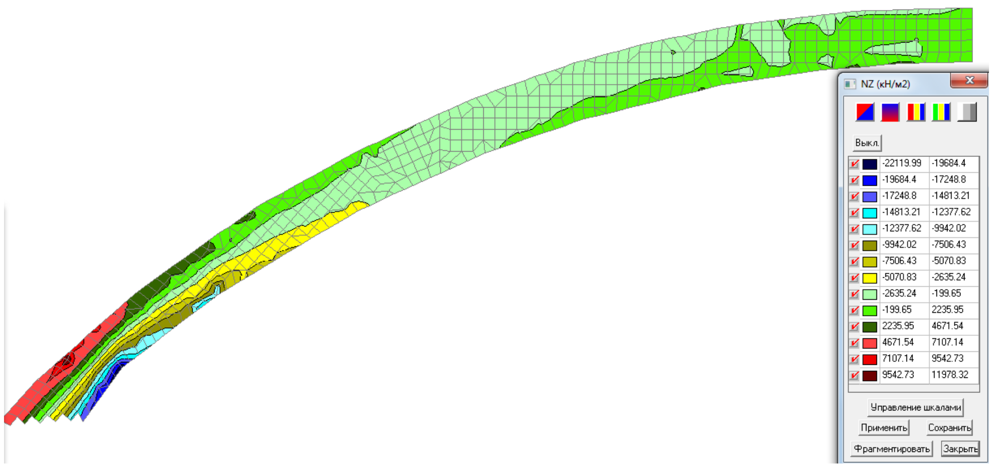


Fig. 4. Isofields and isolines of normal stresses in the fragment of the model (right part of the top vault) from its own weight: a) along the horizontal axis; b) along the vertical axis

Table 1

Calculation of equivalent stresses according to the fourth theory of strength from self-weight and moving load of NK-80

Point number	Stress, MPa			Equivalent stress, MPa / Safety margin
	Normal, along X axis	Normal, along Z axis	Tangent in XZ plane	
Point 1	-26,08	2,24	-2,57	25,43 / 0,7
Point 2	29,84	2,24	-5,01	32,21 / 0,5
Point 3	-26,09	-22,12	-22,09	56,67 / 0,3
Point 4	9,86	11,98	12,07	28,21 / 0,6
Point 5	-19,5	-16,64	7,66	34,02 / 0,5
Point 6	-24,7	-3,97	6,21	28,98 / 0,6
Point 7	47,6	5,53	-11,15	54,15 / 0,3

Analysis of the presented table shows that the recommended measures significantly improve the stress state of the station structure. However, at point 7 in the first and second loadings and point 3 in the second loading, the safety margin value is very small and equals to 0.3, i.e. cracking should be expected in these locations. But analysis of stress distribution patterns at these concentration points shows that the crack formation zones are insignificant.

Concentration points 5 and 6 require a recommended measure in the form of changing the haunch thickness or its reinforcing bars spacing. The same recommended measure regarding reducing reinforcement spacing applies to points 3 and 7, since changing the thickness in these places is impractical. Otherwise, the new station design as a result of the comparative analysis is comprehensively justified and, in contrast to the standard design, has significant advantages.

Originality and practical value

The originality of the study consists of the obtained results of numerical analysis for a single-vaulted metro station options, which allowed to find out which of the options passed the strength check. The practical value lies in obtaining the results of the calculation using the finite element method, which allowed to find the strength of the station structure and reasonably choose the metro station option.

Conclusions

In recent years, the single-vaulted metro station has become the underground structure most often used during construction. The design options for the single-vaulted station proposed by designers necessarily require scientific substantiation. As part of the study, the results of which are presented in the article, a numerical analysis of the single-vaulted station, which has two design options, was performed. The created finite element models reflect the features of the developed options in a spatial setting. The numerical analysis performed for dead weight and moving load allowed for finding out the parameters of the stress-strain state. Based on the determined parameters, the overall strength and stability of the single-vaulted station were evaluated and recommendations for their increase were provided.

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ЧИСЕЛЬНИЙ АНАЛІЗ ВАРІАНТІВ ОДНОСКЛЕПІНЧАСТОЇ СТАНЦІЇ МЕТРОПОЛІТЕНУ

Мета. Метою дослідження є чисельний аналіз варіантів односклепінчастої станції метрополітену, проведення якого дозволяє з'ясувати, який з варіантів проходить перевірку міцності. Результатами чисельного аналізу методом скінченних елементів, які дозволяють знайти міцність конструкції станції, є значення напружено-деформованого стану, а також еквівалентні напруження. **Методика.** Проведено аналіз напружено-деформованого стану оправи при варіації її конструктивних рішень, для чого в моделі відтворено половину конструкції односклепінчастої станції із додавання другого нижнього склепіння. Моделі односклепінчастої станції побудовані на основі реальних геометричних розмірів на основі розрахункового професійного комплексу Structure CAD for Windows, version 7.29 R.3 (SCAD). **Результати.** Односклепінчаста станція метрополітену в останні роки стає тією підземною конструкцією, яка частіш усього застосовується під час будівництва. Варіанти конструкції односклепінчастої станції, які пропонуються проєктувальниками, обов'язково потребують наукового обґрунтування. В рамках дослідження, результати якого викладено в статті, проведено чисельний аналіз односклепінчастої станції, яка має два варіанти конструкції. Створені скінченно-елементні моделі відображають особливості розроблених варіантів в просторовій постановці. Проведений на власну вагу та рухоме навантаження чисельний аналіз надав можливість з'ясувати параметри напружено-деформованого стану. На основі визначених параметрів оцінено загальну міцність та стійкість односклепінчастої станції й наведено рекомендації по їх збільшенню. **Наукова новизна.** Наукову новизну дослідження складають отримані результати чисельного аналізу варіантів односклепінчастої станції метрополітену, проведення якого дозволило з'ясувати, який з варіантів пройшов перевірку міцності. **Практична значимість.** Практичне значення полягає в отриманні результатів розрахунку методом скінченних елементів, які дозволили знайти міцність конструкції станції і обґрунтовано обрати варіант станції метрополітену.

Ключові слова: метрополітен; односклепінчаста станція; напружено-деформований стан; чисельний аналіз; зміна конструкції

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