теплоутилизационных установках и шахтном компрессоре при их совместной работе. Сравнительный эксергетический анализ систем утилизации тепла сжатого воздуха шахтных компрессорных установок.

Результаты. Выполнен эксергетический анализ теплонасосной, когенерационной технологий утилизации тепла шахтных компрессорных установок, а также технологии прямого нагрева. Установлено, что эксергетический КПД имеет наиболее высокое значение в случае когенерационной утилизации тепла, отводимого от сжимаемого воздуха, при работе теплосиловой установки по теплофикационному циклу.

Научная новизна. Впервые произведен детальный эксергетический анализ элементов систем утилизации тепла шахтных компрессорных установок с установлением наиболее термодинамически совершенной технологии использования низкопотенциального тепла.

Практическая значимость. Построены диаграммы потоков эксергий, позволяющие определить потери эксергии в каждом элементе системы утилизации тепла сжатого воздуха шахтных компрессорных установок.

Ключевые слова: *шахтный компрессор, эксергетический анализ, утилизация тепла, тепловой насос, когенерационная технология*

Рекомендовано до публікації докт. техн. наук В. І. Самусею. Дата надходження рукопису 21.05.15.

УДК 622.28 : 624.11

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GEOMECHANICAL ESTIMATION OF THE EFFECTIVENESS OF SEWER TUNNEL REPAIR BY THE "PIPE IN PIPE" TECHNOLOGY

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ГЕОМЕХАНІЧНА ОЦІНКА ЕФЕКТИВНОСТІ ВІДНОВЛЮВАНОГО РЕМОНТУ КОЛЕКТОРНИХ ТОНЕЛЕЙ МЕТОДОМ „ТРУБА У ТРУБІ"

Purpose. The development of analytical methods for forecasting the stress state of sewer tunnel linings, reconstructed by the "pipe in pipe" technology, including ones in dense urban areas, the use of which allows geomechanical estimation of bearing capacity of the reconstructed facilities in operation in various mining conditions for opening stability to fulfill.

Methodology. Obtaining rigorous solutions of the plane elasticity problems using the theory of analytic functions of a complex variable, conformal mapping method, apparatus of analytic continuation of complex potentials that are regular in the half-plane simulating the rock mass through its border, properties of Cauchy type integrals, Faber polynomials and complex series.

Findings. A mathematical model of the interaction of a sewer tunnel restored by the "pipe in pipe" technology, with the surrounding rock (soil) mass, as elements of a common deformable system that allows more thoroughly considering the impact of mining and geological conditions, external influences, as well as the basic design parameters of the lining produced due to repairs, on the bearing capacity and strength of the reconstructed underground structure as a whole.

Originality. A new approach to evaluating the effectiveness of repairing sewer tunnels, which is based on geomechanical criterion, obtained on a study of the stress state and bearing capacity of three-layer underground construction created by the "pipe in pipe" technology is proposed.

Practical value. The development of an algorithm for determining the stress state of shallow collector tunnel linings, restored by the trenchless technology, under the action of various external loads and impacts, as well as while developing a software that enables to make multivariant designs restore sewer tunnel linings, both for research purposes and in practical design.

Keywords: *sewer tunnel, trenchless repair technology, stress state, lining, bearing capacity, design*

Introduction. Sewer tunnels are a component of modern cities' communal infrastructure. Those structures usually have a circular cross-section and represent shallow underground structures constructed in dense housing. The technical conditions of exploitation of sewer tunnels have to satisfy special requirements in order to prevent any accidents due to filtration and outbreak of waste water into the environment, the consequences of which are estimated as environmental disasters.

The analysis of the causes of sewer tunnel damages shows that the main ones are the lining wearing process in the bottom due to the abrasive action of particles of drains and the corrosion of underground structures in the crown due to the corrosive gas atmosphere above the level of wastewater in the tunnels.

Objectives. In order to prevent accidents and extend the service life of sewers the trenchless "pipe in pipe" technology of rebuilding the worn tunnel linings has gained widespread use in recent years. The technology provides laying of a polyethylene pipe within the tunnel and filling in the cavity between the pipe and the existing tunnel lining applying special cement plugging. The lining restored in such a way represents a three-layer structure, the layers of which are made from different materials with appropriate deformation and strength characteristics. As a rule, the two outer layers of such lining have variable thickness (Fig. 1).

It should be noted that the methods of geomechanical predicting of the stress state of reconstructed sewer linings as three-layer underground structures and determining their bearing capacity during further operations, have not been developed yet. In this regard, studies aimed to create the corresponding analytical design method and identify the regularities of stress state formation in sewer tunnel linings, restored with the "pipe in pipe" technology have been carried out at Tula State University in recent years.

The design method proposed is realized on the base of modern concepts of underground structure mechanics concerning the interaction of underground structures and the surrounding rock mass as elements of a single deformable system. It is based on

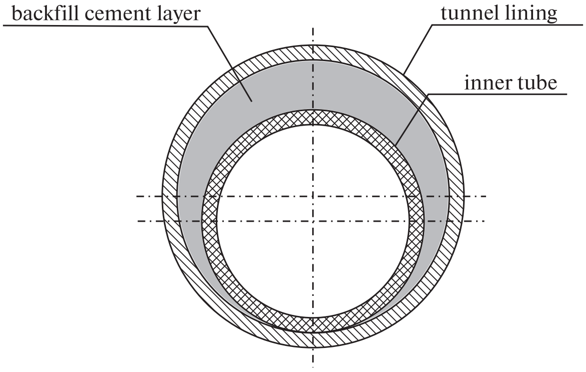

Fig. 1. The cross-section of tunnel lining after reconstruction by the "pipe in pipe" technology

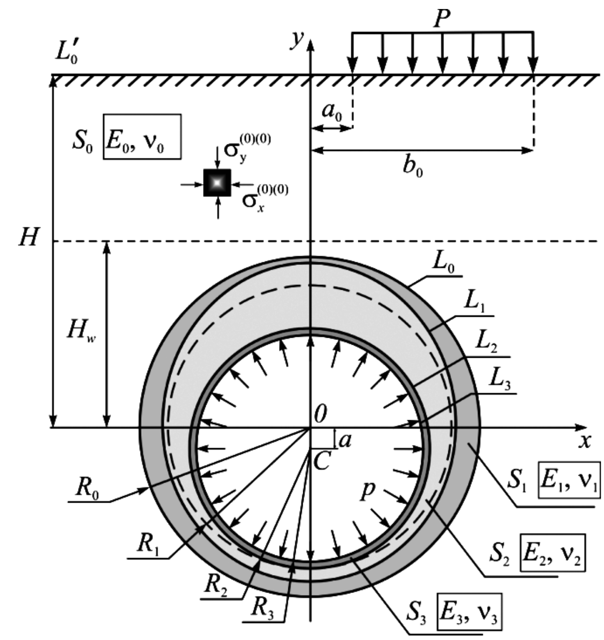

Fig. 2. The design scheme

analytic solutions of four corresponding flat stress problems, the overall design scheme of which is shown in Fig. 2.

Here the S_0 semi-infinite homogeneous linearly deformable weighty medium simulates the rock mass. The deformation properties of the S_0 medium are characterized by applying the E_0 deformation modulus and ν_0 Poisson's ratio. The S_0 area is limited by the L'_0 straight line and the L_0 circular hole which is supported by a three-layer ring S_j ($j = 1, 2, 3$) simulating the tunnel lining created as a result of the repair. The outer layer of the ring S_1 limited by the L_0 and the L_1 contours simulates the existing concrete tunnel lining. So, the L_0 contour has a circular shape with a radius R_0, whereas the shape of the L_1 contour is significantly different from the circular one due to local thickness reduction in the upper and in the bottom parts of the lining. The S_3 inner layer limited by the L_2, L_3 circular contours simulates the inner pipe. The common centre C of the L_2, L_3 circular contours is arranged on the vertical axis and has the $y_c = a$ coordinate. The intermediate layer S_2, bounded by the L_1, L_2 contours, simulates the backfill cement layer which is created during the repair between the existing concrete lining and the inner pipe. Materials of the S_j ($j = 1, 2, 3$) layers possess the corresponding values of the E_j, ν_j ($j = 1, 2, 3$) deformation characteristics.

Layers S_j ($j = 1, 2, 3$) of the ring and the S_0 medium deform together, i.e., the conditions of the displacement and full stress vector continuity are satisfied on the contact lines L_j ($j = 0, 1, 2$).

The gravitational forces due to soil's own weight (task 1) or the pressure of the underground water (task 2) of the level H_w, being measured from the axis of the tunnel, are modelled by the presence of S_j ($j = 0,$

1, 2) the appropriate fields of the initial stresses in the areas [1].

The L_3 inner boundary is free from external forces, or loaded with a uniform normal pressure p (task 3), which corresponds to considering the most dangerous operation mode of sewer tunnel during the spillway.

On the L_0' border of the half-plane the condition of external forces absence is satisfied, or, in the case of the load action on the surface caused by the weight of buildings, structures, and vehicles (task 4), the vertical uniformly distributed load P acting on an arbitrary part of the border is considered.

Presentation of the main research and explanation of scientific results. The solutions of elasticity theory problems have been obtained by applying methods of the theory of analytic functions of complex variables and the conformal mappings, the apparatus of analytic continuation of complex potentials, regular in the lower half-plane (which simulates the soil massif) into the upper half-plane through its straight boundary, properties of integrals of Cauchy type, Faber polynomials and complex series.

After introducing the Kolosov-Muskhelishvili complex potentials $\tilde{\varphi}_j(z),\ \tilde{\psi}_J(z)$ $(j=0,1,2,3)$, characterizing the stress-strain state of the respective areas, the transition to the boundary value problem of the theory of analytic functions of a complex variable is realised under the following boundary conditions for all considered tasks:

- at the L_0' boundary

$$\tilde{\varphi}_0(t)+t\overline{\tilde{\varphi}_0'(t)}+\overline{\tilde{\psi}_0(t)}=f_0^{(0)}(t); \tag{1}$$

- at the L_j ($j=0,\dots,2$) contours

$$\begin{aligned}&\tilde{\varphi}_{j+1}(t_j)+t_j\overline{\tilde{\varphi}_{j+1}'(t_j)}+\overline{\tilde{\psi}_{j+1}(t_j)}=\\&=\tilde{\varphi}_j(t_j)+t_j\overline{\tilde{\varphi}_j'(t_j)}+\overline{\tilde{\psi}_j(t_j)}+f_j(t_j);\\&æ_{j+1}\tilde{\varphi}_{j+1}(t_j)-t_j\overline{\tilde{\varphi}_{j+1}'(t_j)}-\overline{\tilde{\psi}_{j+1}(t_j)}=\\&=\frac{\mu_{j+1}}{\mu_j}\left[æ_j\tilde{\varphi}_j(t_j)-t_j\overline{\tilde{\varphi}_j'(t_j)}-\overline{\tilde{\psi}_j(t_j)}\right];\end{aligned} \tag{2}$$

- at the L_3 contour

$$\tilde{\varphi}_3(t_3)+t_3\overline{\tilde{\varphi}_3'(t_3)}+\overline{\tilde{\psi}_3(t_3)}=f_3(t_3), \tag{3}$$

where $æ_j=3-4\nu_j$; $\mu_j=\dfrac{E_j}{2(1+\nu_j)}$ ($j=0,\dots,3$); t_j is the affix of a point of the contour L_j ($j=0,\dots,3$); $f_j(t_j)$ ($j=0,\dots,3$) are the functions determined depending on the considered load (of the problem).

The $\tilde{\varphi}_j(z)$, $\tilde{\psi}_j(z)$ ($j=1,\dots,3$) complex potentials in the S_j ($j=1,\dots,3$) areas are represented in the form of

$$\begin{aligned}\tilde{\varphi}_j(z)&=\varphi_j(z)+L_j(z);\\ \tilde{\psi}_j(z)&=\psi_j(z)+M_j(z)\ (j=1,2,3),\end{aligned} \tag{4}$$

where the $\varphi_j(z)$, $\psi_j(z)$are the functions regular in corresponding areas S_j which turn to zero at infinity; $L_j(z)$, $M_j(z)$ are the functions of the form of

$$\left.\begin{aligned}L_j(z)&=-\frac{X^{(j)}+iY^{(j)}}{2\pi(1+æ_j)}\ln z\\ M_j(z)&=æ_j\frac{X^{(j)}-iY^{(j)}}{2\pi(1+æ_j)}\ln z\end{aligned}\right\},$$

here $X^{(j)}+iY^{(j)}=\oint_{L_j}\left(X_n^{(j)}+iY_n^{(j)}\right)ds=2K_j\pi i$ is the main vector of external forces distributed along the contour L_j ($j=0,\dots,3$), K_j is the real value, which is determined according to the external load considered, i is the imaginary unit.

Following the approach proposed by I. G. Aramanovich and successfully developed by prof. N. N. Fotieva [1], after performing the analytic continuation of complex potentials into the upper half-plane through the L_0' straight boundary, it is possible to come to representations similar to (4)

$$\left.\begin{aligned}\tilde{\varphi}_0(z)&=\varphi_0(z)-\frac{iK_0}{1+æ_0}\ln z\\ \tilde{\psi}_0(z)&=\psi_0(z)-\frac{iK_0æ_0}{1+æ_0}\ln z\end{aligned}\right\}.$$

Then with the help of the $z=\omega_j(\zeta_j)$ rational functions the conformal mapping of the exteriors of Γ_j unit circles in the domain of ζ_j variables onto the exteriors of the L_j ($j=0,\dots,3$) contours in the domain of z variable is performed. As a result, after the geometric dimensions were related to the R_0 value the mapping function can be written in the form

$$\left.\begin{aligned}&\tilde{z}=\frac{z}{R_0}=\omega_j(\zeta_j)=\\&=\begin{cases}\zeta_0 & \text{with}\ j=0\\ r_1\left(\zeta_1+\sum\limits_{\nu=0}^{n^*}\tilde{q}_\nu\zeta_1^{-\nu}\right) & \text{with}\ j=1\\ r_j\zeta_j+b & \text{with}\ j=2,3\end{cases}\end{aligned}\right\},$$

here $\tilde{q}_\nu$ ($\nu=1,\dots,n^*$) are the coefficients determined as a result of conformal mapping of the exteriors of unit circle onto the exterior of the L_1 contour (n^* is the number of terms of series being considered to ensure the accuracy of the mapping ; $r_j=\dfrac{R_j}{R_0}$ ($j=0,\dots,3$); $b=\dfrac{ia}{R_0}$.

The complex potentials which are to be determined are represented in the form of

$$\varphi_j(\tilde z)=\begin{cases}\sum_{\nu=1}^{\infty}a_\nu^{(1)(j)}\left[\zeta_j(\tilde z)\right]^{-\nu}+\\ +\delta_{0,j}\sum_{\nu=0}^{\infty}a_\nu^{(3)(j)}\left[\zeta_{j-1}(\tilde z)\right]^{\nu},(j=0,1,3)\\ \sum_{\nu=1}^{\infty}a_\nu^{(1)(j)}\left[\zeta_2(\tilde z)\right]^{-\nu}+\sum_{\nu=0}^{\infty}a_\nu^{(3)(j)}P_\nu^{(1)}(\tilde z);(j=2)\end{cases};$$

$$\psi_j(\tilde z)=\begin{cases}\sum_{\nu=1}^{\infty}a_\nu^{(2)(j)}\left[\zeta_j(\tilde z)\right]^{-\nu}+\\ +\delta_{0,j}\sum_{\nu=0}^{\infty}a_\nu^{(4)(j)}\left[\zeta_{j-1}(\tilde z)\right]^{\nu},(j=0,1,3)\\ \sum_{\nu=1}^{\infty}a_\nu^{(2)(j)}\left[\zeta_2(\tilde z)\right]^{-\nu}+\sum_{\nu=0}^{\infty}a_\nu^{(4)(j)}P_\nu^{(1)}(\tilde z);(j=2)\end{cases}.$$

Here the notation $\delta_{k,s}=\begin{cases}1, & \text{with } k<s\\ 0, & \text{with } k\ge s\end{cases}$ is applied; $P_\nu^{(1)}(z)$ (n=0,...,) are the Faber polynomials for the inner area limited by the L_1 non-circular contour.

Thus, the further solution is based on the development of the approach proposed by G. M. Ivanov [3], according to which the following notations are introduced

$$\left.\begin{aligned}\varphi_j(z)=\varphi_j\left[\omega_p(\zeta_p)\right]=\varphi_{j,p}(\zeta_p)\\ \psi_j\left[\omega_p(\zeta_p)\right]=\psi_{j,p}(\zeta_p)\\ L_j(z)=L_{j,p}(\zeta_p);\quad M_j(z)=M_{j,p}(\zeta_p)\end{aligned}\right\}.$$

Here j = 1, 2, 3.

In order to keep the generality of writing expressions for the potentials characterizing the stress-strain state of the S_0 area the $\varphi_0(z)=\varphi_{0,0}(z)=\varphi_{0,0}(\zeta_0)$, $\psi_0(z)=$ $=\psi_{0,0}(z)=\psi_{0,0}(\zeta_0)$ representations are applied.

Thus, taking into account the expression of $\psi_j(t_j)=$ $=\sigma=e^{i\theta}$ for the contours L_j (j = 0, ..., 3) the next formulae can be written

$$\left.\begin{aligned}\phi_{j,p}(\sigma)=\sum_{k=1}^{\infty}c_k^{(1)(j,p)}\sigma^{-k}+\sum_{k=0}^{\infty}c_k^{(3)(j,p)}\sigma^{k}\\ \psi_{j,p}(\sigma)=\sum_{k=1}^{\infty}c_k^{(2)(j,p)}\sigma^{-k}+\sum_{k=0}^{\infty}c_k^{(4)(j,p)}\sigma^{k}\\ (j=0,\dots,3;p=j,j+1;p\le 3)\end{aligned}\right\},\qquad(5)$$

here the $c_k^{(r)(j,p)}$ coefficients are expressed in the terms of the $a_k^{(r)(j)}$ as it is done in the paper [2].

As a result, the boundary conditions at the transformed domain (1–3) are written as follows

$$\left.\begin{aligned}&\overline{\varphi_{j+1,j}}\left(\frac{1}{\sigma}\right)+\Omega_j\varphi'_{j+1,j}(\sigma)+\psi_{j+1,j}(\sigma)=\\ &=\overline{\varphi_{j,j}}\left(\frac{1}{\sigma}\right)+\Omega_j\varphi'_{j,j}(\sigma)+\psi_{j,j}(\sigma)-\tilde\Lambda_j(\sigma)\\ &(j=0,1,2)\end{aligned}\right\};\qquad(6)$$

$$\left.\begin{aligned}&æ_{j+1}\overline{\varphi_{j+1,j}}\left(\frac{1}{\sigma}\right)-\Omega_j\varphi'_{j+1,j}(\sigma)-\psi_{j+1,j}(\sigma)=\\ &=\frac{\mu_{j+1}}{\mu_j}\left[æ_j\overline{\varphi_{j,j}}\left(\frac{1}{\sigma}\right)-\Omega_j\varphi'_{j,j}(\sigma)-\psi_{j,j}(\sigma)\right]-\tilde\Theta_j(\sigma)\\ &\overline{\varphi_{3,3}}\left(\frac{1}{\sigma}\right)+\Omega_3\varphi'_{3,3}(\sigma)+\psi_{3,3}(\sigma)=\tilde\Lambda_3(\sigma)\end{aligned}\right\},\qquad(7)$$

wherein the $\Omega_j(\sigma)=\dfrac{\overline{\omega_j(\sigma)}}{\omega'_j(\sigma)}$ representation is applied, while the $\tilde\Lambda_j(\sigma),\tilde\Theta_j(\sigma)$ (j = 0, 1, 2, 3) functions are determined depending on the considered kind of the load (of the problem) [3].

Thus, each problem (from the 4 ones considered) reduces to the determination of 7 pairs of the functions, from the conditions (6, 7). A special feature of the described solution is that it reduces to the well convergent iterative process with the consideration of the corresponding task for a three-layered ring in the entire plane provided available additional terms in the boundary conditions which reflect the presence of the boundary of the half-plane in each iteration.

At the beginning of the iteration process these additional terms represented as Laurent series are zeroed and then they are corrected in further iterations. The iterative process continues as long as the differences between the $c_k^{(1)(0)}$ (k = 1,..., N); $c_k^{(2)(0)}$ (k = 1,..., N + + 2); $c_k^{(j)(s)}$ (j = 1, 4; k = 1,..., N); $c_k^{(j)(s)}$ (j = 2, 3; k = = 1,..., N + 2) coefficients of correspondingly shortened infinite series (11) obtained in two next approximations do not become less than a predetermined small value e, for example, $\varepsilon=10^{-6}$.

After the unknown coefficients of the series (5) were calculated, the stresses in the S_j (j = 1, 2, 3) layers simulating the lining, and in the S_0 area simulating the soil mass are determined using the Kolosov-Muskhelishvili formulas. In order to verify the accuracy of the solution obtained, the control of the satisfaction of the boundary conditions (6, 7) is performed. If this satisfaction does not feature sufficient accuracy, the N number of the terms in the infinite series which are used in calculations has to be increased (thus, as experience shows, the retention in series N = 30 of terms provides sufficient accuracy for practical purposes), and the e value, on the contrary, has to be decreased.

The solution described is implemented in the form of full algorithm, on the basis of which appropriate computer software for stress state evaluation of sewer tunnel linings is developed with the purpose of the geomechanical assessment of the effectiveness of reconditioning using the technology of “pipe in pipe”.

In order to consider the approximate effect of the stresses formed in the lining before the repair works, the α^* correction factor [3] determined on the basis of the data of field measurements is entered into the results of the designing the underground construction to be recovered regarding the soil's own weight and the weight of the buildings before the reconstruction of the tunnel.

The spatial character of the problem, due to the limited size of the buildings or structures in the direction of the axis of the tunnel, is taken into account, using the *k* correction factor entered into the results of the calculation. This correction factor is defined as the ratio of vertical stress at the point of elastic half-space corresponding to the lining centre cross-section caused by surface load distributed over a rectangular area calculated using the formula by Love and according to the relevant strip of infinite length (i. e. plane strain).

If the surface load considered simulates the weight of a moving vehicle, the stresses determined as the results of solving the problem described, are to be multiply by the appropriate dynamic factor, which is calculated by the well-known formula as the function of speed of a vehicle. In the case when the vehicle is moving in a direction perpendicular to the axis of the tunnel the stress state of the lining is determined on the basis of multivariant calculations for different load positions relative to the tunnel and it is necessary to plot two envelop diagrams corresponding to the maximum values of tensile (positive) and compressive (negative) normal tangential stresses.

The viscoelastic deformation of soil is considered on the base of the linear hereditary creep theory with the use of the variable modules method, according to which the deformation characteristics of soil are presented as the time-varying functions.

The results obtained according to the method described are to be summarized with the stresses in the lining caused by other types of acting loads (in the most unfavourable combinations), and then the bearing capacity of the lining is checked.

The example of the design. As an example to illustrate the proposed method, the results of the designing the lining of sewer tunnel recovered using the method of "pipe-in-pipe" are presented below. The action of the load on the surface acting after the repair work in the tunnel was considered. The following inputs were accepted: E_0 = 50 MPa, ν_0 = 0.35; E_1 = = 20 000 MPa, ν_1 = 0.2; E_2 = 10 000 MPa, ν_2 = 0.2; E_3 = = 400 MPa, ν_3 = 0.4. The case of the most unfavourable load position regarding the lining stress state, is considered with the parameters a_0 = 0 and b_0 =10 m. The non-circular shape of the L_1 outline adopted reflects the presence of zones of local failure due to corrosion and deterioration of the concrete lining in service.

The results of the design are shown in Fig. 3 in the form of the $\sigma_\theta^{(in)}/(Pk)$ dimensionless diagrams of normal tangential stresses obtained for the outer and inner contours of each layer lining. For comparison, here the dash lines show the corresponding stress distribution in the tunnel lining, which is located at a lesser depth H = 5 m (the values are in brackets).

As it can be seen from the results presented, in the lining considered there are not only compressive but comparable in magnitude tensile normal tangential

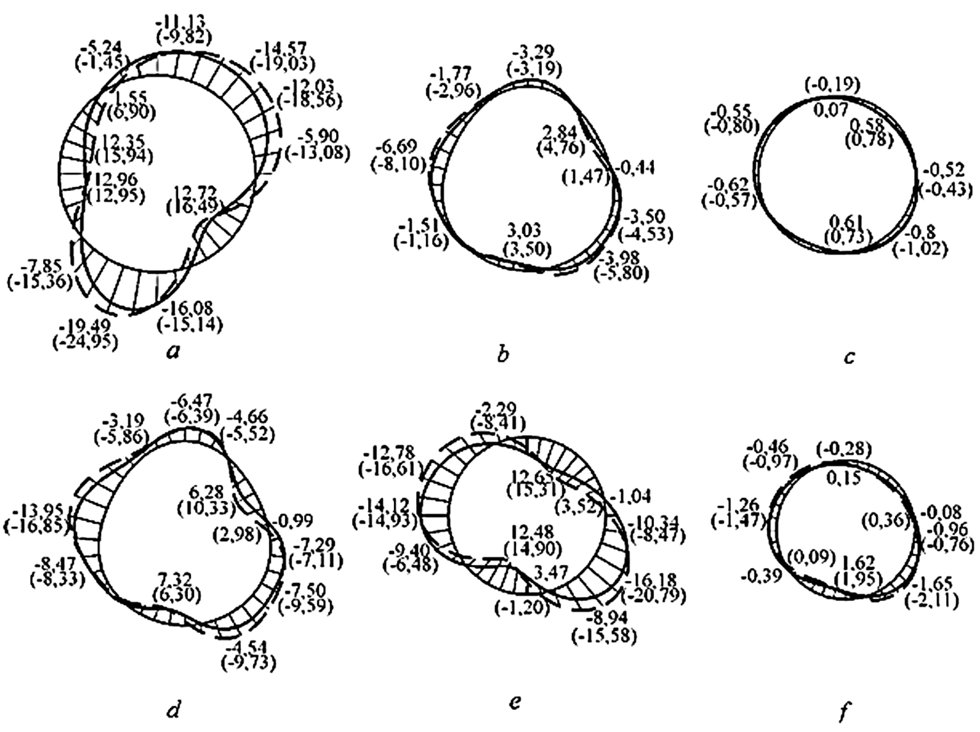

Fig. 3. Normal tangential stresses arising on the external (a, b, c) and internal (d, e, f) outlines of the: outer tunnel lining (a, d), backfill cement layer (b, e) and inner tube (c, f) caused by the load on the surface

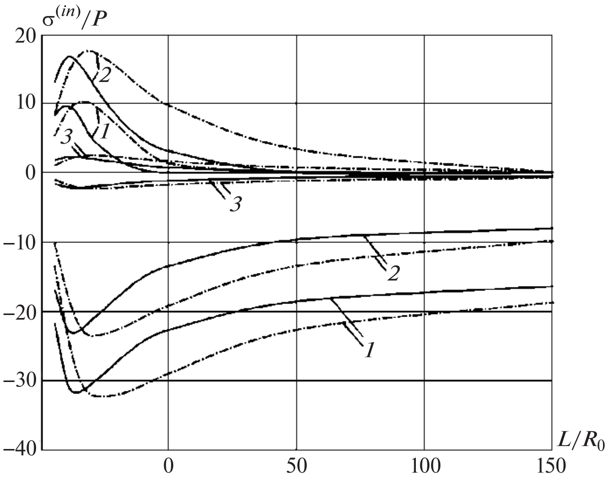

Fig. 4. The extremal normal tangential stresses dependences on the width of the surface load in the reconstructed tunnel lining:

1 — before repair; 2 — in backfill cement layer; 3 — in the inner tube

stresses. It can be also noted that the stresses in the inner tube are significantly lower than in other layers of the reconstructed underground construction.

Using the developed computer software multiple calculations were made and the basic regularities of stress state formation in the 3-layer tunnel lining, created as a result of repair, under various external influences were stated. So, the dependencies of the extremal (maximum compressive and tensile) normal tangential stresses arising at the points of internal cross-sectional contour of each layer under consideration lining on the main influencing factors were examined including the ratio of the modules of deformation of soils and lining layers materials, the depth of the tunnel, the position of the centre of the inner tube relative to the axis tunnel, the position and width of the loading area on the surface.

Fig. 4 illustratively shows the dependences of extremal normal tangential stresses at the points of the internal contours of the underground structure described above existing before the repair (curves *1*) in backfill cement layer (curve *2*) and in the inner tube (curve *3*) on the L/R_0 width loading surface applied after the reconstruction of the tunnel symmetrically about its axis. We consider two cases, corresponding to the depth of the tunnel $H/R_0 = 5$ (solid lines) and $H/R_0 = 10$ (dash lines).

As it can be seen from Fig. 4, all dependencies of the stresses on the width of the surface load possess an extremal nature, while, as before, the stresses in the inner tube are small and only marginally affected.

In general, the analysis of the formation of the stress state of linings of sewer tunnels, reconstructed by the "pipe in pipe" technology using the method proposed can indicate in each case a position of the inner pipe cross-section relative to the axis of the tunnel, which can significantly (up to 50 %) reduce the extremal values stresses in all layers of the lining. This fact should be taken into account while designing the repair work in sewer tunnels.

Conclusions. In conclusion it should be noted that the proposed analytical method and the installed laws of stress state formation in the reconstructed underground structures in different mining conditions for the geomechanical substantiation of engineering solutions, associated with the restoration of sewers tunnels stability are essential.

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Мета. Розробка аналітичного методу оцінки напружено-деформованого стану кріплення колекторних тунелів, що реконструюються методом „труба у трубі", у тому числі — в умовах щільної міської забудови, використання якого дозволяє здійснювати геомеханічний прогноз несучої здатності відновлених споруд у процесі експлуатації в різних гірничо-технічних умовах для забезпечення стійкості виробок.

Методика. Полягає в отриманні аналітичних рішень пласких задач теорії пружності з використанням теорії аналітичних функцій комплексної змінної, методу конформного відображення, апарату аналітичного продовження комплексних потенціалів, що є регулярними у півплощині, властивостей інтегралів типу Коші, поліномів Фабера та комплексних рядів.

Результати. Розроблена математична модель взаємодії кріплення колекторного тунелю, що відновлений методом „труба у трубі", з навколишнім масивом порід (грунтом), як елементів єдиної деформованої системи. Це дозволяє більш повно враховувати вплив гірничо-геологічних умов, зовнішніх впливів, а також основних конструктивних параметрів кріплення, що створене в результаті ремонту, на несучу здатність і міцність реконструйованої підземної споруди в цілому.

Наукова новизна. Запропоновано новий підхід до оцінки ефективності відновлювального ремонту колекторних тунелів, в основу якого покладено геомеханічний критерій, що базується на дослідженні напруженого стану та несучої здатності кріплення, яке створене методом „труба у трубі" та розглянуте як тришарова підземна конструкція.

Практична значимість. Полягає в розробці алгоритму визначення напруженого стану кріплення колекторного тунелю неглибокого закладення, відновленого методом „труба у трубі", за різних навантажень і впливів, а також у створенні програмного забезпечення, що дозволяє виконувати багатоваріантні розрахунки відновлених колекторних тунелів як у дослідницьких цілях, так і при практичному проектуванні.

Ключові слова: *колекторний тунель, відновлювальний ремонт, безтраншейна технологія, кріплення, напружений стан, несуча здатність, розрахунок*

Цель. Разработка аналитического метода оценки напряженного состояния обделок коллекторных тоннелей, реконструируемых методом „труба в трубе", в том числе – в условиях плотной городской застройки, использование которого позволяет осуществлять геомеханический прогноз несущей способности восстановленных сооружений в процессе эксплуатации в различных горно-технических условиях для обеспечения устойчивости выработок.

Методика. Включает получение аналитических решений плоских задач теории упругости с использованием теории аналитических функций комплексного переменного, метода конформного отображения, аппарата аналитического продолжения комплексных потенциалов, регулярных в полуплоскости, моделирующей массив пород, через ее границу, свойств интегралов типа Коши, полиномов Фабера и комплексных рядов.

Результаты. Разработана математическая модель взаимодействия восстановленной методом „труба в трубе" обделки коллекторного тоннеля с окружающим массивом пород (грунта), как элементов единой деформируемой системы. Это позволяет более полно учитывать влияние горно-геологических условий, внешних воздействий, а также основных конструктивных параметров обделки, создаваемой в результате ремонта, на несущую способность и прочность реконструированного подземного сооружения в целом.

Научная новизна. Предложен новый подход к оценке эффективности восстановительного ремонта коллекторных тоннелей, в основу которого положен геомеханический критерий, базирующийся на исследовании напряженного состояния и несущей способности, создаваемой методом „труба в трубе", обделки как трехслойной подземной конструкции.

Практическая значимость. Заключается в разработке алгоритма определения напряженного состояния обделки коллекторного тоннеля мелкого заложения, восстановленного методом „труба в трубе", при различных нагрузках и воздействиях, а также в создании программного обеспечения, позволяющего производить многовариантные расчеты обделок восстановленных коллекторных тоннелей как в исследовательских целях, так и при практическом проектировании.

Ключевые слова: *коллекторный тоннель, восстановительный ремонт, бестраншейная технология, обделка, напряженное состояние, несущая способность, расчет*

Рекомендовано до публікації докт. техн. наук О. О. Сдвижковою. Дата надходження рукопису 09.04.15.