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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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ANALYSIS OF STRESS-STRAIN STATE COMPONENTS FOR INTERACTING HORIZONTALLY SUPPORTED METRO WORKINGS

Purpose. The purpose of this research is to analyse the components of the stress-strain state (SSS) for two horizontally supported metro workings to determine the parameters of their mutual influence. To achieve this, a numerical analysis of several finite element 3D models has been conducted, allowing consideration of the interaction between the surrounding massif and the linings, as well as changing the distance between them. **Methodology.** During the construction of extended horizontally oriented underground structures with a circular cross-section, a common scenario occurs where two tunnels influence each other. To perform a numerical analysis of the interacting supported metro workings, a general finite element model has been developed. Cutting fragments and assigning appropriate deformation characteristics to the soil and lining material, it allows for fast and efficient adjustment to specific design cases by changing the distance between the workings (*b*). **Findings.** The analysis of the obtained SSS results for the supported workings clearly shows that the isolines and isofields in the second design case undergo drastic changes compared to the distribution of displacements and stresses in the first (unsupported workings). The essence of the installation of the lining in the unsupported workings, meaning the shift from the first to the second design case, lies precisely in the new formation of the SSS. For unsupported workings, it depended on their diameter and soil mass properties such as the modulus of elasticity, Poisson's ratio, and specific gravity. For supported workings, the lining characteristics are added to these parameters. **Originality** of the research results lies in obtaining, for the first time, the stress-strain state distribution of mutually influencing supported workings by varying the distance between linings. These results demonstrate that the interaction between the supported workings at a distance of one diameter between linings ($b=D$) becomes more active due to the formation of a common field of decreasing horizontal and vertical displacements, while all components of the stress state in the linings increase. **Practical value** of the results lies in the development of a general finite element model. By cutting fragments and assigning specific deformation characteristics to the soil and lining material, the model can be quickly and effectively adapted to specific design scenarios when varying the distance between workings.

Keywords: metro; horizontally supported workings; lining; workings influence each other; stress-strain state; numerical analysis

Introduction

During the construction of extended horizontally oriented underground structures with a circular cross-section, a common scenario occurs where two tunnels influence each other. For running tunnels that start from and approach a metro station, the line design most often provides for a corresponding change in the distance between these tunnels (Fang, Zhang, Li, & Wong, 2015).

Any unsupported working driven in a rock massif disrupts the geological formation in which it is located, as well as a specific area of the surrounding massif. This disturbance unequivocally leads to fluctuations in the stress-strain state (SSS) of the rock massif, specifically resulting in increased stress levels and displacements at the contour of outcrop. The emergence of a second working at some distance from the first one can lead to an intensification of the SSS growth, since the influence of the workings becomes mutual.

Installing permanent support, i.e., lining, does not solve the problem of mutual influence, which is significantly modified (Tiutkin, & Bondarenko, 2022). Even during shield tunneling, where the excavation is supported by the tunnel boring machine, mutual interaction between the workings remains evident. This is because the supported working has a lining made from structural materials with specified strength and deformation properties (concrete, reinforced concrete, cast iron) (Wu,

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Bannikov, Kuprii, & Wu, 2025). Accordingly, the SSS of the unsupported workings and their mutual influence change radically.

In two supported workings spaced at a certain distance, SSS is formed depending on the lining material and its deformation capacity (Тютькін, & Демченко, 2025). At the same time, if the overall stress state in the system of the two mutually influencing workings remains within regulatory limits, the deformed state can increase, enhancing their mutual influence.

The use of numerical methods, especially the finite element method (FEM), is a fruitful approach to determine the SSS of supported, interacting workings. Its use enables modelling of complex underground structures, and the results obtained with its help are isolines and isofields of displacements and stresses, which are easy to interpret (Chehade, & Shahrour, 2008; Boldini, Losacco, Bertolin, & Amorosi, 2018; Nawel, & Salah, 2015; Alnmr, Sheble, Ray, & Ahmad, 2023).

To perform a numerical analysis of the interacting supported metro workings, a general finite element model has been developed. Cutting fragments and assigning appropriate deformation characteristics to the soil and lining material, it allows for fast and efficient adjustment to specific design cases by changing the distance between the workings (hereafter with letter *b*).

Purpose

The purpose of this research is to analyse the components of the stress-strain state for two horizontally supported metro workings to determine the parameters of their mutual influence. To achieve this, a numerical analysis of several finite element 3D models has been conducted, allowing consideration of the interaction between the surrounding massif and the linings, as well as changing the distance between them.

Methodology

Creating 3D models helps us eliminate the assumptions inherent in 2D models and, by considering the plane deformation condition, obtain the full SSS without cutting the components acting along the finite element model (Figure 1) (Do, & Dias, 2017; Chortis, & Kavvadas, 2021).

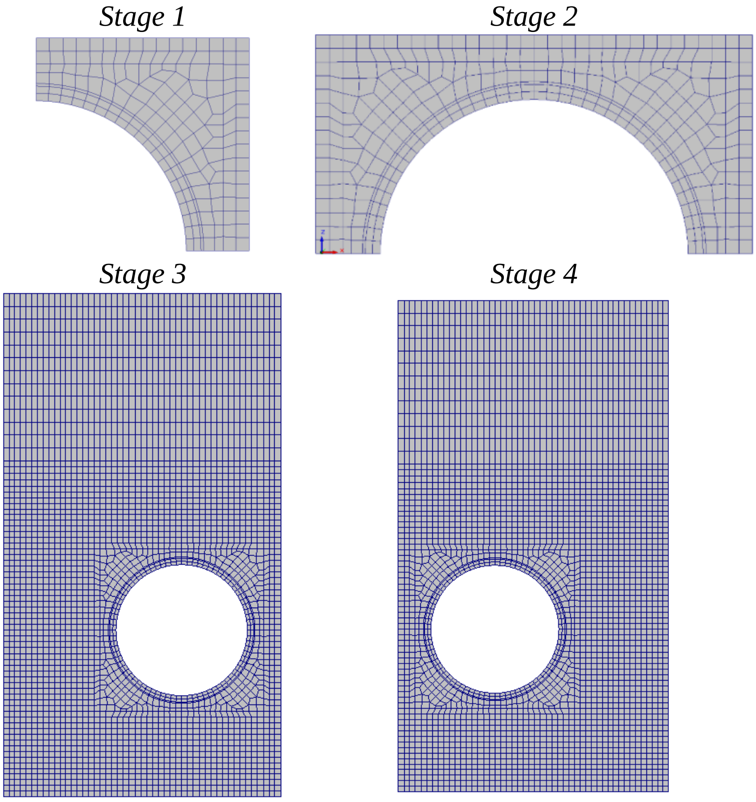

Figure 1. Stages of creating the geometry of finite element models for unsupported and supported horizontal workings

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When creating 3D models of supported workings, the surrounding massif of the lining, typical for the Kyiv Metro, consists of loam with the following properties: a modulus of elasticity E = 30 MPa, Poisson's ratio μ = 0.3, and specific gravity γ = 20 kN/m³. The linings are prefabricated, made of reinforced concrete blocks based on concrete of class C25/30 with the following properties: a modulus of elasticity E = 30,000 MPa, Poisson's ratio μ=0.2, specific gravity γ = 24.5 kN/m³, and a calculated compressive strength R_b=17 MPa.

All 3D model calculations of supported workings that interact during numerical analysis were based on the multifrontal method with automatic selection of stiffness matrix optimization, enabling the highest computational accuracy.

Findings

The distribution of stresses and displacements for the second design case (supported workings) has changed considerably from that for the first (unsupported workings); therefore, the analysis of the SSS components was performed using a more detailed layout of points (Figure 2).

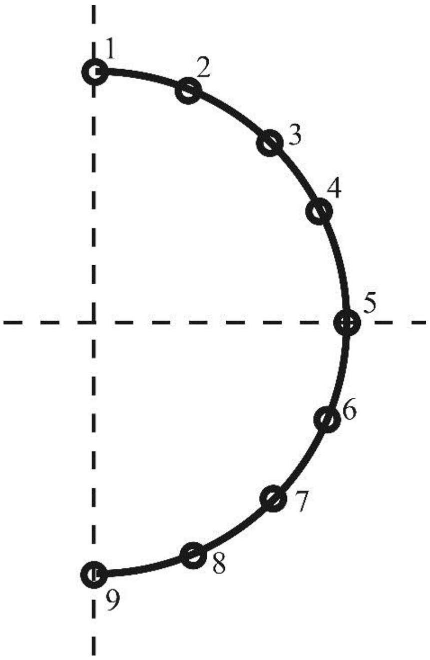

Figure 2. Layout of points
for analyzing displacement and stress components
in the lining of a supported working

Such a layout of points for analyzing the SSS has already successfully proven itself for the supported variant, which has been validated in practice and scientifically substantiated. Figures 3 and 4 show the results of calculating the SSS of supported linings with varying distances between them. Additionally, the most characteristic components of displacements and stresses are presented, and to save space in the article, all other details are omitted but analyzed in the text.

The analysis of the obtained SSS results for the supported workings clearly shows that the isolines and isofields in the second design case undergo drastic changes compared to the distribution of displacements and stresses in the first (unsupported workings). The essence of the installation of the lining in the unsupported workings, meaning the shift from the first to the second design case, lies precisely in the new formation of the SSS. For unsupported workings, it depended on their diameter and soil mass properties such as the modulus of elasticity, Poisson's ratio, and specific gravity. For supported workings, the lining characteristics are added to these parameters.

The installation of the lining slightly decreases the horizontal displacements of the general finite element model, which, unlike the unsupported variant, are reduced by 1 mm. A detailed analysis of this component of the strain state proves that in the variants with varying distances, the displacements are quantitatively identical, but their qualitative pattern changes. Thus, for the variant with the spacing between the linings equal to one diameter (b=D), an asymmetry in the distribution of horizontal displacements appears in the crown (point 1) and in the invert (point 9) sections. These displacements are 1 mm smaller than those in a single working or in variants where (b=(3 … 5)D), which indicates the mutual influence of the workings.

This influence is more clearly demonstrated by the pattern of the vertical component distribution of the strain state (Figure 3), which is natural since the emergence of a ring with a modulus of elasticity much higher than that of the soil massif in the unsupported working aims at a sharp decrease in deformation intensity.

Qualitatively, the vertical displacements distribution in the supported variant differs from the unsupported one by a smooth distribution of isolines around the working. When the distance between the workings equals the diameter (b=D), there is a thickening of the isofield between points on the horizontal diameter (point 3 (90°)), which is common to both linings.

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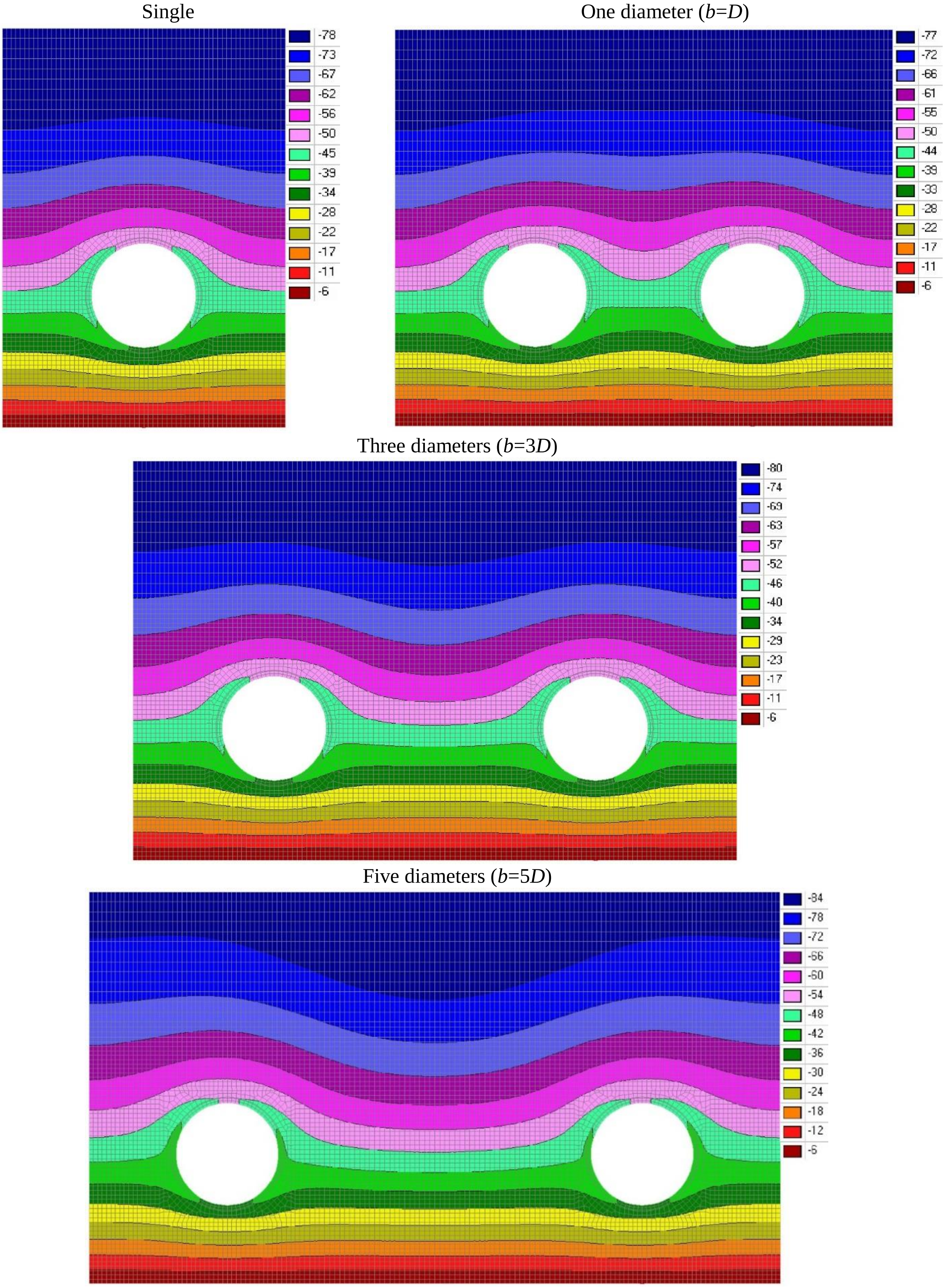

Figure 3. Isolines and isofields of vertical displacements in the lining
of the 3D model of supported workings with varied distance *b*

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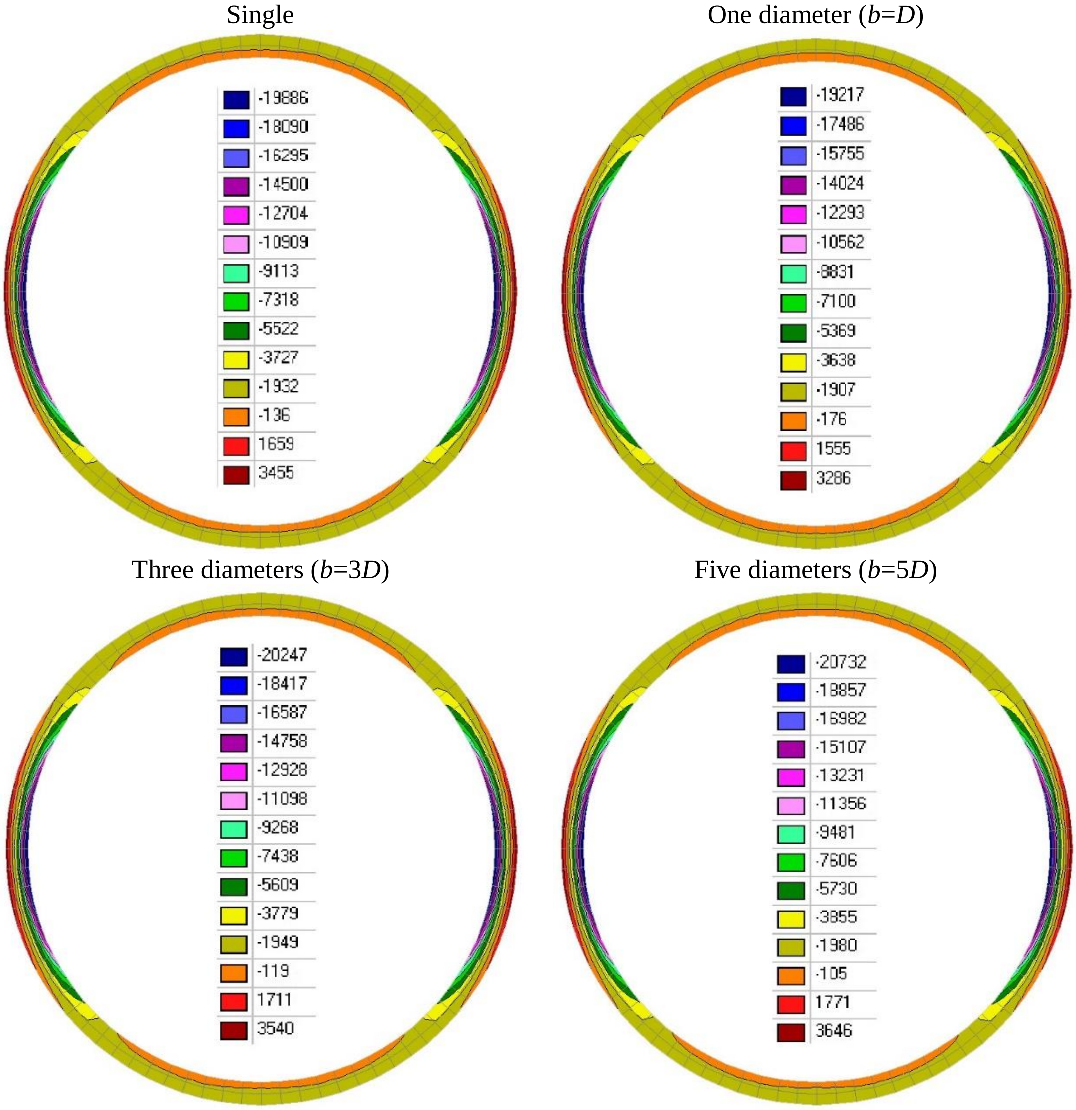

Figure 4. Isolines and isofields of vertical stresses in the lining of the 3D model of supported workings with varied distance *b*

For the variant with a distance of three diameters (*b=3D*), this pattern disappears, and with a five-diameter distance (*b*=5*D*), exhibits a distribution of vertical displacements close to that of a single working. A quantitative analysis of this deformation component allows us to observe the influence of installing the lining with a decrease in the intensity of displacements by 2.5 … 2.6 times (Figure 3) compared to the unsupported variant. Moreover, as for the horizontal component, when the distance between workings is equal to the diameter (*b=D*), the vertical displacements decrease quantitatively by 1 mm, and then, with varying distances (*b*=(3 … 5)*D*), they tend to resemble the case of a single working.

The change in deformation properties within the overall system has a more significant impact on the development of the stressed state, and this is clearly evident across all three components being analyzed. Unlike the unsupported variant, changes in the supported one are both qualitative and quantitative in nature. Specifically, for horizontal normal stresses, the stress concentrators in the lining (in contrast to the unsupported variant) shift from the horizontal diameter to the crown (point 1) and increase by approximately 40 … 45 times. Such an intensification of stress should not cause concern, since the concentrators of the horizontal component are less in value than the strength of reinforced concrete blocks based on concrete class

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C25/30 with a design compressive strength of R_b = 17 MPa.

Qualitatively, the distribution patterns of horizontal stress isolines and isofields are identical, with no asymmetry observed, similar to the strain state components. Moreover, when the distance between workings is one diameter ($b=D$), the horizontal stresses are quantitatively lower by approximately 300 … 500 kN/m², confirming a zone of mutual influence. If displacements along the horizontal axis, due to the significant rigidity of the linings, cannot form an intensive mutual influence zone, then the stresses along this axis are mutually compensated. When the distance between workings varies (b=(3 … 5)D), their mutual influence disappears, and the horizontal stress components approach the values of a single working, while increasing slightly.

For vertical stresses in the linings, the localization zone (Figure 4) remains unchanged, unlike the unsupported working, and the concentrators are positioned on the horizontal diameter, increasing the value by 25 … 27 times. This also should not cause concern since the design compressive strength of concrete (R_b=17 MPa) is sufficient to maintain the overall strength of the lining. However, it should be noted that stresses reach 19 … 21 MPa, i.e., exceed the design resistance in the zone on the horizontal diameter. But, the size of the concentrator only indicates the possibility of cracking. Qualitatively, the distribution patterns of isolines and isofields of vertical stresses are identical, while when the distance between the workings equals the diameter ($b=D$), the quantitative values are approximately 600 … 1000 kN/m² lower. This suggests the presence of a mutual influence region, which disappears when the distance (b=(3 … 5)D) between the workings varies.

Qualitatively, the nature of the shear stress distribution in the vertical plane within the linings has not changed compared to the unsupported working condition; the stress concentration of this component occurs at approximately 45° and 135°, and the quantitative values have increased by 24 to 25 times.

Having conducted a qualitative SSS analysis of the unsupported and supported workings, when the distance between them is one diameter ($b=D$), we can identify zones of mutual influence, which differ in nature (Figures 5 and 6).

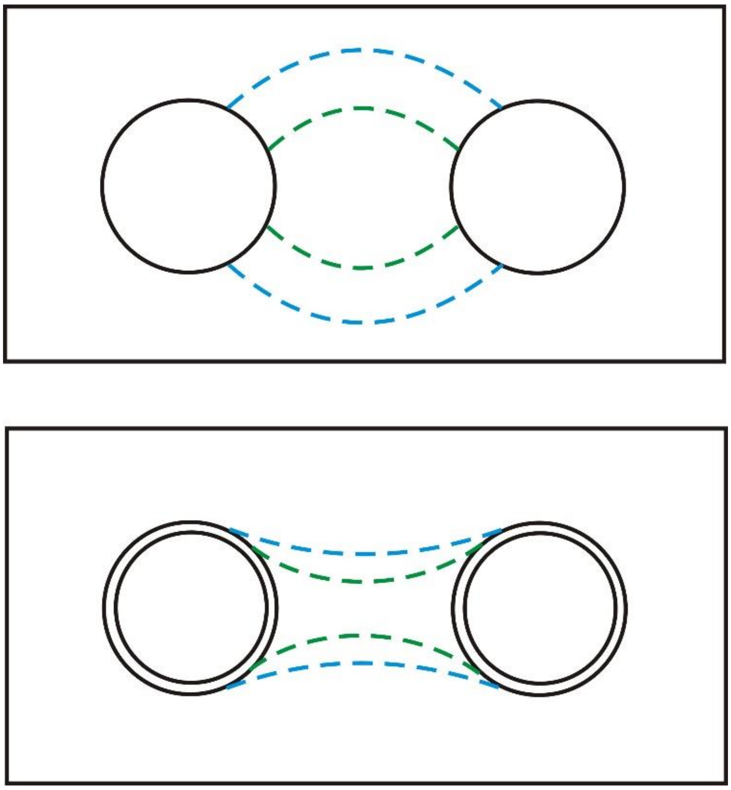

Figure 5. The nature of the formation of the mutual influence zone of the strain state for the first and second design cases

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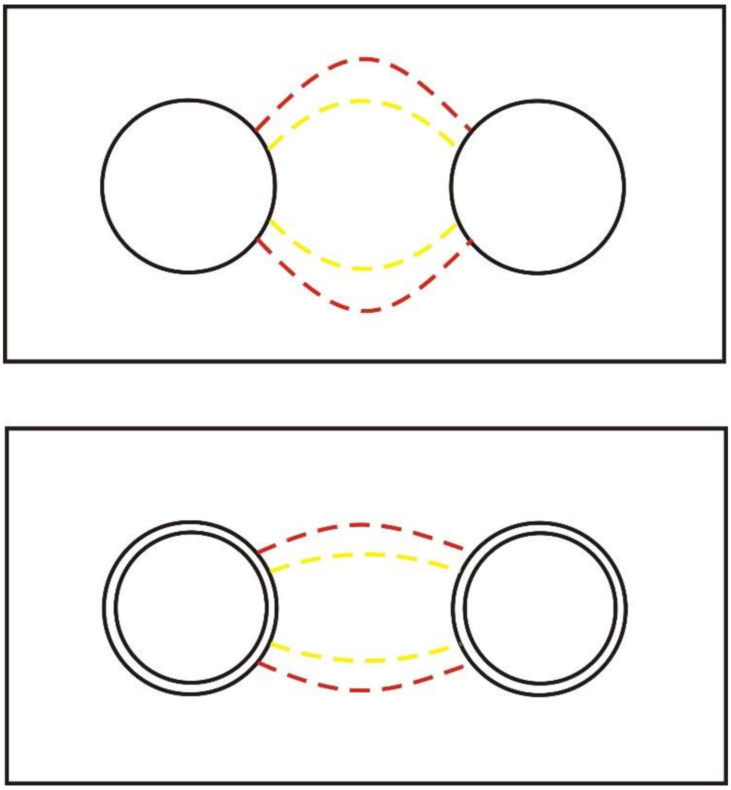

Figure 6. The nature of the formation of the mutual influence zone of the stressed state for the first and second design cases

Blue and green curves represent the areas of general and peak mutual influence of the strain state, respectively, while red and yellow curves indicate the areas of the stressed state. A key observation is the shift in the displacement area shape during mutual influence: it transitions from convex in the first design case (unsupported workings) to concave in the second (supported workings). This shift highlights the impact of additional stiffness provided by installing the lining. By reinforcing the modulus of elasticity, the lining transforms the mutual influence from negative (increased displacements in interacting unsupported workings) to positive, resulting in mutual displacement compensation in the case of supported workings.

Originality and practical value

The originality of the research results lies in obtaining, for the first time, the stress-strain state distribution of mutually influencing supported workings by varying the distance between linings. These results demonstrate that the interaction between the supported workings at a distance of one diameter between linings ($b=D$) becomes more active due to the formation of a common field of decreasing horizontal and vertical displacements, while all components of the stress state in the linings increase.

The practical value of the results lies in the development of a general finite element model. By cutting fragments and assigning specific deformation characteristics to the soil and lining material, the model can be quickly and effectively adapted to specific design scenarios when varying the distance between workings.

Conclusions

In the course of the numerical analysis of components of the stress-strain state of mutually influencing horizontally supported metro workings, it was found that the characteristic SSS parameters for variants with different distances between linings have the following values: horizontal displacements – 5 mm (point 3, 90°, horizontal diameter); vertical displacements – 46 mm (point 1, crown); stresses along the horizontal axis – 12 785 kN/m² (points 1, crown, and 5, invert); stresses along the vertical axis – 19 217 kN/m² (point 5, 90°, horizontal diameter); shear stresses in a single lining at points 1, 5, and 9 are zero, and

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at a distance of one diameter ($b=D$) – 659 kN/m².

A well-supported conclusion is that, unlike the first design case (mutually influencing unsupported excavations), when installing the lining in two horizontal circular tunnels, the nature of displacements and stresses changes significantly. Both displacement components decrease, while stresses increase. At a distance between linings equal to one diameter ($b=D$), displacements and stresses are minimal, which is explained by the mutual compensation of the stress-strain state resulting from the interaction between the workings.

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АНАЛІЗ КОМПОНЕНТ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ГОРИЗОНТАЛЬНИХ ЗАКРІПЛЕНИХ ВИРОБОК МЕТРОПОЛІТЕНУ, ЩО ВЗАЄМНО ВПЛИВАЮТЬ

Мета. Метою наданого дослідження є аналіз компонент напружено-деформованого стану (НДС) двох горизонтальних закріплених виробок метрополітену для визначення параметрів взаємного впливу. Для досягнення поставленої мети проведено чисельний аналіз низки скінченно-елементних 3D-моделей, які дозволяють врахувати взаємодію між оточуючим масивом й оправами, а також змінювати відстань між ними. **Методика.** В ході будівництва протяжних підземних споруд горизонтального орієнтування колового окреслення часто виникає ситуація, в якій два тунелі починають взаємно впливати. Для проведення чисельного аналізу закріплених виробок метрополітену, що впливають, створена загальна скінченно-елементна модель. Вона, за допомогою операцій із вирізання фрагментів та присвоєння відповідних деформаційних характеристик ґрунту та матеріалу оправи, дозволяє швидко і ефективно підлаштовуватися під конкретний розрахунковий випадок, змінюючи відстань між виробками (b). **Результати.** Аналіз отриманих результатів НДС за-

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кріплених виробок безсумнівно свідчить про те, що ізолінії та ізополя другого розрахункового випадку мають корінні зміни на відміну від розподілу переміщень та напружень першого (незакріплені виробки). Сутність постановки оправи в незакріплену виробку, тобто перехід від першого до другого розрахункового випадку, полягає саме у новому формування НДС, який для незакріплених виробок залежав від їхнього діаметру та характеристик ґрунтового масиву (модуль пружності, коефіцієнт Пуасона, питома вага), а для закріплених до вказаних параметрів додаються характеристики оправи. **Наукова новизна** результатів дослідження полягає у тому, що вперше під час варіації відстані між оправами отримано й проаналізовано розподіл напружено-деформованого стану закріплених виробок, що взаємно впливають. Ці результати доводять, що взаємодія між закріпленими виробками при відстані між оправами, котра дорівнює одному діаметру (b=D), стає більш активною по причині формування загального поля горизонтальних і вертикальних переміщень, які зменшуються, при цьому всі компоненти напруженого стану в оправах збільшуються. **Практична значимість** викладених результатів полягає в розробці загальної скінченно-елементної моделі, яка, за допомогою операцій із вирізання фрагментів та присвоєння відповідних деформаційних характеристик ґрунту та матеріалу оправи, дозволяє швидко і ефективно підлаштовувати її під конкретний розрахунковий випадок під час варіації відстані між виробками.

Ключові слова: метрополітен; горизонтальна закріплена виробка; оправа; виробки, що взаємно впливають; напружено-деформований стан; чисельний аналіз

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