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МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

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ANALYTICAL REGULARITIES OF FORCE FACTORS IN THE LINING OF A THREE-VAULTED METRO STATION WITH VARIATION OF THE ELASTIC RESISTANCE COEFFICIENT OF THE ROCK

Purpose. The purpose of the scientific article is to conduct a numerical analysis of pylon station models and obtain force factors for its lining. Based on the obtained factors (bending moments and normal forces), it is planned to obtain their analytical regularities for the varying elastic resistance coefficient of the rock. **Methodology.** The calculation scheme of the station structure should be chosen so that it corresponds to the real operating conditions of the lining to the greatest extent, reflecting the design features, lining material, geological conditions, and the construction method. The SCAD calculation software was used to calculate the pylon-type station. **Findings**. The foundations of mathematical modeling of a pylon station by the finite element method in a spatial setting were developed using the modified Metrodiprotrans method (based on FEM), models calculations for pylon deep metro stations were carried out by determining the parameters of equivalent bars in a spatial setting. Using the results of the regularities between the strength coefficient and the deformation characteristics of the soil (deformation modulus and Poisson's ratio), analytical regularities of force factors were determined for varying properties of the surrounding massif (elastic resistance), which for moments are power nonlinear regularities, and for normal forces are linear functions, furthermore the change in the elastic resistance coefficient with respect to the strength coefficient is a nonlinear polynomial. **Originality**. The originality of the conducted research lies in obtaining analytical regularities of force factors for varying properties of the surrounding massif based on the results of numerical analysis conducted on the basis of the finite element method using the modified Metrodiprotrans method. These regularities allow predicting the change in bending moments and normal forces depending on the change in geological conditions at the design stage. **Practical value.** The practical value of the research lies in developing the basics of the methodology for taking into account the spatial factor in the calculations of three-vaulted metro stations. This allows for more complete consideration of the complex irregular structure of pylon-type stations and obtaining force parameters in its lining that are more adequate to the real situation.

Keywords: metro; pylon-type station; force factors in the lining; elastic resistance coefficient; analytical regularities

Introduction

The currently existing methods for calculating the structural elements of deep three-vaulted metro stations are based on the construction of planar calculation schemes of the structure and the interpretation of the surrounding massif with some assumptions that simplify its real behavior.

An important critical remark for the use of planar schemes when searching for force factors (bending moments and normal forces) is that increasing the complexity of the model and transforming it into a spatial one is not always suitable. However, taking into account the spatial factor in models of irregular objects, such as three-vaulted pylon or column-type stations, is mandatory at this stage of development of calculations for underground structures (Банніков, Купрій, & Вотченко, 2021; Alkhdour, Tiutkin, Bannikov, & Heletiuk, 2023; Банніков, Нетеса, Купрій, & Дубінчик, 2024).

It should be noted that omitting at the stage of developing calculations of bar schemes for tunnel structures and replacing of the interaction in the "lining – massif" system with elastic resistance is somewhat rashly, since bar schemes have a number of advantages. The main advantage is the possibility of creating an engineering methodology that is characterized by significant simplicity and algorithmic qualities. Another important advantage is that the search results are the force factors in the lining of three-vaulted stations.

A particular point of criticism of bar schemes is the significant simplification of the lining interaction with the massif, its replacement with elastic rods, forces, etc. This is what deserves special attention, since the development of theoretical provisions for the interaction in the "lining – massif" system allows for a more reasonable use of rod schemes in the calculation of tunnel structures.

But when using rod schemes, one should not fall into the other extreme, that is, into simplification, which can be introduced at all stages of model creation. The use of the finite element method allows for overcoming some of the difficulties of creating finite element models of such complex structures as three-vaulted stations, which are complex structures with significant changes in stiffness and made in the form of cylindrical shells with cutouts, which are supported by elements of significant stiffness (pylons or columns) (Deb, 2012; Тютькін, 2020; Feng, Tan, Ma, Zhang, Pan, et al., 2023; Zhou, Mei, Ke, Liu, & Xu, 2024). The system of lintels transforms the repeating elements of three-vaulted stations structures into spatial irregular systems, and ignoring the spatial factor of the distribution of force factors in them is a false step in numerical analysis.

The problem of irregularity of the structure is exacerbated by the fact that the distribution of elastic resistance, the intensity and limits of which are unknown at the first stage of the study, significantly affects the formation of force factors in the lining. Numerical analysis of a pylon-type metro station with variations in the properties of the surrounding massif is an important current problem, marked by originality.

Purpose

The purpose of the scientific article is to conduct a numerical analysis of pylon station models and obtain force factors for its lining. Based on the obtained factors (bending moments and normal forces), it is planned to obtain their analytical regularities for the varying elastic resistance coefficient of the rock.

Methodology

The complexity of calculating station structures necessitates resorting to various assumptions that idealize both the lining structure and the soil massif (Li, Jin, Lv, Dong, & Guo, 2016; Sun, Dias, Guo, & Li, 2019). It is practically impossible to apply known calculation methods directly to the analysis of a real underground structure. Therefore, calculation methods are usually applied to mathematical models.

The calculation scheme of the station structure should be chosen so that it corresponds to the real operating conditions of the lining to the greatest extent, reflecting the design features, lining material, geological conditions, and the construction method. When assigning a calculation scheme, certain assumptions are inevitable. The reliability and accuracy of the calculation results depend on how well-founded the assumptions are and the degree to which they correspond to the actual operating conditions of the station structure. The assumptions adopted must ensure a safety margin for the lining.

The basis for constructing the calculation scheme of the station tunnel structure located in a homogeneous soil environment is a planar problem. This assumption is valid, since the length of the tunnel usually significantly exceeds the dimensions of its cross-section. For the calculation, a planar system with a width of 1 m along the station axis (for monolithic reinforced concrete structures) or the width of the deck blocks or slabs (for prefabricated structures) is selected. The calculated loads should be scaled to the width of this flat system.

This approach simplifies the calculation scheme and is quite justified for single-span structures, in particular, for single-vaulted stations, as well as for blind sections of pylon stations. To compile flat calculation schemes of pylon stations, which are an alternation of pylons and passages between them, a typical section is allocated along

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the station, the length of which is equal to the distance between the axes of the pylons or passages between them. The geometric characteristics of the cross-sections of the elements of the typical alternating section must be adjusted to the width of the flat system allocated for calculation.

In the calculation of station structures operating in the mode of specified loads, it is assumed that the lining is subjected to active loads. These loads are defined as the weight of the soil in the potential collapses volume or as the total weight of the soil column above the tunnel. Under the influence of active loads, the lining deforms, and in that part of the contour where these deformations are directed towards the soil, has a force interaction with it (Федоров, & Тюткін, 2024).

If the soils are sufficiently strong and elastic, they limit the deformations of the lining caused by the action of the active load. In this case, the lining should be considered as a structure in an elastic environment and calculated not only for the specified active vertical and horizontal loads, but also its interaction with the soil should be considered. In the calculation scheme, the force interaction can be replaced by the forces of elastic resistance of the soil (the local deformations hypothesis).

The most widespread are the calculation schemes built in accordance with the basic assumptions of the Metrodiprotrans method. In them, the design of the station lining is defined in the form of a rod system located in an elastic medium. As a result of the calculation, the elastic resistance reactions forces of the soil and the forces in the cross-sections of the structure (bending moments, normal and transverse forces), as well as the displacements of the lining elements, are determined.

In the Metrodiprotrans method, modernized on the basis of the finite element method, the calculation scheme of the structure or construction is represented as a set of some typical finite elements connected to each other and with the base at the nodes. The SCAD software was used to calculate the pylon-type station (Карпиловский, Криксунов, Перельмутер, et al., 2000; Петренко, В. І., Петренко, В. Д., & Тюткін, 2004). Fig. 1 shows the calculation bar scheme of the pylon-type station.

a)

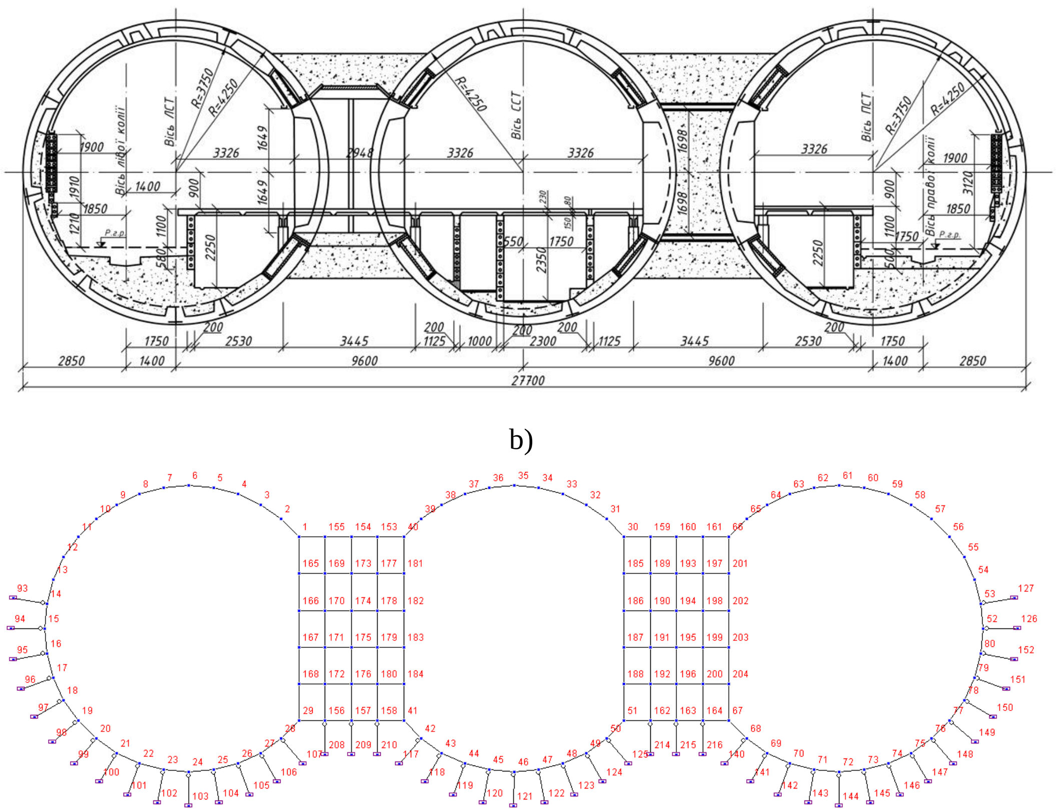

Fig. 1. Pylon-type station:
a) structure; b) spatial finite element model (frontal view)

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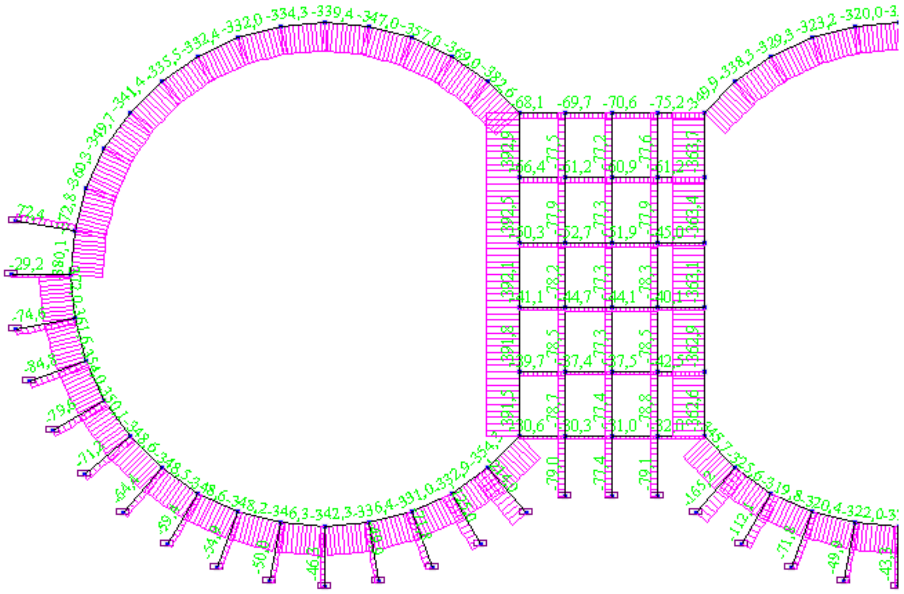
The entire rod system corresponds to a common coordinate axis system. It is used when assigning loads to the calculation scheme, and the displacements of the nodes are determined in this system.

In SCAD, the straight XYZ coordinate axis system is used. The flat rod system is located in the XOZ plane.

Findings

After performing the numerical analysis using the modified Metrodiprotrans method, its results were obtained in the form of diagrams of normal forces *N* and bending moments *M* (Fig. 2). Since the model is symmetrical about the central axis, only half of it is shown.

a)



b)

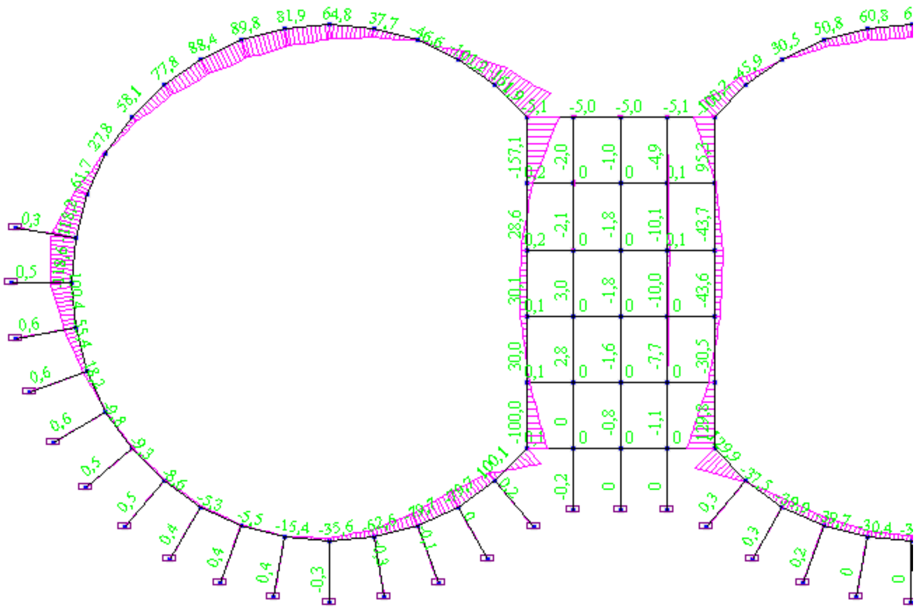


Fig. 2. Diagrams of normal forces (a) and bending moments (b)

Using the results of previously conducted studies (Банніков, Купрій, & Вотченко, 2021), let's conduct a number of additional calculations and find the relationship between the strength coefficient f and the deformation characteristics of the soil (deformation modulus E and Poisson's ratio μ). Let's write the formulas for determining the specific elastic resistance coefficient k_0, respectively:

$$k_0=E/(1+\mu)\cdot 1,\ \text{kN/m}^3, \quad (1)$$

$$k_0= f\cdot 10^7/(26-f),\ \text{kN/m}^3. \quad (2)$$

Equating expressions (1) and (2) and transforming the equation, we obtain the dependence of the strength coefficient on E and μ:

$$f=26\cdot E/[(1+\mu)\cdot 10^7+E],\ \text{kN/m}^3. \quad (3)$$

As can be seen from the above formulas (1)-(3), the strength coefficient depends on the strength and deformation characteristics.

Let's assume the variation of the strength coefficient f=1.5; 4.5; 13.5 and calculate by formula (1) the variations of the corresponding coefficients of elastic resistance approximately: k_1=61000 kN/m^3, k_2=210000 kN/m^3, k_3=1080000 kN/m^3 and present the regularities of the force factors (Fig. 3 and 4). The corresponding values for the bending moments and normal forces have been calculated, but the results are not presented in the form of diagrams to save space.

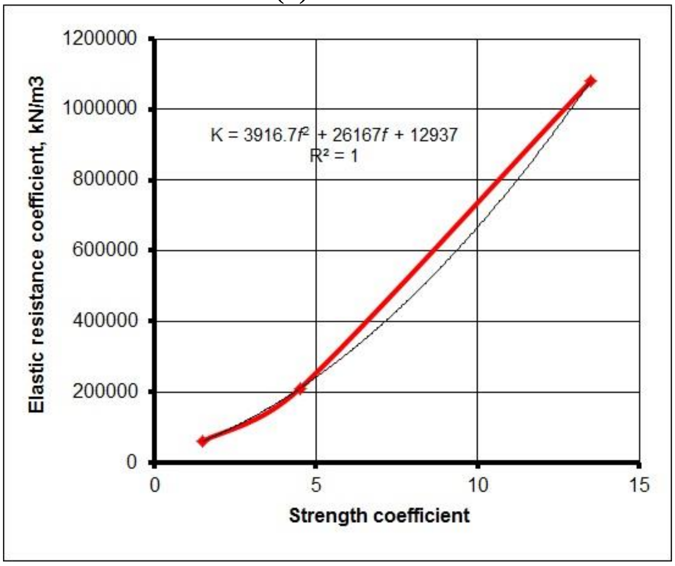


Fig. 3. Analytical regularity of the elastic resistance coefficient under the variation of the strength coefficient

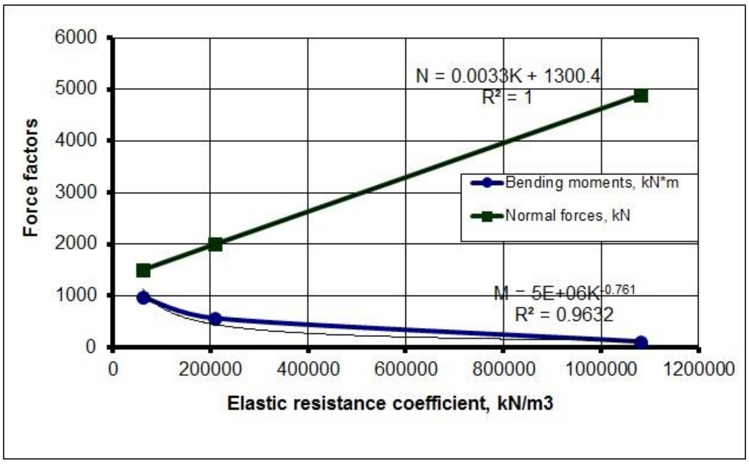


Fig. 4. Analytical regularities of bending moments and normal forces with variation of elastic resistance

It should be noted that the static uncertainty of the spatial scheme in the pylon station is amplified by the spatial factor of its operation, therefore the distribution of force factors in the analytical laws are clearly nonlinear for moments. The provided calculation can only be considered preliminary, as all studies of this issue should be conducted separately.

Originality and practical value

The originality of the conducted research lies in obtaining analytical regularities of force factors for varying proper-ties of the surrounding massif based on the results of numerical analysis conducted on the basis of the finite element method using the modified Metrodiprotrans method. These regularities allow predicting the change in bending moments and normal forces depending on the change in geological conditions at the design stage.

The practical value of the research lies in developing the basics of the methodology for taking into account the spatial factor in the calculations of three-vaulted metro stations. This allows for more complete consideration of the complex irregular structure of pylon-type stations and obtaining force parameters in its lining that are more adequate to the real situation.

Conclusions

The foundations of mathematical modeling of a pylon station by the finite element method in a spatial setting were developed using the modified Metrodiprotrans method (based on FEM), models calculations for pylon deep metro stations were carried out by determining the parameters of equivalent bars in a spatial setting.

Using the results of the regularities between the strength coefficient and the deformation characteristics of the soil (deformation modulus and Poisson's ratio), analytical regularities of force factors were determined for varying properties of the surrounding massif (elastic resistance), which for moments are power nonlinear regularities, and for normal forces are linear functions, furthermore the change in the elastic resistance coefficient with respect to the strength coefficient is a nonlinear polynomial.

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АНАЛІТИЧНІ ЗАКОНОМІРНОСТІ СИЛОВИХ ФАКТОРІВ В ОПРАВІ ТРИСКЛЕПІНЧАСТОЇ СТАНЦІЇ МЕТРОПОЛІТЕНУ ПРИ ВАРІАЦІЇ КОЕФІЦІЄНТУ ПРУЖНОГО ВІДПОРУ ПОРОДИ

Мета. Метою наукової статті є проведення чисельного аналізу моделей пілонної станції і отримання силових факторів в її оправі. На основі отриманих факторів (згинальні моменти й нормальні сили) заплановано отримати їхні аналітичні закономірності при варіації коефіцієнту пружного відпору породи. **Методика.** Розрахункову схему конструкції станції необхідно вибирати так, щоб вона найбільшою мірою відповідала реальним умовам роботи оправи, відображаючи конструктивні особливості, матеріал оправи, геологічні умови, а також спосіб виконання робіт. Для розрахунку станції пілонного типу застосовано розрахунковий комплекс SCAD. **Результати.** Розроблено основи математичного моделювання пілонної станції методом скінченних елементів в просторовій постановці за допомогою модифікованого методу Метродіпротрансу (на основі МСЕ), проведено розрахунки моделей пілонних станцій метрополітену глибокого закладення за допомогою визначення параметрів еквівалентних стержнів в просторовій постановці. Користуючись результатами закономірностей між коефіцієнтом міцності і деформаційними характеристиками ґрунту (модулем деформації і коефіцієнтом Пуассона), визначено аналітичні закономірності силових факторів при варіації властивостей оточуючого масиву (пружного відпору), які для моментів є степеневими нелінійними закономірностями, а для нормальних сил лінійними функціями, причому зміна коефіцієнту пружного відпору від коефіцієнту міцності є нелінійною поліноміальною. **Наукова новизна.** Наукова новизна проведеного дослідження полягає в отриманні аналітичних закономірностей силових факторів при варіації властивостей оточуючого масиву на основі результатів чисельного аналізу, проведеного на основі методу скінченних елементів за допомогою модифікованого методу Метродіпротрансу. Ці закономірності дозволяють ще на етапі проєктування прогнозувати зміну згинальних моментів й нормальних сил в залежності від зміни геологічних умов. **Практична значимість.** Практична значимість дослідження полягає в розробці основ методики врахування просторового фактору в розрахунках трисклепінчастих станцій метрополітену. Це дозволяє більш повно враховувати складну нерегулярну структуру станцій пілонного типу й отримувати більш адекватні реальній ситуації силові параметри в її оправі.

Ключові слова: метрополітен; станція пілонного типу; силові фактори в оправі; коефіцієнт пружного відпору; аналітичні закономірності

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