Design of mine working support constructed in preliminary grouted rock mass upon the underground water pressure

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ABSTRACT

The method of designing mine working support constructed in the preliminary grouted rock mass upon the action of the underground water pressure taking into account the water percolation through the grouted rock zone and the support having different forms of their cross-sections is proposed in the paper presented.

INTRODUCTION

A preliminary grouting (Kipko, Polozov at al., 1984) consisting in the injection of a clay-cement solution through a series of inclined bore-holes from the earth surface or from the opening face is being applied at construction of vertical mine shafts and horizontal mine workings in fissured watered rock mass with the aim of water suppression. As a result a hydroisolating curtain is being formed around the opening the material of which possesses deformation and permeability characteristics different from those of the rest of the rock mass. If the massif has a directed fracturing the form of the curtain cross-section around a mine shaft is near to the elliptical one (Kipko, Polozov et al., 1984). In case of horizontal working that curtain may have the irregular form.

The presence of a curtain leads to a redistribution of the residual heads of underground water percolating through the grouted rock zone and through the support and may render a substantial influence on the working support stress state. With the aim of stress analysis the method of designing shafts linings erected with the application of fissured rocks preliminary grouting has been proposed by Fotieva and Savin (1988). The method was based on the investigation of interacting the shaft lining and the surrounding rock mass including the elliptical grouted zone as parts of the integrated deformable system undergoing the action of gravitational forces and residual heads of water infiltrating through the grouted zone and the lining.

On the base of the approach mentioned above the method of designing the support of horizontal mine workings of an arbitrary cross-section shape constructed with the application of preliminary grouting has been developed. The method allows the stress state of the support caused by gravitational forces and by the underground water head taking into account the possible water infiltration through the grouted zone and support to be determined.

THE METHOD OF THE DESIGN

The method is based on the analytic solution of the elasticity theory plane contact problem for a ring of a non-circular shape simulating the working support surrounded by the field of an arbitrary form simulating the grouted rock zone in a linearly deformable infinite medium simulating the rock mass.

The design scheme is given in Figure 1.

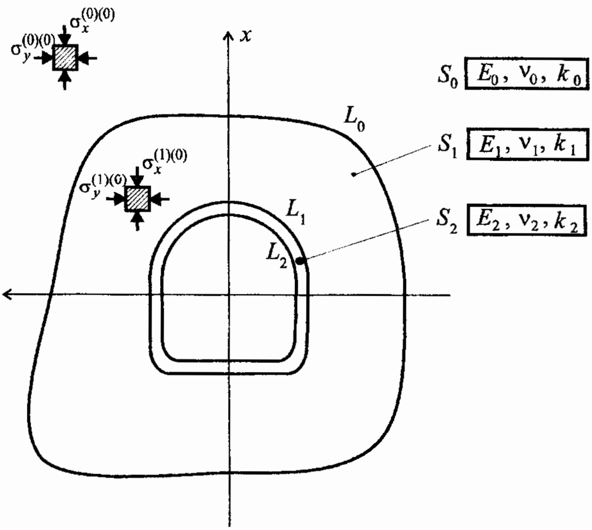


Figure 1: The design scheme

Here the S_0 infinite medium characterised by the E_0 deformation modulus, ν_0 Poisson's ratio and k_0 filtration coefficient simulates the rock mass. The S_1 area restricted by two different curves (the L_1 is the external outline of the non-circular support cross-section, the L_0 is the border of a grouted zone) possessing the corresponding E_1, ν_1 and k_1 characteristics simulates the rock zone strengthened by grouting. The inner S_2 area the material of which has the E_2. ν_2 and k_2

characteristics simulates the working support.

The action of the rock's own weight is simulated by a presence in the S_0, S_1 areas of the initial stresses

$$\sigma_x^{(0)(0)} = \sigma_x^{(1)(0)} = -\gamma H\alpha^*, \quad \sigma_y^{(0)(0)} = \sigma_y^{(1)(0)} = -\lambda\gamma H\alpha^*, \quad \tau_{xy}^{(0)(0)} = \tau_{xy}^{(1)(0)} = 0 \tag{1}$$

where γ is the rock unit weight, H is the depth of the working, α^* is the correcting multiplier introduced for an approximate registration of the l_0 distance between the support being constructed and the working face determined by empirical formula (Manual... 1983):

$$\alpha^* = \exp(-1.3 l_0 / R_1) \tag{2}$$

where R_1 is the average radius of the working.

The action of the underground water pressure (its change with the height of the grouted zone at great heads is not taken into account) is simulated by assignment of initial stresses in the S_0 and S_1 fields equal to the residual heads of percolating water. Those initial stresses are determined by formulae (Manual... 1983):

- in S_0 area

$$\sigma_x^{(0)(0)} = \sigma_y^{(0)(0)} = -\gamma_w H_w \frac{\frac{1}{k_2}\ln\frac{R_1}{R_2} + \frac{1}{k_1}\ln\frac{R_0}{R_1}}{\frac{1}{k_2}\ln\frac{R_1}{R_2} + \frac{1}{k_1}\ln\frac{R_0}{R_1} + \frac{1}{k_0}\ln\frac{R_t}{R_0}} \tag{3}$$

- in S_1 area

$$\sigma_x^{(1)(0)} = \sigma_y^{(1)(0)} = -\gamma_w H_w \frac{\frac{1}{k_2}\ln\frac{R_1}{R_2}}{\frac{1}{k_2}\ln\frac{R_1}{R_2} + \frac{1}{k_1}\ln\frac{R_0}{R_1} + \frac{1}{k_0}\ln\frac{R_t}{R_0}} \tag{4}$$

where γ_w is the water specific weight, H_w is the underground water level being counted out from the centre of co-ordinates; R_0, R_1, R_2 are average radii of the L_0, L_1, L_2 outlines correspondingly; R_t is an agreed radius of feeding (Manual... 1983).

The S_0, S_1 and S_2 fields undergo compatible deformations, i.e. the conditions of continuity of displacements and total stress vectors are fulfilled on the L_j $(j = 0,1)$ boundaries. The L_2 internal boundary is not loaded.

The contact problem has been solved with the application of the complex variable analytic functions theory (Muskhelishvili 1966) using the apparatus of conform mapping, Faber's polynomes and complex series.

Total stresses are given in the form of sums of initial stresses (1) or (3),(4) and additional stresses appearing due to the presence of the opening; displacements are considered only the additional ones.

On the complex potentials $\varphi_j(z)$, $\psi_j(z)$ $(j = 0, 1, 2)$ regular in corresponding spheres S_j $(j = 0, 1, 2)$ and being turned to zero upon infinity (combined with additional stresses and displacements by the Kolosov-Muskhelishvili formulae) being introduced, the contact problem is reduced to the solution of the boundary problem of the complex variable analytic functions theory.

With the aid of the rational function of the kind

$$z = \omega_j(\zeta_j) = \widetilde{R}_j\left(\zeta_j + \sum_{\nu=0}^{s} m_\nu^{(j)} \zeta_j^{-\nu}\right) \quad (j = 0, 1, 2) \tag{5}$$

conform transformations of the $\widetilde{R}_j = 1$ radii circles exteriors upon the exteriors of the L_j $(j = 0, 1, 2)$ outlines are made.

Complex potentials $\varphi_j(z)$, $\psi_j(z)$ $(j = 0, 1, 2)$ are represented in the form (Ivanov 1972):

$$\varphi_0(z) = \sum_{\nu=1}^{\infty} a_\nu^{(1)(0)} [\zeta_0(z)]^{-\nu}; \qquad \psi_0(z) = \sum_{\nu=1}^{\infty} a_\nu^{(2)(0)} [\zeta_0(z)]^{-\nu}; \tag{6}$$

$$\begin{aligned} \varphi_{j+1}(z) &= \sum_{\nu=1}^{\infty} a_\nu^{(1)(j+1)} \left[\zeta_{j+1}(z)\right]^{-\nu} + \sum_{\nu=0}^{\infty} a_\nu^{(3)(j+1)} P_\nu^{(j)}(z); \\ & \qquad\qquad\qquad\qquad\qquad\qquad (j = 0, 1) \\ \psi_{j+1}(z) &= \sum_{\nu=1}^{\infty} a_\nu^{(2)(j+1)} \left[\zeta_{j+1}(z)\right]^{-\nu} + \sum_{\nu=0}^{\infty} a_\nu^{(4)(j+1)} P_\nu^{(j)}(z); \end{aligned} \tag{7}$$

where $P_\nu^{(j)}(z)$ are Faber's polynoms for interiors of fields S_j $(j = 1, 2)$ restricted by outlines L_j $(j = 0, 1, 2)$.

Following Ivanov (1972) we signify

$$\varphi_j[\omega_k(\zeta_k)] = \varphi_{j,k}(\zeta_k), \quad \psi_j[\omega_k(\zeta_k)] = \psi_{j,k}(\zeta_k), \quad \Omega_j(\sigma) = \frac{\omega_j(\sigma)}{\overline{\omega'(\sigma)}}, \quad \sigma = e^{i\theta}. \tag{8}$$

Then taking into account that $\zeta_k(t_k) = \sigma$ on boundaries L_k $(k = 0, 1, 2)$ one can obtain representations of the complex potentials $\varphi_{j,k}(\sigma)$, $\psi_{j,k}(\sigma)$ $(k = j-1, j)$.

Decomposing polynomes $P_k^{(j)}(t_{j+1})$ into the series of Faber's polynomes $P_n^{(j+1)}(\sigma)$ for inner fields (Ivanov 1972) and functions $\left[\zeta_{j+1}(z)\right]^{-k}$ $(k = 1,\ldots,\infty)$ into the series of $\left[\zeta_j(z)\right]^{-n}$ functions we have

$$\varphi_{p,j}(\sigma)=\sum_{k=1}^{\infty}c_k^{(1)(p,j)}\sigma^{-k}+\sum_{k=0}^{\infty}c_k^{(3)(p,j)}\sigma^{k},$$

$$(j=0,\ 1,\ 2;\ p=j,j+1;\ p\le 2) \qquad (9)$$

$$\psi_{p,j}(\sigma)=\sum_{k=1}^{\infty}c_k^{(2)(p,j)}\sigma^{-k}+\sum_{k=0}^{\infty}c_k^{(4)(p,j)}\sigma^{k},$$

where coefficients $c_k^{(r)(p,j)}$ are determined through the $a_k^{(r)(j)}$ coefficients and $c_k^{(3)(0,0)}=c_k^{(4)(0,0)}=0$.

Taking into account the relationships (8) boundary conditions of the problem set forth in the transformed sphere and written in the following way $(j=0,\ 1)$:

$$\bar{\varphi}_{j+1,j}\left(\frac{1}{\sigma}\right)+\bar{\Omega}_j\left(\frac{1}{\sigma}\right)\varphi'_{j+1,j}(\sigma)+\psi_{j+1,j}(\sigma)=\bar{\varphi}_{j,j}\left(\frac{1}{\sigma}\right)+\bar{\Omega}_j\left(\frac{1}{\sigma}\right)\varphi'_{j,j}(\sigma)+\psi_{j,j}(\sigma)$$

$$-\gamma_w H_w p_j\bar{\omega}_j\left(\frac{1}{\sigma}\right)-\lambda_{j,1}\gamma H\alpha^*\left[\frac{1+\lambda}{2}\bar{\omega}_j\left(\frac{1}{\sigma}\right)+\frac{1-\lambda}{2}\omega_j(\sigma)\right] \qquad (10)$$

$$x_{j+1}\bar{\varphi}_{j+1,j}\left(\frac{1}{\sigma}\right)-\bar{\Omega}_j\left(\frac{1}{\sigma}\right)\varphi'_{j+1,j}(\sigma)-\psi_{j+1,j}(\sigma)=\frac{\mu_{j+1}}{\mu_j}\left[x_j\bar{\varphi}_{j,j}\left(\frac{1}{\sigma}\right)-\bar{\Omega}_j\left(\frac{1}{\sigma}\right)\varphi'_{j,j}(\sigma)-\psi_{j,j}(\sigma)\right]$$

(11)

$$\bar{\varphi}_{2,2}\left(\frac{1}{\sigma}\right)+\bar{\Omega}_2\left(\frac{1}{\sigma}\right)\varphi'_{2,2}(\sigma)+\psi_{2,2}(\sigma)=0 \qquad (12)$$

where

$$x_i=3-4\nu_i,\ \mu_i=\frac{E_i}{2(1+\nu_i)}\quad(i=0,\ 1,\ 2),\quad \lambda_{i,k}=\begin{cases}1 & \text{at } i=k\\ 0 & \text{at } i\neq k\end{cases};$$

$$p_0=\frac{\frac{1}{k_1}\ln\frac{R_0}{R_1}}{\frac{1}{k_2}\ln\frac{R_1}{R_2}+\frac{1}{k_1}\ln\frac{R_0}{R_1}+\frac{1}{k_0}\ln\frac{R_t}{R_0}};\quad p_1=\frac{\frac{1}{k_2}\ln\frac{R_1}{R_2}}{\frac{1}{k_2}\ln\frac{R_1}{R_2}+\frac{1}{k_1}\ln\frac{R_0}{R_1}+\frac{1}{k_0}\ln\frac{R_t}{R_0}}; \qquad (13)$$

If the permeability coefficient of the rocks in natural state is $k_0>10^{-4}\,m/\sec$ then the following formulae may be applied to determine the p_0 and p_1 values:

$$p_0=\frac{\frac{1}{k_1}\ln\frac{R_0}{R_1}}{\frac{1}{k_2}\ln\frac{R_1}{R_2}+\frac{1}{k_1}\ln\frac{R_0}{R_1}};\quad p_1=1-p_0. \qquad (14)$$

In the particular case when water percolating through the grouted zone is absent $(k_1 = 0)$ then from formula (14) we receive $p_0 = 1$, $p_1 = 0$; and if water seepage through the support is absent $(k_2 = 0)$ we have $p_0 = 0$, $p_1 = 1$.

Substituting series (9) into the (10), (11) boundary conditions and equating the coefficients at the same degrees of the σ variable to each other in the left and right parts of the equations obtained we have the relationships combining the coefficients $c_k^{(s)(j+1,j)}$ with coefficients $c_k^{(s)(j,j)}$ $(s = 1,\ldots,4; j = 0, 1; k = 1,\ldots,\infty)$. Then on expressing coefficients $c_k^{(s)(j+1,j+1)}$ through corresponding coefficients $c_k^{(s)(j+1,j)}$ $(s = 1,\ldots,4; j = 0, 1; k = 1,\ldots,\infty)$ we obtain relationships combining coefficients $c_k^{(s)(2,2)}$ of the expansions of potentials $\varphi_{2,2}(\sigma)$, $\psi_{2,2}(\sigma)$ with coefficients $c_k^{(s)(0,0)}$ of potentials $\varphi_{0,0}(\sigma)$, $\psi_{0,0}(\sigma)$. Substituting those relationships into the last boundary condition (12) on the internal outline L_2 we come to the infinite system of linear algebraic equations relative to unknown coefficients $c_\nu^{(s)(0,0)}$ $(s = 1, 2; \nu = 1,\ldots,\infty)$. On solving above system being correspondingly restricted and applying the relationships mentioned above the stress state of the S_2 field simulating the working support may be determined by the Kolosov-Muskhelishvili formulae.

A final calculation algorithm has been developed on the basis of the solution obtained. The computer programme has been created.

Results of designing concrete support of horizontal mine working located in zone of tectonic breaks are given below.

THE EXAMPLE OF THE DESIGN

The form and sizes of the support and clay-cement curtain cross-section are given in Figure 2, a, b correspondingly.

The input data are the following: $E_0 = 640\,MPa$, $\nu_0 = 0.48$; $E_1 = 18400\,MPa$, $\nu_1 = 0.31$; $E_2 = 30000\,MPa$, $\nu_2 = 0.15$; $H = 230m$, $\gamma = 24kN/m^3$, $\lambda = 0.92$, $l_0 = 2m$, $H_w = 156m$, $\gamma_w = 10kN/m^3$; $k_0 = 0.01m/\text{sec.}$, $k_1 = 5\cdot 10^{-7}\,m/\text{sec.}$, $k_2 = 0.183\cdot 10^{-7}\,m/\text{sec.}$

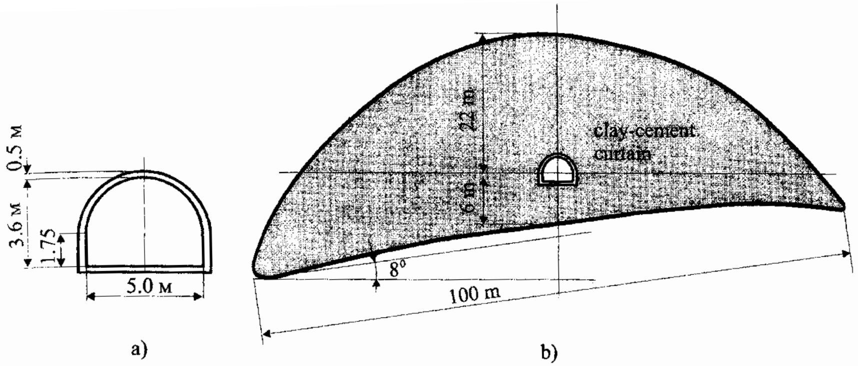


Figure 2: Cross-sections of the support and clay-cement curtain

Diagrams of $\sigma_\theta^{(ex)}$, $\sigma_\theta^{(in)}$ normal tangential stresses (in *MPa*) upon the external and internal outlines of the support cross-section correspondingly are shown by dash lines in Figure 3, a, b.

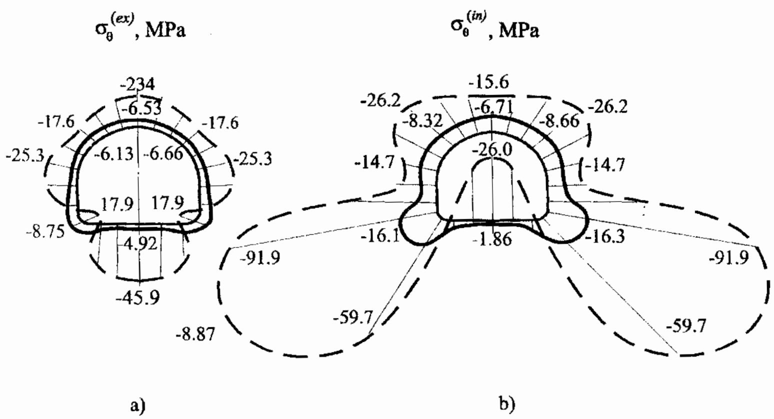
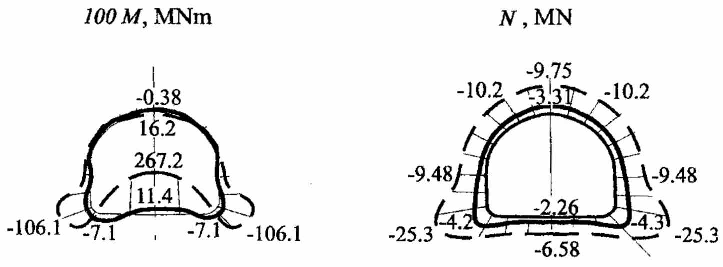


Figure 3: Diagrams of $\sigma_\theta^{(ex)}$, $\sigma_\theta^{(in)}$ normal tangential stresses

Diagrams of the M bending moments and N longitudinal forces in support cross-sections are given by dash lines in Figure 4, a, b.



a) b)

Figure 4. Diagrams of M bending moments and N longitudinal forces

For comparison the stresses and forces diagrams in the same support constructed without the application of grouting are shown in Figures 3, a, b, 4, a, b by dotted lines.

The results obtained show that in a number of cases taking into account the presence of strengthened zone around a working the structures may be lighten considerably by reducing their thickness or percentage of reinforcement.

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