ГЕОМЕХАНИКА. РАЗРУШЕНИЕ ГОРНЫХ ПОРОД

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Design of fully grouted rock bolts – a reinforcement concept: analytical and numerical calculation

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Abstract

Introduction. *Among the common support systems in tunnelling and mining, rock bolts have been widely used to reinforce rock mass and also to reduce geological hazards. Furthermore rock bolts can be applied under varying different geological conditions with cost-effectiveness. Although different methods are developed for grouted rock bolts design until now, the interaction mechanism of the rock bolts and rock mass is still very complicated issue.*

Methods of research. *The paper addresses a simple analytical model and numerical simulation for the analysis and design of fully grouted rock bolts based on the reinforcement principle. According to this concept the jointed rock mass reinforced by grouted rock bolts is considered as composite material which includes rock mass, the grout material and the bolt shank. The mechanical properties of this composite material depend on the ratio of the components. The closed-form solution was developed based on the assumption that the rock mass around a circular tunnel remained elastic after installing fully grouted rock bolts.*

Results. *The main parameters of the rock-bolt system (the diameter and length of bolt shank, the space between the bolts) are then easily estimated from the obtained solution. For non-circular tunnel, the numerical simulation is performed to show how the design of rock bolts could be done by using numerical methods.*

Keywords: *grouted rock bolts; analytical model; rock reinforcement; bolt density; circular tunnel.*

INTRODUCTION. Rock bolts are nowadays an effective and widely used support measure and an element of reinforcement in civil engineering and mining. Furthermore, rock bolts can be applied under very different geological and technical conditions to stabilize the rock mass. Rock bolts are cost effective because of their simple composition and their relatively low labour and energy consumption.

Although a great number of empirical, experimental, analytical and numerical methods have been developed to simulate bolting effects and at the end to design rock bolts as a support means in underground excavations, informed and discussed in many published articles, the interaction mechanisms of the rock bolts and the rock mass stay still a very complicated issue and are not well understood. There isn't a concrete theoretical concept for determining all the parameters of a rock bolts system. Design of systematic rockbolt reinforcement in tunnelling is normally done by application of empirical and rational approaches.

Several analytical models have been developed to study the interaction behavior of bolts and rock mass, and to evaluate the effect of the bolts on stress and strain behavior of the rock around the underground opening (Hoek and Brown, 1980 [1]; Bieniawski, 1989 [2]; Indraratna and Kaiser, 1990 [3]; Li and Stillborg, 1999 [4]; Nguyen, 2001 [5]; Nguyen et al., 2011 [6]; Oreste, 2003 [7]; Cai et al., 2004a [8], 2004b [9]; Fahimifar and Soroush, 2005 [10]; Bobet, 2006 [11]; Osgoui and Ünal, 2009 [12]; Carranza-Torres, 2009 [13]; Osgoui and Oreste, 2010 [14]; Martín et al., 2013 [15]; Cao et al., 2013 [16]).

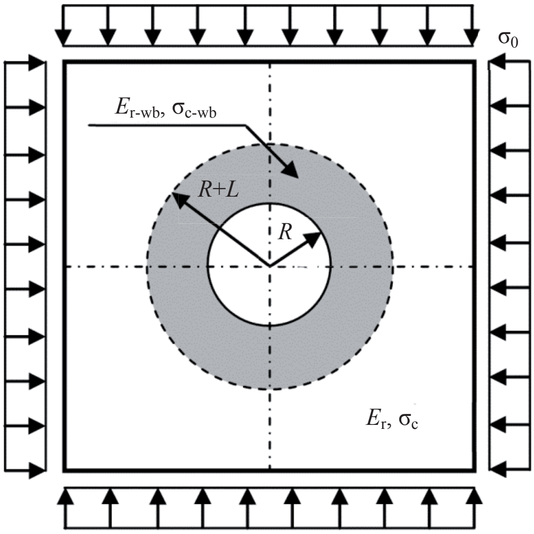

Figure 1. The axisymmetric tunnel problem
Рисунок 1. Осесимметричная задача

Samit and Anand (1997) [17] proposed an analytical model using beam-column theory to analyze the reinforcement by the rockbolts. They found that the critical buckling load of the rock beam is influenced by the rock modulus. Another analytical model has been suggested by Li and Stillborg (1999) [4] in order to describe the reinforcement effect of rockbolts. Indraratna and Kaiser (1990) [3] have also developed an analytical model using convergence - confinement method to analyze the effect of the bolt pattern on the extent of the yield zone and tunnel deformation. Carranza-Torres (2009) [13] has proposed an analytical model of rockbolt reinforcement around tunnels and found that reinforcement can have a significant mechanical effect: increasing the confinement and decreasing the convergences. A simple analytical method was proposed by Bobet (2006) [11] for the analysis of the load on a single rockbolt. Those methods are based on rock-support interaction theory or convergence-confinement approach or based on composite material concept.

The analytical solutions for the composite element of the rock bolts and rock mass have been found in elsewhere (Indraratna and Kaiser, 1990; Bernaud et al., 1995 [18]; Cai et al., 2004; Bobet, 2006 [11]; Buhan et al., 2008 [19]). A new analytical algorithm for the interaction between the bolt and rock under a seismic load based on the bearing mechanism of fully grouted rock bolts in underground caverns is proposed by Lui et al. (2017) [25], but only considering shear damage on the anchoring interface.

An interesting parametric study was performed by Das R. et al. (2021) [26] to determine the influence of different bolt parameters (bolt length and diameter) on the maximum induced boundary displacements in jointed rockmass, using a numerical method based on finite element code.

However, such analytical models did not consider the material components of rock bolt include the rock mass, steel bar and grout in detail.

Although rockbolt is the most widely used support element in support systems in underground mines and civil tunnels. But according to Li C. C. (2017) [27] until now rockbolting design is mainly based on experience and it appears that rockbolting design is simply a business of selection of rockbolt types and the determination of bolt length and spacing, but, one essentially uses, either explicitly or implicitly, a methodology in a specific rockbolting design.

Table 1. The results for the length of rock bolts
Таблица 1. Длины анкеров

a (m)	0.8	0.7	0.6
A_0	0.403	0.527	0.717
n_{max}	1.015	1.08	1.18
n	1	1	1
L (m)	2.9	1.1	0.5

It can be marked that Russian researchers are also underway aimed at the improving the design methods for the rock bolts of mine workings [28–30].

The paper presents at first a simple analytical method for design of rock bolts based on the reinforcement principle and proposes a procedure for design of rock bolts system. Numerical simulation are carried out to demonstrate how rock bolts system could be designed by using numerical methods, in these cases with FLAC 3D and 2D.

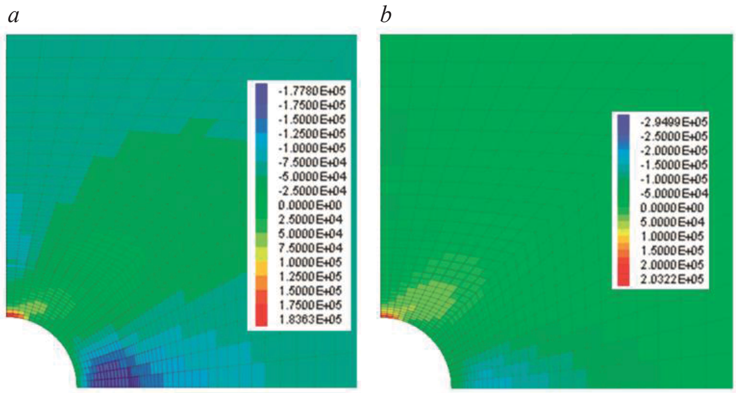

Figure 2. Maximum principal stress distribution around the tunnel cross-section:
a – reinforced rock bolts; *b* – interaction principle
Рисунок 2. Распределение максимального главного напряжения по поперечному сечению выработки:
a – армированные анкеры; *b* – принцип взаимодействия

ANALYTICAL SOLUTION. Simplify model and concept. The problem to be solved is a circular tunnel of radius R excavated at a depth H in a homogeneous, isotropic and initially elastic rock mass. The tunnel is subjected to a hydrostatic stress field $\sigma_0 = \gamma H$, where γ is the ground unit weight. The rock mass in primary state is elastic and the mechanical properties are described by the Young modulus E_{rm}, Poisson's ratio ν_{rm} and axial compressive strength σ_{crm}. After excavation a plastic zone would be built around the tunnel perimeter, at a certain distance behind the face if no support is installed. So a grouted rock bolts system is to be installed just in time in order to keep the rock mass elastic based on the assumption that the rock bolts system could improve the strength and decrease the deformability of the supported rock mass as a composite material. There are two zones that exist around the tunnel now, a zone of elastic rock composite and a zone of elastic rock mass (Figure 1). The rock composite has then the Young modulus $E_{\text{rm-wb}}$, the Poisson'ratio $\nu_{\text{rm-wb}}$ and axial compressive strength $\sigma_{\text{c-wb}}$. For simplification it's assumed that $\nu_{\text{rm}} = \nu_{\text{rm-wb}} = 0.5$ (Nguyen et al., 2018) [20].

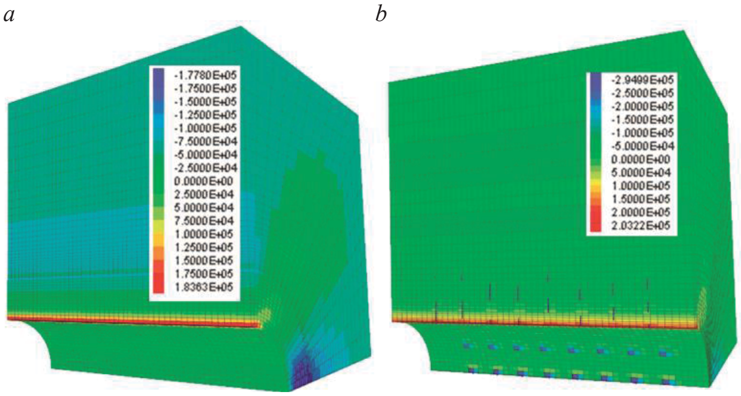

Figure 3. Maximum principal stress distribution around the tunnel in three-dimensional:
a – reinforced rock bolts; *b* – interaction principle
Рисунок 3. Распределение максимального главного напряжения вокруг выработки в трехмерном виде:
a – армированные анкеры; *b* – принцип взаимодействия

To evaluate the stability of the rock mass before excavation a stability factor n_0 is used in simple way based on the elastic solution for stress and displacement distribution. The stability factor n_0 is defined as the ratio between axial compressive strength of rock mass σ_{crm} and the maximal tangential stress on the perimeter $\sigma_\theta = 2\sigma_0$ from the well-known solution as followed:

$$n_0 = \frac{\sigma_{\text{crm}}}{2\sigma_0}. \tag{1}$$

The rock mass is stable if $n_0 \geq 1$ and is not stable if $n_0 < 1$, and needs to support, in these case, for example, with grouted rock bolts.

The grouted bolts with the length of L are placed along the radial direction around the tunnel. The mechanical properties of the rock mass with bolts are characterized by elastic modulus $E_{\text{r-wb}}$, Poisson's ratio ν and axial compressive strength $\sigma_{\text{c-wb}}$ and are calculated from the mechanical parameters of the rock mass, the grouted material, the bolt rank and the geometrical parameters of the borehole, the steel bar and the opening based on the homogenization theory at any point as a function of r as follows (Nguyen, 2001 [5]):

$$\frac{E_{\text{rm-wb}}}{E_{\text{rm}}} = \frac{\sigma_{\text{c-wb}}}{\sigma_{\text{c}}} = \alpha = 1 + \frac{\pi}{4}\frac{d_{\text{bh}}^2(E_{\text{grt}} - E_{\text{rm}}) + d_{\text{sb}}^2(E_{\text{sb}} - E_{\text{grt}})}{a^2 E_{\text{rm}}}\frac{R}{r} = 1 + A_0\frac{R}{r} \tag{2}$$

$$\text{with } A_0 = \frac{\pi}{4}\frac{d_{\text{bh}}^2(E_{\text{grt}} - E_{\text{rm}}) + d_{\text{sb}}^2(E_{\text{sb}} - E_{\text{grt}})}{a^2 E_{\text{rm}}}. \tag{3}$$

Where: d_{bh}, d_{sb}, E_{grt}, E_{sb}, a and α are the diameter of the borehole, the diameter of the steel bar, the elastic modulus of the grout, the elastic modulus of steel bar, the distance between the rock-bolts and the reinforcement factor respectively.

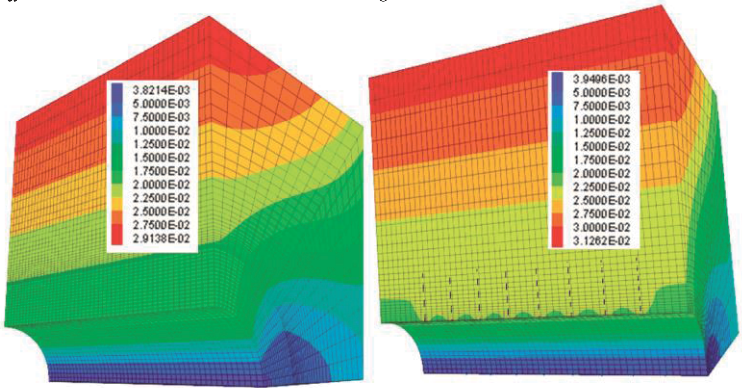

Figure 4. The rock mass displacement after bolting:
a – reinforced rock bolts; *b* – interaction principle
Рисунок 4. Смещение горного массива после установки крепи:
а – армированные анкеры; *b* – принцип взаимодействия

By the way, it is also noted that the effect of reinforcing the rock mass when anchoring has also been confirmed by Wullschläger and Natau (1987) [21], Wullschläger (1988) [22] and Sakurai (2010) [23] by their experiments.

The tunnel has then a support with uniform bolts on the perimeter of the tunnel, and it is subjected to far-field stresses $\sigma_0 = \gamma H$. The rock bolts system is to design so that the supported rock mass will be stable and remain elastic.

Solving this boundary problem, we obtain the stress field distribution in the rock mass zone with bolts surrounding the tunnel in polar coordinates as follows:

$$\begin{aligned}
\sigma_{\text{r-wb}} &= 2\sigma_0 \frac{1}{B}\left[-\frac{1}{2r^2} - \frac{A}{3r^3} + \frac{1}{2R^2} + \frac{A}{3R^3}\right];\\
\sigma_{\theta\text{-wb}} &= 2\sigma_0 \frac{1}{B}\left[\frac{1}{2r^2} + \frac{2A}{3r^3} + \frac{1}{2R^2} + \frac{A}{3R^3}\right];\\
\sigma_{\text{r-w0b}} &= \sigma_0 - \left[\sigma_0 - \sigma_0\left(1 - \frac{1}{(R+L)^2}\frac{1}{B}\right)\right]\left(\frac{R+L}{r}\right)^2;\\
\sigma_{\theta\text{-w0b}} &= \sigma_0 + \left[\sigma_0 - \sigma_0\left(1 - \frac{1}{(R+L)^2}\frac{1}{B}\right)\right]\left(\frac{R+L}{r}\right)^2.
\end{aligned} \tag{4}$$

Where: $\sigma_{\text{r-wb}}$ is the radial stresses in rock mass with bolt-grout support; $\sigma_{\theta\text{-wb}}$ is the tangential stresses in rock mass with bolt-grout support; $\sigma_{\text{r-w0b}}$ is the radial stresses in rock mass without bolt-grout support; $\sigma_{\theta\text{-w0b}}$ is the tangential stresses in rock mass without bolt-grout support;

$$A = \frac{\pi}{4}\frac{d_{\text{bh}}^2(E_{\text{grt}} - E_{\text{rm}}) + d_{\text{sb}}^2(E_{\text{sb}} - E_{\text{grt}})}{a^2 E_{\text{rm}}} R = A_0 R;$$

$$B = \frac{1}{R^2} + \frac{2}{3} A \frac{\left(R+L\right)^3 - R^3}{R^3\left(R+L\right)^3}.$$

The tangential stress at the perimeter of the tunnel is determined by substitution $r = R$ into equation (4):

$$\sigma_{\theta\text{-wb-R}} = 2\sigma_0 \frac{1 + A_0}{1 + \frac{2}{3} A_0 \frac{\left(R+L\right)^3 - R^3}{\left(R+L\right)^3}} = 2\sigma_0 \frac{\left(1 + A_0\right)\left(R+L\right)^3}{\left(1 + \frac{2}{3} A_0\right)\left(R+L\right)^3 - \frac{2}{3} A_0 R^3}. \quad (5)$$

The normal displacement at the perimeter of the tunnel can be estimated by the following equations:

$$u_{\text{n-wb-R}} = \frac{3\sigma_0}{2E_{\text{rm}}} \frac{R}{1 + \frac{2}{3} A_0 \left(1 - \frac{R^3}{\left(R+L\right)^3}\right)} = u_0 \frac{1}{1 + \frac{2}{3} A_0 \left(1 - \frac{R^3}{\left(R+L\right)^3}\right)}.$$

Where: u_0 is the normal displacement of the tunnel perimeter before bolting. And the compressive strength of the rock mass after bolting is determined from equation (2) as follows:

$$\sigma_{\text{cm-wb-R}} = \left(1 + A_0\right)\sigma_{\text{cm}}. \quad (6)$$

The tangential stress and normal displacements at the perimeter of the tunnel before bolting can be expressed by using elastic solution as follows:

$$\sigma_{\theta 0} = 2\sigma_0;$$
$$u_0 = \frac{3\sigma_0}{2E_{\text{rm}}} R.$$

Comparison of the stress and displacement in the rock mass with bolts and without bolts, it is shown that:

$$\sigma_{\theta\text{-wb-R}} > \sigma_{\theta 0} \text{ and } u_{\text{n-wb-R}} < u_0.$$

This demonstrates that the displacement of the rock mass surrounding tunnel after bolting is smaller than rock mass before bolting. But the stress is greater. Therefore, the stability of the rock mass after bolting needs to be estimated carefully by calculating and adjusting the bolt parameters.

Assuming that n_0 and n are the safety factor in terms of the rock mass before and after bolting on the perimeter of the tunnel respectively, defined as follows:

$$n_0 = \frac{\sigma_{\text{cm}}}{\sigma_{\theta 0}} = \frac{\sigma_{\text{cm}}}{2\sigma_0};$$

$$n = \frac{\sigma_{\text{cm-wb-R}}}{\sigma_{\theta\text{-wb-R}}}. \tag{7}$$

If $n_0 < 1$, the rock mass surrounding tunnel is considered instable and needs to be bolted to maintain stable with $n > 1$. Hence, if the safety factor n for the rock mass is given, it is clearly that the bolt parameters (length, density, diameter of bolt, diameter of borehole, etc.) can be easily determined in relation of the mechanical properties of the rock mass and bolts.

After substituting the expressions (5) and (6) into equation (7), the safety factor of rock mass on the perimeter of the tunnel after bolting can be presented as:

$$n = \frac{\sigma_{\text{cm-wb-R}}}{\sigma_{\theta\text{-wb-R}}} = \frac{(1+A_0)\sigma_{\text{cm}}}{\sigma_{\theta\text{-wb-R}}} = (1+A_0)\frac{\sigma_{\text{cm}}}{2\sigma_0}\frac{\left(1+\frac{2}{3}A_0\right)(R+L)^3 - \frac{2}{3}A_0 R^3}{(1+A_0)(R+L)^3} =$$
$$= \left(1+\frac{2}{3}A_0\right)n_0 - \frac{2}{3}A_0 n_0 \frac{R^3}{(R+L)^3} \Rightarrow \frac{(R+L)^3}{R^3} = \frac{\frac{2}{3}A_0 n_0}{\left(1+\frac{2}{3}A_0\right)n_0 - n}. \tag{8}$$

The length of bolt can be expressed from equation (8) as follows:

$$L = R\left(\sqrt[3]{\frac{\frac{2}{3}A_0 n_0}{\left(1+\frac{2}{3}A_0\right)n_0 - n}} - 1\right). \tag{9}$$

Because the length of the bolt must be greater than 0 ($L > 0$), so that means:

$$\left(1+\frac{2}{3}A_0\right)n_0 - n > 0 \quad \Rightarrow \quad A_0 > \frac{3}{2}\left(\frac{n}{n_0} - 1\right). \tag{10}$$

Combination of equation (3) and (10) leads to determine the distance between the bolts at the perimeter of tunnel based on the diameter of bolt, diameter of borehole, grout properties as follows:

$$a < \sqrt{\frac{\pi}{4}\frac{d_{\text{bh}}^2\left(E_{\text{grt}} - E_{\text{rm}}\right) + d_{\text{sb}}^2\left(E_{\text{sb}} - E_{\text{grt}}\right)}{\frac{3}{2}\left(\frac{n}{n_0} - 1\right)E_{\text{rm}}}}. \tag{11}$$

However, the distance between the bolts can be estimated also based on experience. It can be seen from (10) that the safety factor n of the rock mass surrounding the tunnel after bolting can be reached maximum value as following expression:

$$n_{\max} = \left(1 + \frac{2}{3}A_0\right)n_0. \tag{12}$$

That means the safety factor n of the rock mass after bolting is varied in the range of: $1 < n < n_{\max}$.

Calculation example. The case analyzed corresponds to a deep circular tunnel with $R = 4.0$ m, excavated at a depth $H = 300$ m in a homogeneous rock mass. The rock mass has following elastic properties: axial compressive strength, $\sigma_{cr} = 60$ MPa; unit weight, $\gamma = 27$ kN/m^3; rock mass rating index, RMR = 72; elastic modulus, $E_r = 0.5$ GPa. The support of the tunnel is provided by rock bolts uniformly distributed along the perimeter of the tunnel. The properties of the rock bolts are: elastic modulus of steel bar, $E_{sb} = 210$ GPa; elastic modulus of grout, $E_{grt} = 30$ GPa; diameter of steel bar, $d_{sb} = 25$ mm; diameter of borehole, $d_{bh} = 42$ mm.

The strength of the rock mass can be estimated according to Hoek-Brown criterion as follows:

$$\sigma_{cm} = \sigma_{cr}\sqrt{s}.$$

Where:

$$s = \exp\left(\frac{\mathrm{RMR} - 100}{9}\right) = \exp\left(\frac{72 - 100}{9}\right) = 0.0466 \Rightarrow$$
$$\Rightarrow \sigma_{cm} = 60\sqrt{0.0466} = 12.96 \text{ MPa}.$$

Assuming that the tunnel subjected to a hydrostatic stress field, the normal stress at the perimeter of excavated tunnel is calculated as:

$$\sigma_{\theta 0} = 2\sigma_0 = 2\gamma H = 2 \times 0.027 \times 300 = 16.2 \text{ MPa}.$$

The safety factor of the rock mass before bolting is given as follows:

$$n_0 = \frac{\sigma_{cm}}{\sigma_{\theta 0}} = \frac{12.96}{16.2} = 0.8.$$

Substitute the given parameters into equation (11), it is obtained the distance between bolts at the perimeter of the tunnel: $a < 0.829$ m.

Using the equations (3) and (12) to determine the values of A_0 and $n_{\max}$ with the distance between bolts are 0.8 m; 0.7 m and 0.6 m. The safety factor of the rock mass requirement after bolting is $n = 1.0$. The length of rock bolts can be estimated then by equation (9). Table 1 lists the calculated results of rock bolts length with safety factor and distance between rock bolts are given.

The calculated rock bolts parameters indicated that it is quite consistent with the reality conditions and other methods.

SOLVING COMPLEX PROBLEMS USING NUMERICAL MODELS. The analytical solution proposed in the previous section is only appropriate for simple problems. In practice, the problems are always associated with the complex geometry conditions and nonlinear boundary conditions. Therefore, using numerical methods to simulate problems with complex boundary conditions is needed. In this section outlines the procedure to simulate reinforced rock bolts in the rock mass around tunnel using FLAC program.

a *b*

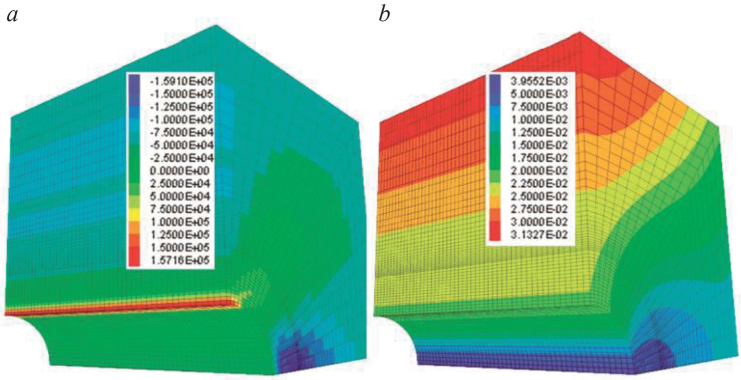

Figure 5. Maximum principal stress and displacement of the rock mass before bolting:
a – maximum principal stress; *b* – displacement
Рисунок 5. Максимальное главное напряжение и смещение массива горных пород перед установкой крепи:
a – максимальное главное напряжение; *b* – смещение

Numerical simulation with FLAC3D. It can be easily seen that cannot be assigned accurately rock mechanical properties according to the expression (1) and (2) when using numerical methods to simulate reinforced rock bolts. Hence, to consider to the variation of mechanical parameters, we need to divide the reinforced area into a smaller area and assigned the mechanical properties to each area. The mechanical properties are mean values and which are integral depending on the dividing of reinforced area.

a *b*

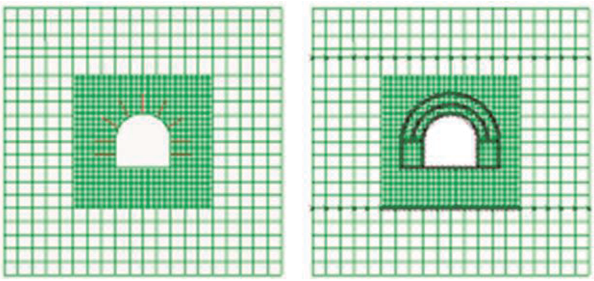

Figure 6. Rock bolts calculation scheme based on the interaction principle – *a* and the principle of reinforcement – *b*
Рисунок 6. Схема расчета анкерной крепи по принципу взаимодействия – *a* и по принципу армирования – *b*

Circular tunnel. The problem is a circular tunnel reinforced by grouted bolts. The rock bolts are modelled in two different ways:

(i) interaction between rock bolts and rock mass;

(ii) rock mass reinforced by rock bolts, the mechanical properties of the reinforced area and non-reinforced area is different.

The problem to be simulated is a three-dimensional horizontal tunnel of radius $R = 2$ m, excavated at a depth $H = 60$ m in a homogeneous and elastic rock mass. The mechanical properties of the rock mass are: the rock unit weight, $\gamma = 2600$ kg/m^3; Poisson's ratio, $\nu = 0.3$; elastic modulus, $E_{rm} = 90$ MPa; horizontal stress ratio, $k = \nu/(1 - \nu)$. The mechanical

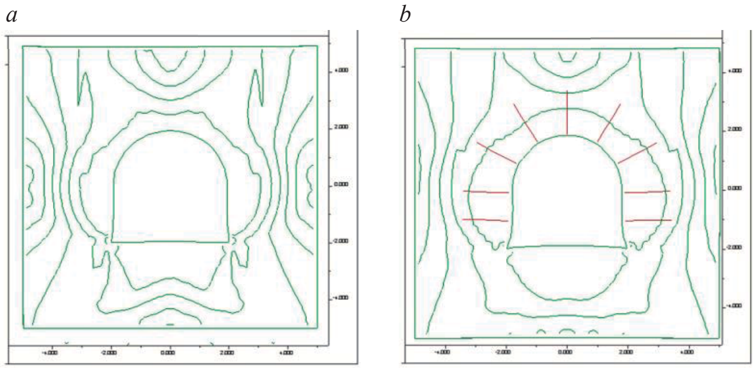

Figure 7. Maximum principal stress distribution:
a – interaction principle; *b* – the principle of reinforcement
Рисунок 7. Распределение максимального главного напряжения:
a – принцип взаимодействия; *b* – принцип армирования

properties of the grouted bolts are: the length of bolt, $L = 1.5$ m; diameter of steel bar, $d_{sb} = 20$ mm; diameter of borehole, $d_{bh} = 36$ mm; the bolt spacing, $a = 1$ m; elastic modulus of steel bar, $E_{sb} = 98$ GPa; elastic modulus of grout, $E_{grt} = 29$ GPa; shear modulus of grout, $G_{grt} = 9$ GPa; compressive strength of grout, $\sigma_g = 9$ MPa; tension strength of steel bar, $\sigma_{t\text{-}sb} = 0.5$ MN.

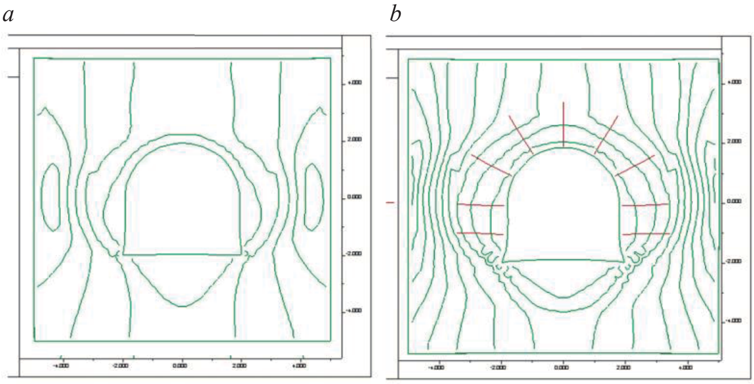

Figure 8. Minimum principal stress distribution:
a – interaction principle; *b* – the principle of reinforcement
Рисунок 8. Распределение минимального главного напряжения:
a – принцип взаимодействия; *b* – принцип армирования

Only quarter of the tunnel was modelled because of the symmetry of the analyzed problem.

Simulation procedure. To solve this problem using FLAC3D program, here it can consider to the bolt spacing according to reinforced rock mass and interaction principle.

Case 1: Reinforced rock mass.

The reinforced rock mass is divided into 5 annular areas. The mean value of elastic modulus of each annular is calculated by equation as follows:

$$E_{\mathrm{n}}(r) = E_0\left(1+\frac{A}{r}\right);$$

$$A = \frac{\pi}{4}\frac{d_{\mathrm{bh}}^2(E_{\mathrm{grt}} - E_{\mathrm{rm}}) + d_{\mathrm{sb}}^2(E_{\mathrm{sb}} - E_{\mathrm{grt}})}{a^2 E_{\mathrm{rm}}}R.$$

Case 2: interaction principle.

In FLAC3D, the grout shear stiffness, k_{g}, is simply given by

$$k_{\mathrm{g}} = \frac{2\pi G_{\mathrm{grt}}}{10\ln\left(1+\dfrac{2t}{d_{\mathrm{sb}}}\right)}$$

and neglecting frictional confinement effects, c_{g}, may then be obtained from:

$$c_{\mathrm{g}} = \pi\left(d_{\mathrm{sb}} + 2t\right)\tau_{\mathrm{peak}}; \qquad \tau_{\mathrm{peak}} = 0.5\sigma_{\mathrm{g}}.$$

Where: G_{grt} is the grout shear modulus, t is the grout thickness, d_{sb} is the steel bar diameter, τ_{peak} is the peak shear strength of grout, σ_{g} is the compressive strength of grout.

$$k_{\mathrm{g}} = \frac{2\pi G_{\mathrm{grt}}}{10\ln\left(1+\dfrac{2t}{d_{\mathrm{sb}}}\right)} = \frac{2\pi\cdot 9}{10\ln\left(1+\dfrac{2\cdot 0.008}{0.02}\right)} = 9.628\ \text{GPa}.$$

$$c_{\mathrm{g}} = \pi\left(d_{\mathrm{sb}} + 2t\right)\tau_{\mathrm{peak}} = \pi\left(0.02 + 2\cdot 0.008\right)0.5\cdot 9 = 0.5\ \text{MPa}\cdot\text{m}.$$

Results and discussions. Using the three-dimensional program can be determined the mechanical process of rock mass surrounding the tunnel considering the sequence of the tunnel excavation. In this study introduce some basic results indicated the effectiveness of the proposed model. The distribution of the maximum principal stress for the case of the reinforced rock bolts (*a*) and interaction principle (*b*) are shown in Figure 2 and Figure 3 shows the maximum principal stress distribution around a circular tunnel in three-dimensional.

The rock mass displacement after bolting was estimated by reinforced rock bolts (*a*) and interaction principle (*b*) is shown in Figure 4.

The numerical simulation results show that the maximum principal stress distribution around a circular tunnel is in good agreement in both the reinforced rock bolts and interaction principle. However, the input mechanical properties of rock mass are a little a bit different, so the amplitude of the largest and smallest of the output parameters is slightly different. It is important for both calculations indicated that the rock mass properties after bolting are improved comparing to the rock mass before bolting. This is illustrated in Figure 5 for the maximum principal stress (*a*) and displacement (*b*) of rock mass around tunnel before bolting

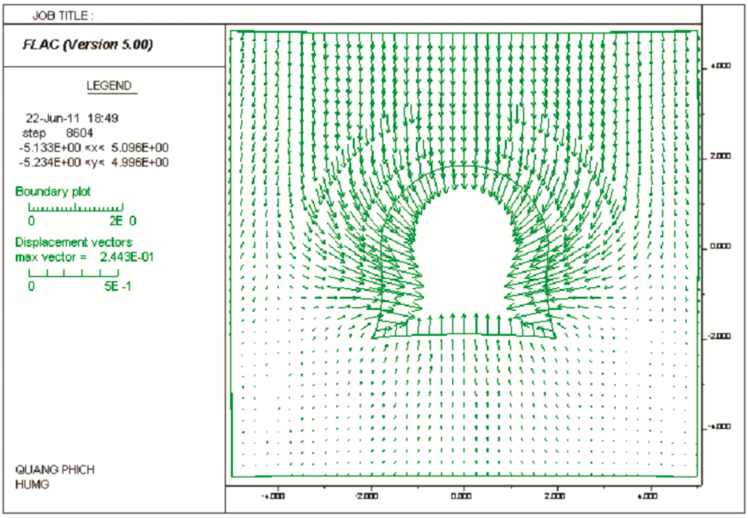

Figure 9. The displacement vectors of reinforced rock mass
Рисунок 9. Векторы сдвига армированного массива

The numerical simulation results for both reinforced rock bolts and interaction principle are shown that the maximum principal stress distribution and displacement of the reinforced rock mass around a circular tunnel is in good agreement. Using FLAC-3D can be considered to be three-dimensional. However, it is not analyzed in more detail here.

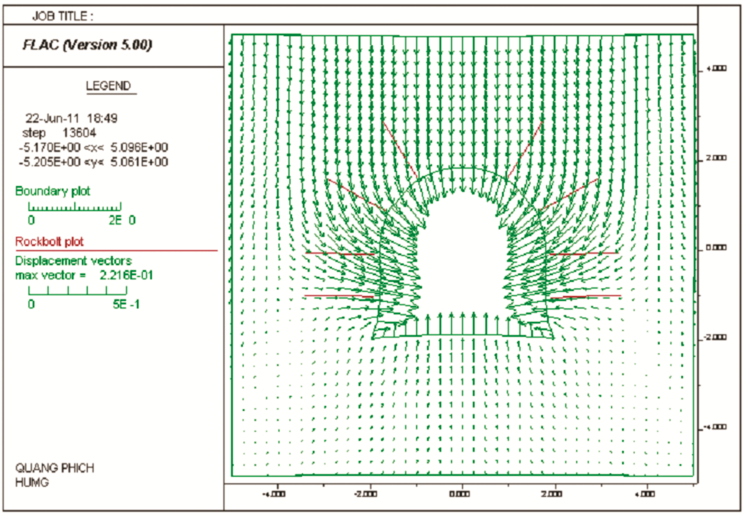

Figure 10. The displacement vectors calculated according to interaction principle
Рисунок 10. Векторы сдвига, рассчитанные по принципу взаимодействия

Numerical simulation with FLAC2D. The problem was simulated for both reinforced rock bolts and interaction principle using FLAC2D.

Figure 6, *a* shows the problem, the rock bolts are located in the roof and side wall of the tunnel. The rock bolts calculation based on the principle of reinforcement is illustrated in Figure 6, *b*. The reinforced area is divided into two smaller areas from the inside out with the mechanical parameters are mean values for each areas. The mechanical parameters of rock mass in side walls are constant because the rock bolts located in this area are parallel.

Simulation results. The maximum principal stress, minimum principal stress and displacement of the rock mass surrounding tunnel for two cases are illustrated in Figure 7, 8, 9 and 10.

CONCLUSION. The rock bolts are widely used as supporting system in mining and tunnelling. Rockbolt systems are designed until now by application of empirical and rational approaches. An analytical model and its theoretical solutions are presented in this paper, and a procedure for design of fully grouted rockbolt system based on the reinforcement principle is developed. The calculated rock bolts parameters based on this method indicated that it is quite consistent with the reality conditions and other methods. The numerical simulations by using Flac 3D and 2D shown that the results obtained from the proposed model and the interaction principle model are very similar. Therefore, it is completely possible to apply the proposed model for designing rock bolts system.

REFERENCES

1. Hoek E., Brown E. T. *Underground excavation in rock*. London: Institution of Mining and Metallurgy; 1980.

2. Bieniawski Z. T. *Engineering rock mass classifications*. New York: Wiley; 1989.

3. Indraratna B., Kaiser P. K. Analytical model for the design of grouted rock bolts. *International Journal for Numerical and Analytical Methods in Geomechanics*. 1990; 14: 227–251.

4. Li B., Stillborg B. Analytical models for rock bolts. *Int. J. Rock. Mech. Min. Sci*. 1999; 36: 1013–1029.

5. Nguyen Q. P. *Rock reinforcement*. Hanoi: Hanoi University of Mining and Geology; 2001. (In Vietnamese).

6. Nguyen Q. P. et al. *Investigation on development and completion of models for calculation and design of fully grouted rock bolts*. Research report. 2011. Code number: B2009-02-76TĐ. (In Vietnamese).

7. Oreste P. P. Analysis of structural interaction in tunnels using the convergence-confinement approach. *Tunnelling and Underground Space Technology*. 2003; 18: 347–363.

8. Cai Y., Esaki T., Jiang Y. An analytical model to predict axial load in grouted rock bolts for soft rock tunneling. *Tunnelling and Underground Space Technology*. 2004; 19: 607–618.

9. Cai Y., Esaki T., Jiang Y. A rock bolt and rock mass interaction model. *Int. J. Rock. Mech. Min. Sci*. 2004; 41: 1055–1067.

10. Fahimifar A., Soroush H. A theoretical approach for analysis of the interaction between grouted rockbolts and rock masses. *Tunnelling and Underground Space Technology*. 2005; 20: 333–343.

11. Bobet A. A simple method for analysis of point anchored rockbolts in circular tunnels in elastic ground. *Rock Mechanics and Rock Engineering*. 2006; 39: 315–338.

12. Osgoui R. R., Ünal E. An empirical method for design of grouted bolts in rock tunnels based on the Geological Strength Index (GSI). *Engineering Geology*. 2009; 107: 154–166.

13. Carranza-Torres C. Analytical and numerical study of the mechanics of rockbolt reinforcement around tunnels in rock masses. *Rock Mechanics and Rock Engineering*. 2009; 42: 175–228.

14. Osgoui R. R., Oreste P. Elasto-plastic analytical model for the design of grouted bolts in a Hoek-Brown medium. *Int. J. Numer. Anal. Meth. Geomech*. 2010; 34: 1651–1686.

15. Martín L. B., Tijani M., Hadj-Hassen F., Noiret A. Assessment of the bolt-grout interface behaviour of fully grouted rockbolts from laboratory experiments under axial loads. *Int. J. Rock. Mech. Min. Sci*. 2013; 63: 50–61.

16. Cao C., Nemcik J., Aziz N., Ren T. Analytical study of steel bolt profile and its influence on bolt load transfer. *Int. J. Rock. Mech. Min. Sci*. 2013; 60: 188–195.

17. Samit R., Anand B. R. Analysis of rockbolt reinforcement using beam-column theory. *International Journal for Numerical and Analytical Methods in Geomechanics*. 1996; 34(4): 241–253.

18. Bernaud D., Buhan P. D., Maghous S. Numerical simulation of the convergence of a bolt-supported tunnel through a homogenization method. *International Journal for Numerical and Analytical Methods in Geomechanics*. 1995; 19: 267–288.

19. Buhan P., Bourgeois E., Hassen G. Numerical simulation of bolt-supported tunnel by means of a multiphase model conceived as an improved homogenization procedure. *International Journal for Numerical and Analytical Methods in Geomechanics*. 2008; 32: 1597–1615.

20. Nguyen Q. P. et al. A new design concept of fully grouted rock bolts in underground construction. In: *IOP Conf. Series: Earth and Environmental Science*. 2018; 143: 012017. Available from: doi: 10.1088/1755-1315/143/1/012017

21. Wullschläger D., Natau O. The bolted rock mass as an anisotropic continuum. Material behaviour and design suggestions for rock cavities. In: *Proceedings of the 6th International Congress on Rock Mechanics*. Montreal: 1987. P. 1321–1324.

22. Wullschläger D. *Ein Verbundwerkstoffmodell für die Systemankerung im Tunnelbau. Dissertation*. Universität Karlsruhe: 1988.

23. Sakurai S. Modeling strategy for jointed rock masses reinforced by rock bolts in tunneling practice. *Acta Geotechnica*. 2010; 5: 121–126.

24. Indraratna B., Kaiser P. K. Design for grouted rock bolts based on the convergence control method. *Int. J. Rock Mech. Min. Sci. & Geomech*. 1990; 27(4): 269–281.

25. Guoqing Liu, Ming Xiao, Juntao Chen, Hao Zhou. Study on mechanical characteristics of fully grouted rock bolts for underground caverns under seismic loads. *Hindawi Mathematical Problems in Engineering*. 2017; ID 1657369: 12. Available from: doi.org/10.1155/2017/1657369

26. Das R., Singh Tr. N. Effect of rock bolt support mechanism on tunnel deformation in jointed rock mass: A numerical approach. *Underground Space*. 2021; 6: 409–420.

27. Li C. C. Principles of rock bolting design. *Journal of Rock Mechanics and Geotechnical Engineering*. 2017; 9(3): 396–414.

28. Rusakov V. O., Petrenko Iu. A., Kasianenko A. L. Directions for improving the structure of rock bolting and methods for calculating its parameters. In: *Problems of mining: Proceedings of the 2nd International Forum of students, graduate students and young scientists-miners, dedicated to the 100th anniversary of DonNTU*. Donetsk: Donetsk National Technical University; Institute of Mining and Geology Publishing; 2021. P. 130–135.

29. Aliev S. B., Demin V. F., Tomilov A. N., Miletenko N. A. Designing the parameters of rock bolting at mining working driving in the conditions of coal mines. *Coal*. 2021; 4(1141): 15–19. (In Russ.)

30. Dudin A. A., Vakhrushev E. V., Matveev A. S., Kirillov I. B., Lapshin A. V., Datskevich N. Iu. Formation of a consolidated massif with rock bolting of the ab series in conditions of highly fractured rocks of the immediate roof of a coal seam. *Ugol*. 2020; 2(1127): 4–7.

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Концепция армирования при проектировании армоцементных анкеров: аналитический и численный методы вычисления

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Реферат

Введение. *При проходке горизонтальных выработок и разработке месторождений наряду с общепринятыми типами горной крепи для армирования горного массива и уменьшения вероятности возникновения опасных геологических процессов и явлений широко используется анкерная крепь. Применение анкерной крепи при различных геологических условиях позволяет также минимизировать издержки. До настоящего времени были разработаны различные методы проектирования армоцементных анкеров, но механизм взаимодействия анкеров и горного массива все еще остается крайне сложной проблемой.*
Методология. *Для анализа и проектирования армоцементных анкеров, закрепленных по всей длине шпура, на основе принципа армирования исследуются простая расчетная*

и численная модели. В соответствии с этим подходом трещиноватый массив горных пород, армированный армоцементными анкерами, рассматривается как композитный материал, заключающий в себе массив горных пород, цементный раствор и стержень анкера. Механические свойства этого композитного материала зависят от соотношения компонентов. Предположение о том, что горный массив вокруг выработки круглого сечения сохраняет упругие свойства после установки армоцементных анкеров, закрепленных по всей длине шпура, легло в основу аналитического решения.
Результаты. *Из полученного решения рассчитываются основные параметры анкерной крепи (диаметр и длина стержня анкера, расстояние между штангами). Для выработки некруглого сечения выполнено численное моделирование, чтобы показать, как проектируется анкерная крепь с использованием численных методов.*

Ключевые слова: *армоцементный анкер; расчетная модель; армирование горных пород; плотность установки крепи; выработка круглого сечения.*

БИБЛИОГРАФИЧЕСКИЙ СПИСОК

1. Hoek E., Brown E. T. Undreground excavation in rock. London: Institution of Mining and Metallurgy, 1980.
2. Bieniawski Z. T. Engineering rock mass classifications. New York: Wiley, 1989.
3. Indraratna B., Kaiser P. K. Analytical model for the design of grouted rock bolts // International Journal for Numerical and Analytical Methods in Geomechanics. 1990. No. 14. P. 227–251.
4. Li B., Stillborg B. Analytical models for rock bolts // Int. J. Rock. Mech. Min. Sci. 1999. No. 36. P. 1013–1029.
5. Nguyen Q. P. Rock reinforcement. Hanoi: Hanoi University of Mining and Geology, 2001. (In Vietnamese).
6. Nguyen Q. P. et al. Investigation on development and completion of models for calculation and design of fully grouted rock bolts. Research report. 2011. Code number: B2009-02-76TĐ. (In Vietnamese).
7. Oreste P. P. Analysis of structural interaction in tunnels using the convergence-confinement approach // Tunnelling and Underground Space Technology. 2003. No. 18. P. 347–363.
8. Cai Y., Esaki T., Jiang Y. An analytical model to predict axial load in grouted rock bolts for soft rock tunneling // Tunnelling and Underground Space Technology. 2004. No. 19. P. 607–618.
9. Cai Y., Esaki T., Jiang Y. A rock bolt and rock mass interaction model // Int. J. Rock. Mech. Min. Sci. 2004. No. 41. P. 1055–1067.
10. Fahimifar A., Soroush H. A theoretical approach for analysis of the interaction between grouted rockbolts and rock masses // Tunnelling and Underground Space Technology. 2005. No. 20. P. 333–343.
11. Bobet A. A simple method for analysis of point anchored rockbolts in circular tunnels in elastic ground // Rock Mechanics and Rock Engineering. 2006. No. 39. P. 315–338.
12. Osgoui R. R., Ünal E. An empirical method for design of grouted bolts in rock tunnels based on the Geological Strength Index (GSI) // Engineering Geology. 2009. No. 107. P. 154–166.
13. Carranza-Torres C. Analytical and numerical study of the mechanics of rockbolt reinforcement around tunnels in rock masses // Rock Mechanics and Rock Engineering. 2009. No. 42. P. 175–228.
14. Osgoui R. R., Oreste P. Elasto-plastic analytical model for the design of grouted bolts in a Hoek-Brown medium // Int. J. Numer. Anal. Meth. Geomech. 2010. No. 34. P. 1651–1686.
15. Martín L. B., Tijani M., Hadj-Hassen F., Noiret A. Assessment of the bolt-grout interface behaviour of fully grouted rockbolts from laboratory experiments under axial loads // Int. J. Rock. Mech. Min. Sci. 2013. No. 63. P. 50–61.
16. Cao C., Nemcik J., Aziz N., Ren T. Analytical study of steel bolt profile and its influence on bolt load transfer // Int. J. Rock. Mech. Min. Sci. 2013. No. 60. P. 188–195.
17. Samit R., Anand B. R. Analysis of rockbolt reinforcement using beam-column theory // International Journal for Numerical and Analytical Methods in Geomechanics. 1996. No. 34(4). P. 241–253.
18. Bernaud D., Buhan P. D., Maghous S. Numerical simulation of the convergence of a bolt-supported tunnel through a homogenization method // International Journal for Numerical and Analytical Methods in Geomechanics. 1995. No. 19. P. 267–288.
19. Buhan P., Bourgeois E., Hassen G. Numerical simulation of bolt-supported tunnel by means of a multiphase model conceived as an improved homogenization procedure // International Journal for Numerical and Analytical Methods in Geomechanics. 2008. No. 32. P. 1597–1615.
20. Nguyen Q. P. et al. A new design concept of fully grouted rock bolts in underground construction // IOP Conf. Series: Earth and Environmental Science. 2018; 143: 012017. DOI: 10.1088/1755-1315/143/1/012017
21. Wullschläger D., Natau O. The bolted rock mass as an anisotropic continuum. Material behaviour and design suggestions for rock cavities // Proceedings of the 6th International Congress on Rock Mechanics, Montreal, 1987. P. 1321–1324.
22. Wullschläger D. Ein Verbundwerkstoffmodell für die Systemankerung im Tunnelbau. Dissertation, Universität Karlsruhe, 1988.

23. Sakurai S. Modeling strategy for jointed rock masses reinforced by rock bolts in tunneling practice // Acta Geotechnica. 2010. No. 5. P. 121–126.

24. Indraratna B., Kaiser P. K. Design for grouted rock bolts based on the convergence control method // Int. J. Rock. Mech. Min. Sci. & Geomech. 1990. Vol. 27. No. 4. P. 269–281.

25. Guoqing Liu, Ming Xiao, Juntao Chen, and Hao Zhou. Study on mechanical characteristics of fully grouted rock bolts for underground caverns under seismic loads // Hindawi Mathematical Problems in Engineering. Vol. 2017. Art. ID 1657369. 12 p. https://doi.org/10.1155/2017/1657369

26. Das R., Singh Tr. N. Effect of rock bolt support mechanism on tunnel deformation in jointed rockmass: a numerical approach // Underground Space. 2021. No. 6. P. 409–420.

27. Li C C. Principles of rockbolting design // Journal of Rock Mechanics and Geotechnical Engineering. 2017. Vol. 9. Iss. 3. P. 396–414.

28. Русаков В. О., Петренко Ю. А., Касьяненко А. Л. Направления совершенствования конструкции анкерной крепи и методики расчета ее параметров // Проблемы горного дела: сб. науч. тр. II Междунар. форума студентов, аспирантов и молодых ученых-горняков, посвященного 100-летию ДонНТУ. Донецк: ДНТУ, ИГДиГ, 2021. С. 130–135.

29. Алиев С. Б., Демин В. Ф., Томилов А. Н., Милетенко Н. А. Расчет параметров анкерного крепления при проведении горных выработок в условиях угольных шахт // Уголь. 2021. № 4(1141). С. 15–19.

30. Дудин А. А., Вахрушев Е. В., Матвеев А. С., Кириллов И. Б., Лапшин А. В., Дацкевич Н. Ю. Формирование консолидированного массива анкерной крепью серии АБ в условиях сильнотрещиноватых пород непосредственной кровли угольного пласта // Уголь. 2020. № 2(1127). С. 4–7.

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