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ТРАНСПОРТНЕ БУДІВНИЦТВО

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ANALYSIS OF DEFORMED STATE STRUCTURES OF THE KYIV METRO RUNNING TUNNELS ON A TRANSITION ZONE FROM SPONDYLOV'S CLAY TO BUCHATSKIY SANDS

Purpose. In the section of changes geotechnical conditions of spondylov's clay to buchatskiy sands may have significant structural deformation of running tunnels. It is necessary to identify the cause of deformities develop ways to minimize and based modeling and calculations to prove the effectiveness of measures to reduce deformation. **Methodology.** To solve the analysis problem of the stress-strain state (SSS) of the system «structure array» it was conducted the numerical simulation using the finite element method (FEM). On the basis of the obtained results the graphs were constructed and the dependencies were determined. **Findings.** The presence of weak water-saturated soils in tray of the tunnel on an area of transition from spondylov's clay to buchatskiy sand causes significant increasing in strain construction of tunnels and general vibration liquefaction in soil basis. Also change the physical and mechanical characteristics of soils within the frames of tunnels influences on the level of strain state of most frames. Improved strain state settings of tunnels in areas of change soil characteristics of the array (especially at the bottom of casing) can be achieved by chemical consolidation of weak soils. Composition of solutions for fixing the weak soils should be determined based on the study of grain size, porosity, and other parameters of physical and mechanical and physical and chemical characteristics of soils. **Originality.** The basic cause significant strain on transition zone from spondylov's clay to buchatskiy sands is found, that is explained by saturated phenomenon vibration liquefaction basis under the tunnel. **Practical value.** The approaches to reduce the strain in the construction of running tunnels in the transition zone from spondylov's clay to buchatskiy sands are developed, as well as in the area of the station «Glybochytska» the Kyiv Metro.

Keywords: vibration liquefaction of water-innundated basis; finite element method; stress-strain state; transition from spondylov's clay to buchatskiy sands; analysis of strains

Introduction

Currently, preparations have began for the design and construction of running tunnels near the station «Glybochytska» in the direction of Podolsk-Vyhuryivskoyi metro line to housing estate «Troeshchyna» in Kyiv. In this direction

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engineering-geological conditions have a very high level of complexity, especially in the transition zones from spondylov's clay to Buchatskiy Sands. Therefore, determining the strain state settings and soils in the transitional zone is an actual task which, needs to be resolved.

Purpose

As it is known, running tunnels in spondylov's clay are in a stable condition and deformation not exceeding the maximum allowable for the given category of soils [6, 10]. However, in the transition zone from spondylov's clay to water-saturated sands arising heavy load, which lead to the considerable deformations that is defined in elastic-plastic condition in spondylov's clay [2, 4]. Therefore the purpose of this research is the solution of the task construction running tunnels with a combined casing in complexity engineering-geological conditions which rather often meet in Kyiv.

Methodology

The basis of the calculation method based on the method of finite elements, using as the main unknown displacements and rotations basic units design scheme based on the calculation complex Structure CAD (SCAD) [7, 9, 11]. Type of the finite element, used in the calculation, is determined by its shape, features, which dependence between relocation in nodes of finite element and system nodes, by physical law that defines the relationship between internal forces and internal displacement, and a set of parameters (rigidities) are included in the description of this law and others [11–14]. All nodes and circuit elements are numbered. The numbers assigned to it should be interpreted only as names, which allow making the necessary links.

The sign convention for movement is accepted in such way, that the linear displacement is positive, if they are directed towards increasing the corresponding coordinates, and rotation angles are positive, if they comply with corkscrew rule.

For investigation the stress-strain state (SSS) of running tunnel created a spatial model from volume elements (Fig. 1 and 2).

The model is constructed of isoparametric finite elements such as prisms (34 and 36 type elements in complex SCAD) with consistent nodes [11]. Elements which used in the model of such size in the XZ plane: 0.24×0.24 m (more than 95% of the volume of the FE scheme - the whole soil array and casing); 0.1×0.25 m (2.5% of scheme - modeling layer discharge per frame). It reflects the following features of the real structure [1, 5, 11]:

– the influence of spatial factor on the formation of the stress state, that is the influence of third component σ_y on components and σ_z ;

– the most full reproduction of interaction of a steel concrete casing with a soil array which generally changes its properties.

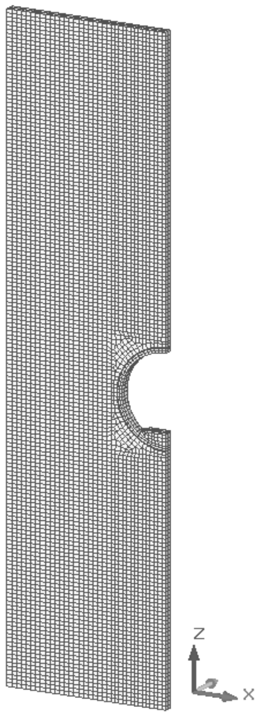

Fig. 1. Finite element model (FE-model) of running tunnel interaction with the surrounding array

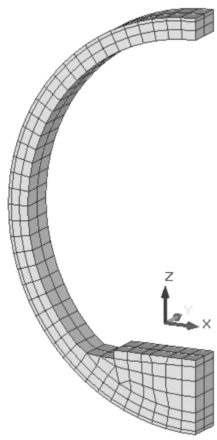

Fig. 2. Part of the running tunnel in a mode of presentation graphics

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Y-direction (along the length of the tunnel) size of items was 0.3 m, which proves less influence of the size of the FE in this area, although for model computational domain that size could be applied and elements of a considerable size, which is proposed in scientific works [1, 5, 11], which provided a recommendation to determine the size of the element as the characteristic size of the computational region.

The FE-model represents a half of real construction as it is the symmetric with the symmetrical load. Reproduction only half of the tunnel reduced the volume of calculations and allowed to carry out exact tunnel splitting and surrounding array on terminal elements that would be impossible by development of the whole model, as the quantity of FE in the applied complex is restricted equal 40 000 pieces.

The FE-model which was applied in all researches has the following sizes: X-direction – 10.0 m, Y-direction – 0.6 m; Z-direction – 40.0 m. That is the normal size of FE it would be possible to accept 2×2×2 m, but it didn't allow reproducing more precisely specific characteristics of the "casing-tunnel" system, for example, a case of primary forcing. The total number FE-model nodes are18 246, the total number of FE is 11 736 pieces. The quantity of FE testifies that the problem which was solved, is the task of average dimensionality (to 20 000 finite elements).

The model was created so that to reproduce all geometrical sizes of running tunnel: diameter internal – 5.6 m, diameter external – 6.04 m (the steel concrete blocks B30).

Applied bounding conditions are imposed to the scheme: model up without fastenings; the sides, parallel to tunnel axes (YZ plane) – inhibits of movements on axes X and Y; the sides are perpendicular to tunnel axes (XZ plane) – inhibits of movements on axis Y (it most precisely corresponds to plane strain condition); model bottom – inhibits of movements on axes X, Y and Z. These boundary conditions most precisely allow recreating a real picture of model deformation [7, 9].

The deformation properties received from real probes of materials were provided to models, the stratigraphic record reflects array part, which surrounds a studied tunnel.

EGE 73 – bluish-greenish-gray marl clay, silty, micaceous, carbonate, with thin layers and nests of gray silty sand, sometimes fractured, water-permeable through cracks and sand layers, tough, medium-hard, firm (spondylov's clay);

EGE 75 – loam bluish-gray-green micaceous, silty, carbonate, and pyrite with phosphorous and pyrite nodule, firm, semi-solid, tough (sandy spondylov's clay);

EGE 77 – sand bluish-greenish-gray shallow, silty, muddy, marl clay, poorly micaceous, average firmness low-damp, damp, sated with water;

EGE 78A – sand grey, greenish-gray in places of average size, mid-weight, heavy, saturated with water.

Properties of engineering-geological elements are given in Table 1.

Stratigraphic record is shown on Fig. 3.

As for deformation properties and the nature of the soil it can be divided into clay and sand, to simplify calculations is formed table 2, which shows the average estimated values of the properties of layers that provide real stratigraphic records and used in numerical calculations (Fig. 4).

This change of real stratigraphic record lists valid, because the thickness of the layers, which are not taken into account, is small (1…2 m) and thus may not significantly influence to the pattern of deformation distribution.

Table 1

Soil Properties EGE

Number EGE	Protodyakonov scale of hardness f	Voids ratio e (unit fraction)	Specific cohesion C'', kPa	Internal friction angle φ'', grade	Deformation modulus E, MPa	Soil density ρ, t/m^3
73	1,0	0,767	78	15	30,0	1,96
75	0,8	0,627	5	18	25,0	2,01
77	0,6	0,574	3	28	20,0	1,82
78a	0,4	0,580	2	28	20,0	1,86

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End of Table 1

Soil Properties EGE

Number EGE	Moisture of soil W_0 , unit fraction	Poriness n , %	Humidity level, S_r , unit fraction	Transmission coefficient $K_ф$, m / day	Design resistance, R_0 , kPa
73	0,273	43,4	0,978	0,005	325
75	0,206	38,5	0,883	0,120	250
77	0,080	36,5	0,330	1,300	200
78a	0,260	36,7	–	5,000	200

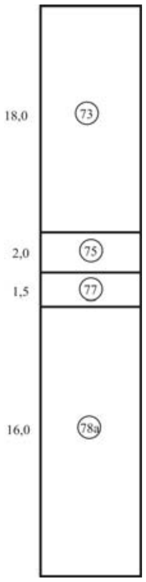

Fig. 3. Stratigraphic records of array part around tunnel

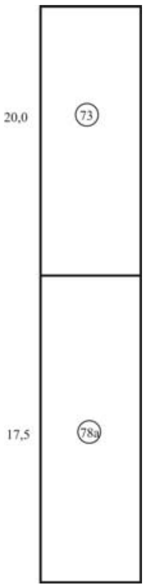

Fig. 4. Given stratigraphic records of array part around tunnel

Table 2

Soil Properties EGE

Number EGE	Protodyakonov scale of hardness f	Deformation modulus E , MPa	Density of soil ρ , t/m^3
73	0,9	27,5	1,99
78a	0,5	20	1,84

Rigidness of the cement-sandy solution which is given on a casing in case of primary injection or grouting was such: the average thickness 0.1 m, the elastic modulus E = 20 000 MPa, Poisson's ratio $\mu = 0,2$, density $\rho = 2,2 \frac{m}{м^3}$.

Deformation properties of steel concrete received as are given characteristics, and for steel concrete on the basis of B30 concrete made: elastic modulus E = 35 000 MPa (in case of reinforcement percentage – 1…3%), Poisson's ratio $\mu = 0,2$, density $\rho = 2,5 \frac{m}{м^3}$.

Calculation of all models was executed on two loadings: 1) action metro train; 2) curb weight surrounding an array and construction. The accounting action of metro train it is reproduced in normative documents, for example, in Ukrainian national construction regulation B.2.3-7-2010. Metro system, p. 9.44. [3]. But estimates of the rolling stock impact remains some verification, as a given fact that the weight of the train is not more than 5…10% from actions of mountain pressure [6, 9]. According to paragraph 9.44 [3] load of rolling metro trains that operate on the track superstructure (TS) are normalized as follows: 1) normative vertical load L – 150 kN per axle; 2) regulatory horizontal longitudinal load from braking or traction – 10% from the standard vertical load of the rolling stock, i. e 15 kN at the level of the rack head; 3) regulatory horizontal transverse loads from impact undercarriages – applied at the level of the rack head uniformly distributed load with the intensity 2 kNm. Further study will be taken into account only – 1st load in the complex, 2nd and 3rd ignored due to the small size unlike the first.

For the application of loads from rolling stock modeled track superstructure (TS), in order to more adequately reproduce the system impact of metro trains. Geometric parameters of TS: ballast depth – 0.8 m, ballast material – concrete class B12.5 (modulus of elasticity E = 27 000 MPa, Poisson's ratio $\mu = 0,2$, density $\rho = 2,5\ \frac{m}{м^3}$). In TS reproduced not all assembled rails and sleepers, but only one sleeper.

Findings

Further researches of the strain state structure in the transition zone from clay to sand is carrying out. A series of calculations for this purpose is executed:

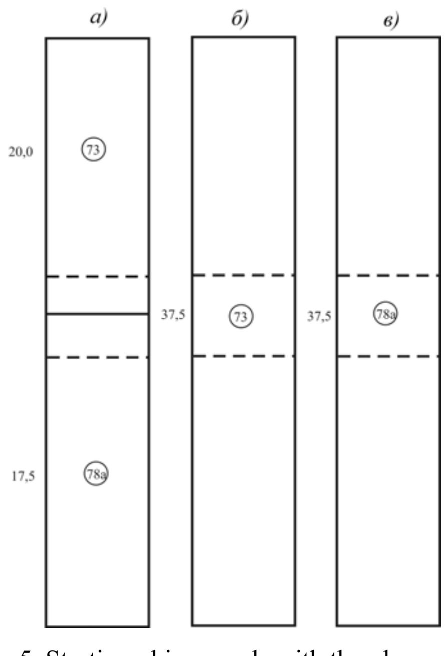

Fig. 5. Stratigraphic records with the placement of the tunnel (the dashed line denotes the position of the lock and tray):
а – option 1; *б* – option 2; *в* – option 3

1) Option 1 – the real case in which the tunnel crosses two soil layers (EGE 73 and EGE 78a, fig. 5, *a*);

2) Option 2 – a possible case where the tunnel lies in only one soil layer (EGE 73, fig. 5, *b*);

3) Option 3 – a possible case where the tunnel lies in only one soil layer (EGE 78a, fig. 5, *c*).

Option 2 and 3, which are hypothetical, provide an opportunity to further comparison strain state structure and array, as they are homogeneous. Strain state calculation of these two cases allows us to compare the value of the Option 1 and made the conclusion about the influence of stratification on the sediment development.

The basis of calculation based on the method of finite elements based on the estimated Complex Structure CAD (SCAD).

After creating the FE-models, held their calculation, the results of which are shown in Fig. 6 and 7.

Analysis downloads models it is the action of metro train allows you to separate it from its own weight array and construction on the principle of superposition can be added to it. The case demonstrates the validity metro train state structure, which interacts with the surrounding array, when all the processes of rock formation pressure have over. Calculation results showed that the impact of metro train for horizontal displacement casing hardly felt as mentioned strains in all three versions are the same (maximum – 0.4 mm in the horizontal diameter of casing). Horizontal deformations in the model, i. e. in the casing, which interacts with an array qualitatively almost identical, and is quantitatively, vary slightly (0.4…0.5 mm).

The same minor change in the model can be demonstrated and caused by the action of the array of horizontal deformations, which are qualitatively coincide in the model and in the fragment model (casing).

Analysis of Fig. 6 and 7 indicates that the impact of metro train on the vertical displacement casing are tangible, as mentioned strains in all three versions is within 10 mm (option 1 – 9.5 mm, option 2 – 7.2 mm, option 3 – 9.7 mm). In this component the difference between the options have significant and make 1.32 times between option 1 and 2 and 1.35 times between options 2 and 3, it is possible to prove that the tab of the array in option 2 (sealing in clay) is the most optimal, and the difference between option 1 and 2 is insignificant. Thus, the partial sealing of the tunnel in clay when sand is underlain by a layer of practically no effect positively on the deformation, due to pain use by another deformation capacity of sand.

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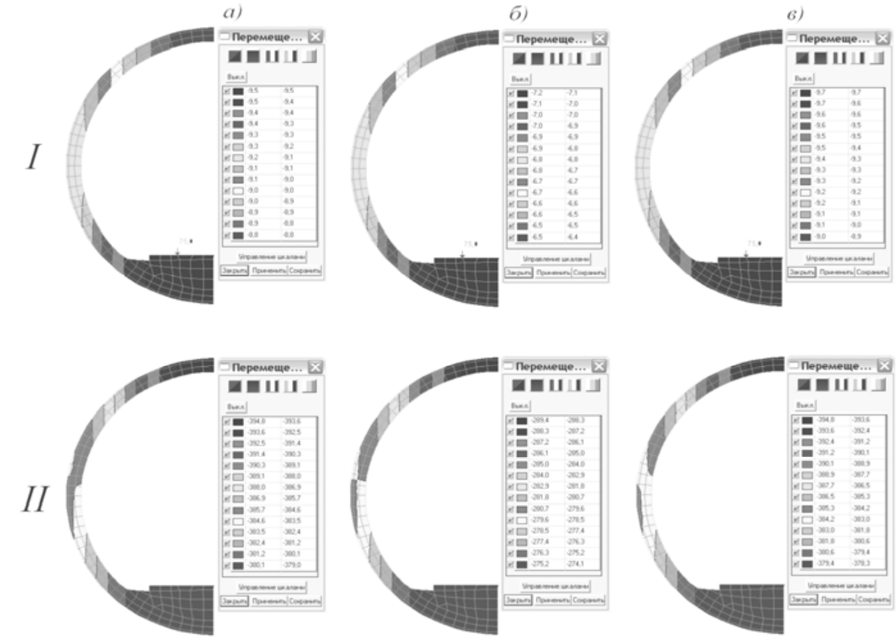

Fig. 6. Isolines and isofields of vertical displacements of tunnel casing from metro train action (I) and own model weight (II):
а – option 1; *б* – option 2; *в* – option 3

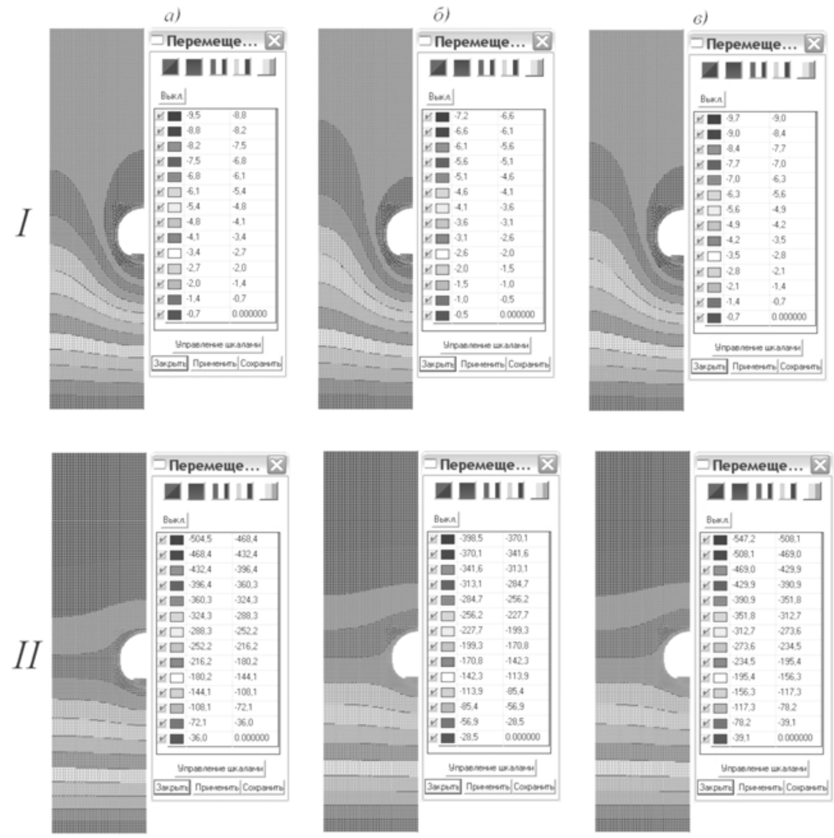

Fig. 7. Isolines and isofields of vertical displacements of array around the tunnel from metro train action (I) and model dead weight (II):
а – option 1; *б* – option 2; *в* – option 3

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The vertical deformation array of actions qualitatively almost identical in the model and the fragment model (casing), but quantitatively they confirm what has been observed in the case of actions metro trains. But we should note the corresponding change in quantitative maximal values of vertical deformation (top model): Option 1 – 394.8 mm, option 2 – 289.3 mm, option 3 – 394.8 m

To find absolute deformations of casing points, for example, in the lock, it is necessary to subtract value of deformation in it from value in a tray. Thus, the maximum values of vertical deformations in the lock make: option 1: – 394.8 – (– 379) = – 15.4 mm, Option 2: – 289.3 – (– 274.1) = 15.2 mm, option 3: – 394.8 – (– 378.3) = 16.5 mm. It also testifies about bigger deformation ability of the array in option 1 and 3 though option 1 in this case of loading actions is closer to option 2.

One of the important factors that influence on the development of deformations, is the change of deformation properties, especially modulus deformation of soil, for example, under the influence of groundwater, especially because the layer of sand (EGE 78A is designated by availability of the underground waters dated to the buchatsko-kanevskogo water-bearing horizon which have tendency to lifting.

Calculation of real case of laying the tunnel (Option 1), but with change of the module of deformation of sand is carried out. It was already calculated the model with the module of deformation E = 20 MPa therefore six more calculations of Option 1 – with E = 17.5 MPa (sub-option 1) are carried out, 2 – E = 15 MPa (sub-option 2), 3 – E = 12.5 MPa (sub-option 3), 4 – E = 10 MPa (sub-option 4), 5 – E = 7.5 MPa (sub-option 5), 6 – E = 5 MPa (sub-option 6) results of calculations which are given in comparison with Option 1. Similarly to the previous calculation has defined maximum vertical deformation in the lock casing. In addition it should be noted that the qualitative picture of the distribution isofield movement has not changed, only the quantitative values.

The limited scope of the article is missing the opportunity to fully reflect the results of calculations. However, its deformed state confirms that the influence of deformation characteristics (deformation module of sand) minor effect on the horizontal deformation in the case of actions metro train, but for the actions of their own weight changes is noted.

Analyzing the absolute vertical deformation of the casing it should be noted that the decrease in the elasticity modulus of sand (modeling soaking) significantly affects to the vertical deformation of the frame. It should also be noted that this calculation was carried out in a static setting, although in real terms the dynamic impact from movement of metro train causes vibration liquefaction soaked sand under the casing of the tunnel.

Also the relationship between the modulus of elasticity and deformation of sand is quite natural character that can be tracked using a graphic (Fig. 8).

The graphic is built in the software package Microsoft Excel program functionality is made approximation of the results. As approximating function was chosen linear dependence, which is reflected by the equation $y = -\ 0{,}15x + 15{,}729$, the value of the accuracy of the approximation is $R^2 = 0{,}9932$, indicating to very high coincidence of approximating linear function.

The maximum vertical deformation of casing constitute 15.6 mm at the slightest given modulus of elasticity of sand – 5 M underground waters Pa.

In real terms the additional dynamic performance of motion metro trains will lead to further growth of strains that will lead to limitation of speed metro trains in this part of the tunnel. Often, to reduce the strain that can occur with a decrease in carrying capacity of the base, use artificial methods of soil base. The simplest and most effective way to strengthen the artificial soil is pumping cement-sand mortar per frame. In order to predict the development of artificial deformation after grouting design model has been created, where at the base tunnel was fixed cement-sand mortar.

The rigidity of cement-sandy mortar, which is served for the casing when attaching, was as follows: modulus of elasticity E = 20 000 MPa, Poisson's ratio $\mu = 0{,}2$, density $\rho = 2{,}2\ \frac{т}{м^3}$. Thickness of a layer of the fixed sand is accepted by equal 1 m.

This way of fixing the soil was simulated when the elasticity module of the sand layer from 5 to 20 MPa. On the basis of calculations, we plot the dependence of the vertical deformation of the frame from the modulus of sand with a cement-sandy consolidation of the soil (Fig. 9). Loading was tried on from the weight of all models.

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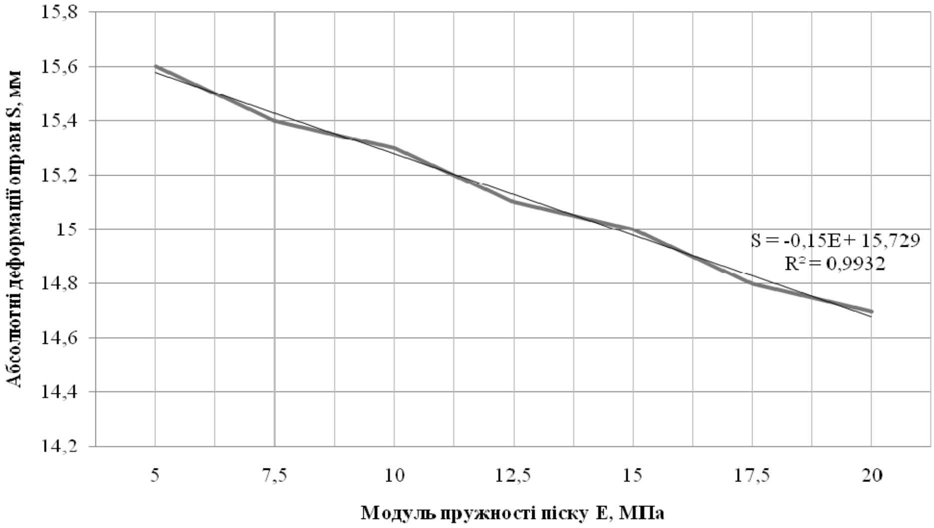

Fig. 8. Dependency diagrams of the vertical deformation of the casing from the module of elasticity sand

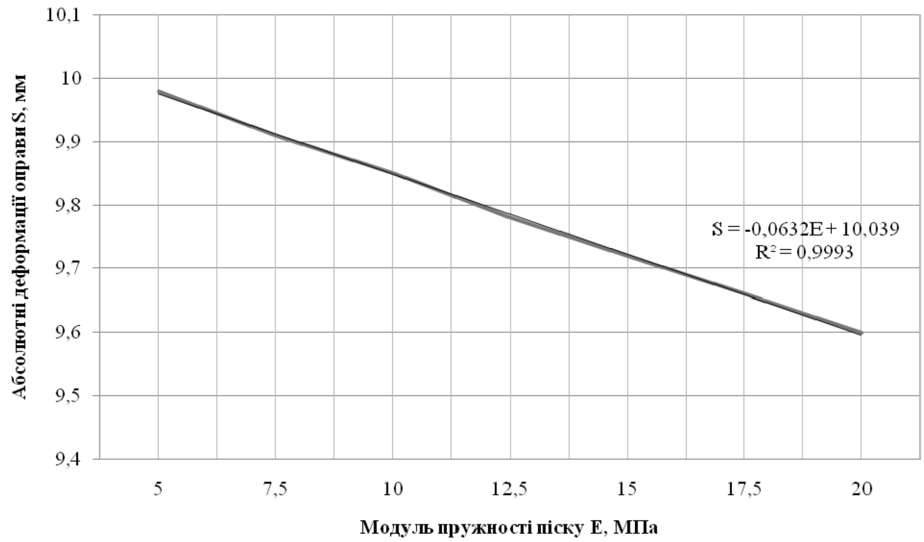

Fig. 9. Dependency diagrams of vertical deformation casing from the modulus of sand when executed grouting

The schedule of deformations in fig. 9 shows that after performance of artificial fixing of soil vertical deformations of a tunnel decreased on the average by 5.5 mm, that is approximately by a third from maximum them deformations in the absence of soil strengthening at the module of elasticity of 5 MPas. Besides such fixing of the soil is effectively as for not watered sand with the high module of elasticity, and water-saturated sand.

Originality and practical value

In paper identifies the main cause significant strain on the transition zones from spondylov's clay to Buchatskiy Sands, due to a phenomenon vibration liquefaction basis under the tunnel and defines scientific novelty of the research. The approaches to reduce the strain in the construction of main line tunnels in the transition zone from spondylov's clay to Buchatskiy Sands, as well as near the station «Glybochytska» of the Kyiv Subway and this is the practical significance of this work.

Conclusions

On the basis of the conducted research of the running tunnels, which designed, near the station «Glybochytska» (the Kyiv subway) the following conclusions were drawn:

1. The presence of weak water-saturated soils in the tray part of tunnels, and also in the area

«Glybochytska», on a transition zone from the spondylov's clay to Buchatskiy Sands causes essential increases of deformations as designs of tunnels, and also the general vibration liquefaction in a soil basis.

2. Executed scientific study shows that changes in physical and mechanical properties of soils within the frames of tunnels influences the level of strain state of most frames.

3. Results of mathematical modeling indicate that the optimum sealing tunnels is the EGE 73 (spondylov's clay), since strain state at such occurrence was characterized by lower values of displacements.

4. Soaking the sand layer in the case of rising groundwater level will increase drawdown structure as a consequence of the reduced modulus of sand. The dependence between the deformation of the frame and a decrease in the elasticity modulus of sand is linear.

5. Injection of cement-sandy solution under tray part of the tunnel significantly reduces vertical deformation of the frame and is quite effective and inexpensive method of dealing with large deformations rims tunnels.

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АНАЛІЗ ДЕФОРМОВАНОГО СТАНУ КОНСТРУКЦІЙ ПЕРЕГІННИХ ТУНЕЛІВ КИЇВСЬКОГО МЕТРОПОЛІТЕНУ НА ДІЛЬНИЦІ ПЕРЕХОДУ ВІД СПОНДИЛОВИХ ГЛИН ДО БУЧАЦЬКИХ ПІСКІВ

Мета. На дільниці зміни інженерно-геологічних умов із спондилових глин на бучацькі піски можуть виникати значні деформації конструкції перегінних тунелів. Тому в представленому дослідженні необхідно виявити причину розвитку деформацій, розробити шляхи її мінімізації та на основі моделювання й розрахунків довести ефективність заходів зі зменшення деформацій. **Методика.** Для вирішення проблеми аналізу напружено-деформованого стану (НДС) системи «конструкція – масив» проведено числове моделювання методом скінченних елементів (МСЕ). На основі отриманих результатів побудовано графіки та встановлено залежності. **Результати.** Наявність слабких водонасичених ґрунтів у лотковій частині тунелів на дільниці переходу від спондилових глин до бучацьких пісків викликає суттєве підвищення деформацій конструкції тунелів, а також загальні віброосідання в ґрунтовій основі. Крім того, зміна фізико-механічних характеристик ґрунтів у межах оправи тунелів суттєво впливає на рівень деформованого стану самих оправ. Покращення деформованого стану оправи тунелів на ділянках зміни характеристик ґрунтів навколишнього масиву (особливо підстеляючих оправу) може бути досягнуто шляхом хімічного закріплення слабких ґрунтів. Склад розчинів для закріплення слабких ґрунтів повинен визначатися на основі вивчення їх гранулометричного складу, показників пористості та інших фізико-механічних і фізико-хімічних характеристик ґрунтів. **Наукова новизна.** Виявлено основну причину значних деформацій на дільниці переходу від спондилових глин до бучацьких пісків, що пояснюється явищем віброосідання водонасиченої основи під тунелем. **Практична значимість.** Розроблено підходи зі зменшення деформацій при будівництві перегінних тунелів на ділянці переходу від спондилових глин до бучацьких пісків, \а також у зоні станції «Глибочицька» Київського метрополітену.

Ключові слова: віброосідання водонасиченої основи; метод скінченних елементів; напружено-деформований стан; перехід від спондилових глин до бучацьких пісків; аналіз деформацій

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АНАЛИЗ ДЕФОРМИРОВАННОГО СОСТОЯНИЯ КОНСТРУКЦИЙ ПЕРЕГОННЫХ ТОННЕЛЕЙ КИЕВСКОГО МЕТРОПОЛИТЕНА НА УЧАСТКЕ ПЕРЕХОДА ОТ СПОНДИЛОВЫХ ГЛИН К БУЧАЦКИМ ПЕСКАМ

Цель. На участке изменения инженерно-геологических условий от спондиловых глин к бучанским пескам могут возникать значительные деформации конструкции перегонных тоннелей. Поэтому в представленном исследовании необходимо выявить причину развития деформаций, разработать пути их минимизации и на основании моделирования и расчетов доказать эффективность мероприятий по уменьшению деформаций**.** **Методика.** Для решения проблемы анализа напряженно-деформированного состояния (НДС) системы «конструкция – массив» проведено численное моделирование методом конечных элементов (МКЭ). На основе полученных результатов построены графики и установлены зависимости. **Результаты.** Наличие слабых водонасыщенных грунтов в лотковой части тоннелей на участке перехода от спондиловых глин к бучанским пескам вызывает существенное повышение деформаций конструкции тоннелей, а также общие виброосадки в грунтовом основании. Кроме того, изменение физико-механических характеристик грунтов в пределах обделки тоннелей существенно влияет на уровень деформированного состояния самих обделок. Улучшение деформированного состояния обделок тоннелей на участках изменения характеристик грунтов окружающего массива (особенно подстилающих обделку) может быть достигнуто путем химического закрепления слабых грунтов. Состав растворов для закрепления слабых грунтов должен определяться на основе изучения их гранулометрического состава, показателей пористости и других физико-механических и физико-химических характеристик грунтов. **Научная новизна.** Обнаружена основная причина значительных деформаций на участке перехода от спондиловых глин к бучанским пескам, что объясняется явлением виброосадки водонасыщенного основания под тоннелем. **Практическая значимость.** Разработаны подходы по уменьшению деформаций при строительстве перегонных тоннелей на участке перехода от спондиловых глин к бучанским пескам, а также в зоне станции «Глыбочицкая» Киевского метрополитена.

Ключевые слова: виброосадка водонасыщенного основания; метод конечных элементов; напряженно-деформированное состояние; переход от спондиловых глин к бучанским пескам; анализ деформаций

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