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THE USE OF INJECTION ROCK BOLTS IN HE MINING AND GEOLOGICAL CONDITIONS OF UKRAINIAN COAL MINES

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Abstract

The article presents the results of simulation of coupled processes of rock deformation and liquid polymer filtration in the disturbed area around the mine working. The problem formulation takes into account the initial permeability of host rocks as well as the permeability due to the mine working driving, time of polymer delivery and hardening, and foaming effect of the polymeric composition in the process of mixing of its components. Certain changes in physicomechanical and filtration characteristics of rocks during the polymer hardening also were taken into account in the problem formulation as well as the fact that a metal delivery pipe starts operating as a reinforcing element after hardening of the polymeric composition is over.

It was demonstrated that the location of rock bolts is important to form a rock-bolts arch. With sufficient density of injection rock bolts, the formed rock-bolts arch may serve as a barrier controlling both water inflow and gas emission from the undermined rocks into the mine working. Dependence of changes in the reinforced area upon the value of initial permeability of the host rocks was derived. If the values of initial permeability are low then size of the rock-bolt supports and their shape are determined using only a value of the unloaded zone around the mine working.

It was shown that steel and injection rock bolts complement each other very well, increasing the stability of the mine working and reducing the filtration permeability of the host rocks. Injection rock bolts exclude the possibility of destruction of host rocks and more effectively reduce the permeability of disturbed rocks in the zone of influence of the tectonic fault. And steel rock bolts better restrain the expansion of the zone of increased difference of the stress tensor components. Therefore, in the case of heavily watered rocks or a high probability of methane breakthroughs into the mine working, it is better to install injection rock bolts and deliver the polymer into the disturbed rock as close as possible to the mine face. Then a water- and gas-proof shell arch around the mine working will be created in the immediate vicinity of the mine face, which will make it possible to quickly prevent emergency water inflows and gas emissions. If there is no such threat and the priority is to maintain the long-term stability of the mine working, then first of all it is necessary to install steel rock bolts with polymer fixing in the borehole.

Key words: injection rock bolts, complicated mining and geological conditions, numerical simulation, supporting technology, mine workings.

1 Introduction

There are a large number of tectonic faults in the coal-bearing strata of the Western Donbass [1, 2]. These faults are surrounded by zones where rocks have a broken structure, reduced strength, are very crushed [3, 4]. Weak, unstable rocks are prone to soaking with subsequent loss of bearing capacity [5, 6]. The total thickness of watered rocks ranges from 20 m to 1660 m in the Western Donbas [7]. The gas content reaches 25 m^3/t in coal seams and 7 m^3/t in sandstones. Mine workings driving in highly fractured, unstable rocks is a serious problem. The high permeability of rocks in the zones of tectonic faults causes the possibility of methane breakthroughs and large water inflows into mine workings [8]. It is very difficult to choose supporting scheme for a mine working in such conditions.

Roof bolting is a spatial structure of steel bolts fixed in boreholes with a polymer fixer [9-11]. This support has significant advantages in all technical and economic indicators compared to traditional types of supporting. Roof bolting makes it possible to ensure the reliable and safe functioning of mine workings throughout the entire period of their maintenance, if the technology of bolts setting is observed [12-14]. However, if a mine working is driving in highly fractured, unstable rocks, additional means of supporting are needed to ensure its stability.

One of the solutions to the problem of mine workings support in highly fractured rocks is the use of injection rock bolts. An injection rock bolt is a metal seamless pipe with a sealer to deliver fortifying solution into the fractured rocks, Fig. 1. After delivery, the metal pipe is used as extra reinforcement facilitating high shear strength. Technical characteristics of IRMA injection rock bolts are given in Tab. 1 [15].

Fig. 1. An injection rock bolt with a sealer [15].

Table 1

Technical characteristics of IRMA injection rock bolts

Characteristic name	IRMA 40	IRMA 110	IRMA 200	IRMA 250
Breaking load, kN	40	110	178	229
Breaking elongation, %	–	–	>15	>15
Tensile strength, N/mm²	360	400	700	700
External diameter, mm	22	22	22	25
Internal diameter, mm	12	12	8	11

Generally, the delivered solution consists of two liquid components pumped separately through the hoses. Then, the components mix in a blender, and deliver under high pressure (6-9 MPa) to the rock mass by means of rock bolt system and a sealer. The density of the composition at 25°C is 1000-1500 kg/m^3, the viscosity at 15°C is 110-670 MPa·s. The reagent mixer is polymerized with 1,5-3,5 times increase in volume. Owing to high pressure, the foamed composition gets even in small fissures of the rock mass .

Injection rock bolts serve to strengthen the disturbed near-contour rock, increase the stability of mine workings, reduce the rock permeability, reduce gas and water inflows into a mine working [15-18]. But what rules should be followed when creating effective supporting schemes? To answer this question, it is necessary to study the mechanism of operation of the injection rock bolt, the principles of forming an impenetrable arch around the mine working, the features of the operation of injection and steel-polymer rock bolts and their interaction. Therefore, the purpose of this work is to develop a mathematical model for studying the mechanism of operation of the injection rock bolt and substantiating the conditions for the formation of a rock-bolts arch around a mine working, which ensures its stability and protects against water and gas inflows.

To achieve the goal, the following tasks were set:

- to develop a mathematical model of the coupled processes of rock deformation around the mine working and liquid polymer filtration in the disturbed area, taking into account changes in the strength and filtration properties of rock in the process of polymer solidification;
- to perform numerical simulation using the finite element method;
- to investigate the process of formation a reinforced support around one injection rock bolt;
- to investigate the formation of a reinforced, impermeable rock-bolts arch around the mine working with injection rock bolts;
- to determine the factors influencing the formation of the rock-bolts arch around the mine working, which ensures its stability and protects against water and gas inflows;
- to investigate the stability and effectiveness of the supporting of the mine working when using steel rock bolts in combination with injection rock bolts.

2 Methods

The coupled processes of rock deformation and liquid polymer filtration in the disturbed rock are described by a system of equations [19]

$$c_g \frac{\partial u_i}{\partial t} = \sigma_{ij,j} + X_i(t) + P_i(t)\,; \quad (1)$$

$$\frac{\partial p}{\partial t} = \frac{k}{\mu \cdot \beta \cdot m}\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}\right) + q(t)\,, \quad (2)$$

where c_g - damping ratio, kg/(c·m^3); u_i - displacements, m; t - time, s; $\sigma_{ij,j}$ - derivatives of the stress tensor components along x, y, Pa/m; $X_i(t)$ - projections of the external forces acting on the volume unit of solid body, N/m^3; $P_i(t)$ - projections of forces caused by liquid polymer pressure in the fracture space, N/m^3; p - liquid polymer pressure, Pa; k - permeability coefficient, D; μ - polymer viscosity, Pa·s; β - polymer compressibility factor, 1/Pa; m - rock porosity, %; $q(t)$ - foaming function, Pa/s.

The problem is solved in elastoplastic formulation. Mathematical description of rock transition into the disturbed state involves Mohr-Coulomb failure criterion.

The initial and boundary conditions for this task set

$$\sigma_{yy}\big|_{t=0} = \gamma H; \quad \sigma_{xx}\big|_{t=0} = \lambda\gamma H; \quad p\big|_{t=0} = 0.1\text{ MPa}\,,$$

$$u_x\big|_{\Omega_1} = 0; \quad u_y\big|_{\Omega_2} = 0; \quad p\big|_{\Omega_3} = p_0; \quad p\big|_{\Omega_4} = 0.1\text{ MPa}\,,$$

where λ - side thrust coefficient; γ - averaged weight of the overlying rocks, N/m^3; H - mining depth, m; p_0 - delivery pressure, MPa; Ω_1 - vertical outer boundaries; Ω_2 - horizontal outer boundaries; Ω_3 - filtering share of a borehole surface; Ω_4 - internal boundary (mine working).

Such geomechanical parameters as Q^*, characterizing the difference of the stress tensor components, and P^*, characterizing a probable rock failure mode, are applied to evaluate the stress state of rock [20]

$$Q^* = (\sigma_1 - \sigma_3)/\gamma H;$$

$$P^* = \sigma_3/\gamma H,$$

where σ_1, σ_3 - maximum and minimum components of the principal stress tensor, Pa.

As a result of mining, the initial stress field changes and crack systems are formed in the host rock. The technological permeability field $k_{tech,}$ stimulated by the mining and dependent on the stress tensor components [21-24], is superimposed on the initial permeability field k_0

$$k = k_0 + k_{tech}\left(\sigma_{ij}\right).$$

The change in the values of the permeability coefficients depending on the components of the principal stress tensor can be described as follows [25]

$$k = k_0 + \begin{cases} 0, \ \ Q^* < 0,4; \ P^* > 0,2; \\ k_{\min}, \ \ 0,4 < Q^* < 0,6; \ \ P^* > 0,1; \\ e^{0,26Q^* - 4,65}, \ \ 0,6 < Q^* < 1,0; \ \ P^* > 0,1; \\ k_{\text{fr}}, \ \ Q^* > 1,0; \ \ P^* < 0,1. \end{cases} \tag{3}$$

where $k_{\min}$ - the minimum permeability value required to start the filtration process, m^2; k_{fr} - permeability in the fractured zone, m^2.

The finite element method [26] was used to solve equations (1)-(3). Each time step *i*, which corresponds to approximately 5 minutes, takes into consideration the stress field influence on the filtration area shaping; influence of the liquid polymer pressure on the stress state of the rock [21]; and changes in physicomechanical as well as filtration characteristics of the rock during the polymer hardening.

Roof bolting is simulated with the help of rod finite elements [27].

3 Simulation of rock reinforcement when the polymer composition is injecting and hardening

Injection rock bolts are usually installed some time after the mine face has been removed for certain distance. For example, when the haulage crosscut was being built at the Heroiv Kosmosu mine in the zone of the Bogdanovsky Fault, polymeric chemical composition was injected into the mine roof and walls with a lag of 5 m from the mine face [17]. During this time, the near-contour rocks around the mine working are partially unloaded from rock pressure, acquiring additional permeability k_{tech}. Therefore, we will not simulate the injection process immediately, starting from the first time step *i*, but a little later, at the time $t=t_{\text{start}}$. t_{inj}=20 min is the delivery period (4 time steps). The same time is necessary for complete hardening of the polymer. p_0=6 MPa is the delivery pressure.

Foaming (increase in volume) of the polymer composition during mixing of its components and chemical reactions is modeled using the source function $q(t)$ in the filtration equation for the liquid components of the polymer composition (2).

When the liquid polymer that fills the cracks and voids in the rock solidifies, the physical-mechanical and filtration properties of the hardened region change. In this study, it was assumed that while the polymer solidifies: the elasticity modulus of the hardened finite element increases linearly by 1.7 times; compressive resistance □$_c$ increases linearly by 1,5 times; ultimate tensile strength □$_p$ increases linearly by 2,0 times; the filtration permeability coefficient of the hardened finite element decreases linearly to 0.

A metal delivery pipe starts its operation as a reinforcing component only after durable fixation within a borehole, that is, after the polymer has solidified. Therefore, we will take into account the reinforcing effect of the rod finite elements, starting from the time $t=t_{start}+t_{inj}$.

The length of the injection rock bolt is 2,5 m. The sealer 0,26 m long is located at a distance of 0,7 m from the bolt head, Fig. 1.

4 Mechanism of forming a reinforced arch in the mine roof using injection rock bolts

4.1 Formation a reinforced support around one injection rock bolt

Let us consider a rectangular cross-section mine working with 5.2 m width and 3,0 m height being driven through the soft rocks (elasticity modulus is E=10^4 MPa; and compressive resistance is □$_c$=28 MPa). To study the process of formation of a reinforced support around an injection rock bolt, we will consider the case when one injection rock bolt is installed in the mine roof. We will also assume that the host rocks are disturbed and have an initial permeability k_0 = 0,01 mD. We will start injection process simulation from the 2nd time step. The metal delivery pipe will start its operation as a reinforcing component only after durable fixation within a borehole, so the influence of rod finite elements will be taken into account starting from the time step i = 6.

Fig. 2 demonstrates the results of calculating Q^* parameter values, zones of inelastic deformations (red color) and permeability coefficients before installing the injection rock bolts and the start of polymer injection.

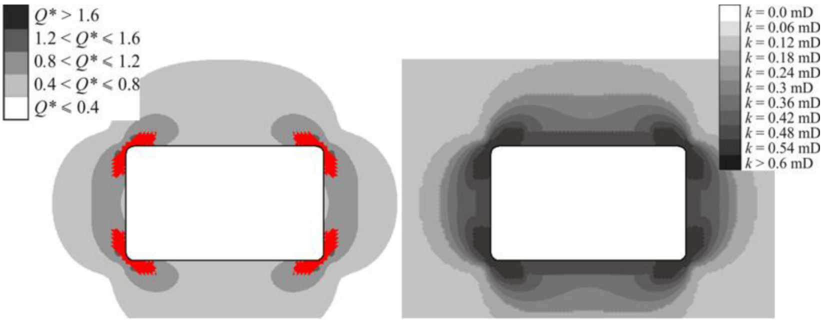

Fig. 2. Distributions of Q^* parameter values and inelastic deformation zones (left side); permeability coefficients (right side)

The mine working driving disturbs the equilibrium state of rocks; there is a redistribution of the initial stress field. By the time the injection rock bolt is installed, the near-contour rocks have been partially unloaded from rock pressure; a zone of increased diversity of components has been formed around the mine working (Fig. 2, left side). Under multicomponent loading, when microcracking occurs in the rock ($0,4 < Q^* < 0,6$), the increase in permeability is very insignificant. This stage of deformation is characterized by the accumulation of single, noninteracting defects [28]. Beyond the elastic limit, before reaching the strength limit ($0,6 < Q^* < 1,0$; $P^* > 0,1$), intense cracking and uncontrolled cracks growth occur. Deformations rapidly increase due to the propagation of cracks and loosening of the rock. When stresses reach the ultimate strength of the rock ($P^* < 0,1$), the process of macroscopic fracture begins. Brittle fracture of the rock is characterized by an increase in deformations, loosening and, accordingly, the volume of the material [28], which causes a sharp increase in permeability. Thus, the values of the permeability coefficients around the mine working increase (Fig. 2, right side).

After drilling a borehole, installing the injection rock bolt and starting the polymer delivery, the stress field noticeably changes, Fig. 3.

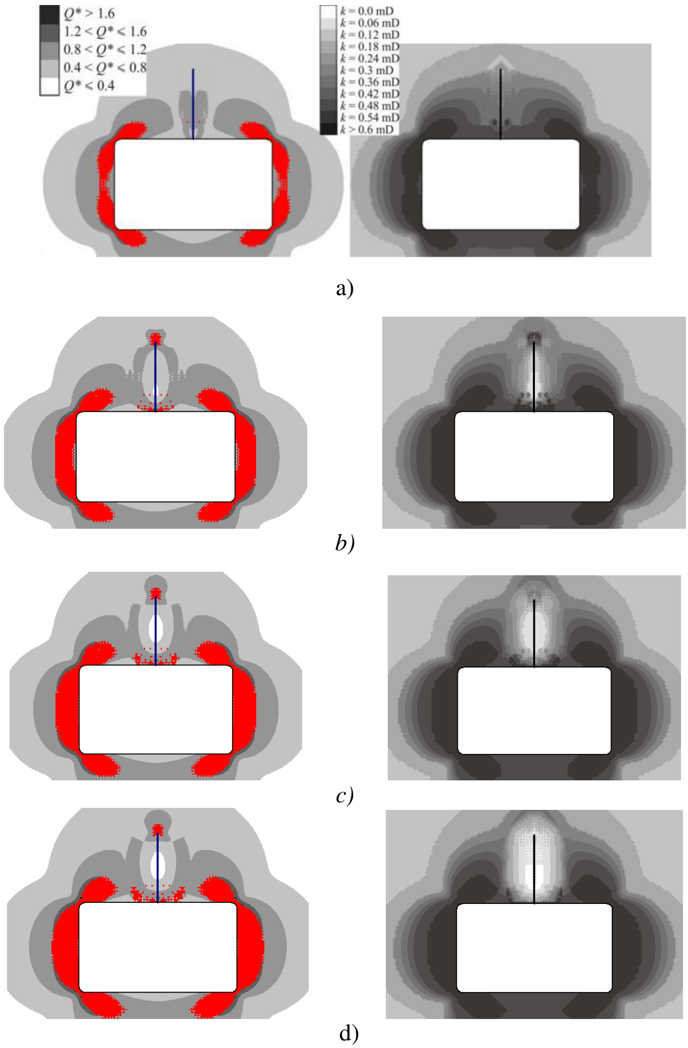

Fig. 3. Distributions of Q^* parameter values and inelastic eformation zones (left side); permeability coefficients (right side): *a* - $i = 4$; *b*- $i = 6$; *c* - $i = 8$; *d* - $i = 10$

The areas of increased difference of the stress tensor components (Q^* parameter) and inelastic deformations around the mine working grow over time, (Fig. 3, left side); the host rock continues to unload from rock pressure. However, at 10-15 minutes of polymer delivery, its effect on the rock stress state and permeability of near-contour rocks begins to show; at the place where the injection rock bolt was installed, in the mine roof, at *i*=4 the connected domain where $0,8<Q^*<1,2$ is broken.

In terms of *i*=6, a delivery process is over, and the polymer has hardened partially. A metal pipe starts operating as an rock bolt. Both elasticity modulus and strength limits of the polymer-reinforced rocks increase. Decrease in the difference of the stress tensor components and the rock permeability is the common result of such transformations. Q^* parameter values around the rock bolt reduce; now in this area $Q^*<0,8$ (Fig. 3*b*, left side). The values of permeability coefficients, although in a small volume of rock, drop to values less than k_0 (Fig. 3b, right side).

After another 2 time steps, at *i*=8 (Fig. 3*c*, left side), the area of reinforced rocks around the injection rock bolt expands, the diameter of the zone where $0,4<Q<0,8$ is 1,4 m. A zone of equal-component compression $Q^*<0,4$ with a diameter of 0,55 m appears. Accordingly, the volume of impermeable rocks around the injection rock bolt increases, which is clearly seen in Fig. 4*c*, right side. The diameter of the zone where $k<0,1$ is 1,1 m.

At *i*=10, the polymer completely solidified; the volume of impermeable rocks around the injection rock bolt increases even more. The diameter of the zone of reduced permeability now reaches 2,0 m.

Next, we will consider the change in the pressure of the polymer composition in the study area during its injection and solidification. To demonstrate the influence of the effect of an increase in the volume of the polymer during chemical reactions on the area of distribution of the reinforcing composition, the results of calculations, which were performed with and without foaming, are shown in Fig. 4.

The reinforcing composition is delivered through the permeable surface of the borehole; the pressure has maximum values there. A filtration process of a liquid polymer is restricted by the rock mass area with rather developed fracture network.

When the components of polymeric composition are being mixed, chemical reaction behaviour increases its volume. While increasing the volume, the polymer generates extra pressure inside a fractured space of the rock. Under pressure, the foamed composition gets even into small fractures of the rock.

a)

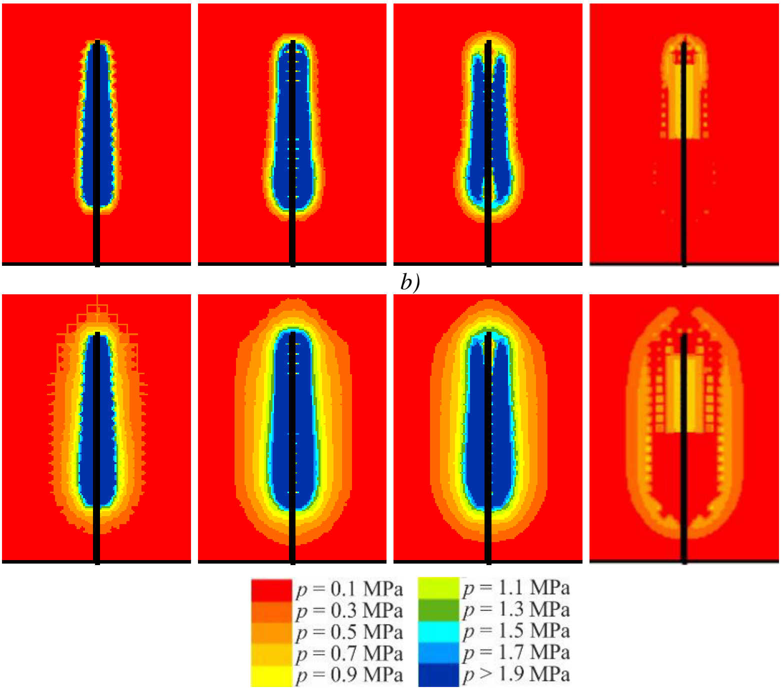

Fig. 4. The liquid polymer pressure at time steps i=4; i=6; i=8; i=10: *a* - ithout foaming of the polymer; *b* - taking into account its foaming

Therefore, the area of high pressure around the injection rock bolt is much larger when foaming is taken into account (Fig. 4*b*).

Starting from the 6th time step, delivery is completed, the polymer continues to solidify, and its pressure decreases.

Fig. 5 shows the rock region around the injection rock bolt, the fracture space of which is filled with polymer, at various points in time.

The calculations were performed without taking into account the polymer foaming and taking it into account polymer foaming. The diameter of the reinforced area in the first case is 1,25 m (Fig. 5*a*, i=10), in the second case it is 2,15 m (Fig. 5*b*, i=10).

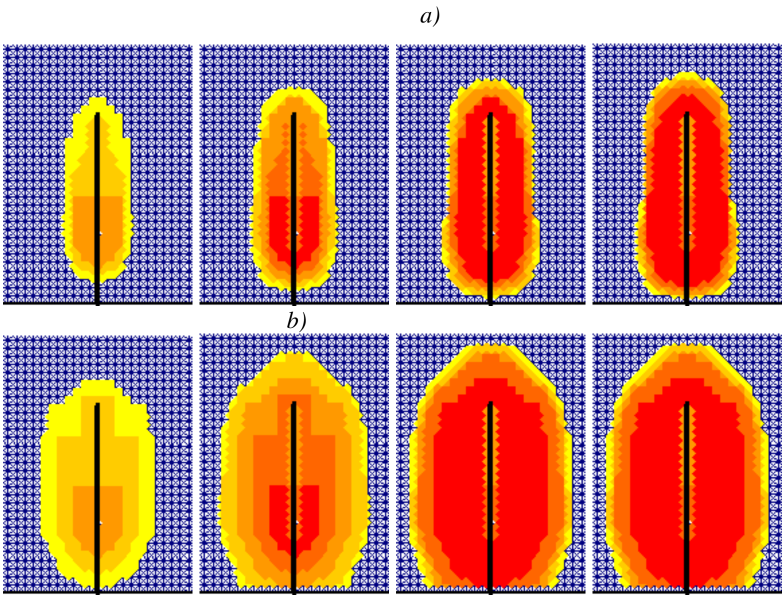

Fig. 5. Reinforced area around the injection rock bolt at time steps *i*=4; *i*=6; *i*=8; *i*=10: *a* - without taking into account the polymer foaming; *b* - taking into account polymer foaming

Thus, after the solidification of foamed polymer, a reinforced gas- and water-proof area is formed around the injection rock bolt. Its shape and dimensions depend upon the configuration and dimensions of a filtration zone being a permeable space in the neighbourhood of an injection rock bolt within which the liquid polymer spreads. Rock permeability in this zone is determined by natural fracture pattern as well as the technological one stipulated by an unloading degree of near-contour rocks.

4.2 Formation of a reinforced, impermeable rock-bolts arch in the mine roof with injection rock bolts

While developing a mine working support scheme using injection rock bolts, one should know how close is interaction of the reinforced zones and whether they form the integrated mechanical structure being a complete arch capable of protecting the mine working against failure, gas emission, and water inflows. If the reinforced zones are not interconnected then breakdown of the arch and roof failure are possible Let us study how the shape and dimensions of the polymer-reinforced area change depending on the density of injection rock bolts setting. We will consider a mine working, which is driving under conditions similar to those described above, and in the roof of which N_a injection rock bolts are installed:

- the first case, N_a=3, distance between bolts is 2 m;
- the second case, N_a=5, distance between bolts is 1,2 m.

The computations have helped obtain distributions of values of geomechanical and filtration parameters at various time steps if N_a=3 and N_a=5. Fig. 6 shows distributions of Q^* parameter values and nonelastic deformation zones (red colour). Fig. 7 demonstrates distributions of permeability coefficients k within the studied area during the polymer delivering and solidification.

In both cases, the areas of high difference of the stress tensor components and nonelastic deformations around the mine working extend in the course of time (Fig. 6); and rock mass releases gradually from rock pressure. However, a zone of high fracturing where $0,8<Q^*<1,2$ decreases within the mine working roof, in the bolted area (Fig. 6a). In such a way, strengthening influence on the stress state of near-contour rocks starts manifesting despite the injection rock bolts are still surrounded with a zone where $0,8<Q^*<1.2$ and roof rock permeability k have experienced minor changes (Fig. 7a).

In terms of i=6, a delivery process is over, and the polymer has hardened partially. A metal pipe starts operating as a rock bolt. Both elasticity modulus and strength limits of the polymer-reinforced rocks increase. As a result, there is a decrease in the difference of the stress tensor components and the rock permeability. Q^* parameter values around the injection rock bolts reduce. In terms of N_a=3, central bolt is surrounded with an area where $Q^*<0,8$. The same is true for three central bolts if N_a,=0,5 (Fig. 6*b*). The values of permeability coefficients k drop down the initial permeability coefficients k_0 (Fig. 7*b*) neutralizing changes caused by the mine working driving. If $N_{a,}$=5 then the greater rock amount is involved.

After the solidification process in terms of i=10 is over (Fig. 6*c*), the area of the reinforced rock around injection rock bolts expands; width of the zone where $0,4 < Q^* < 0,8$ and $N_a = 3$ is 1,7 m. If $N_a = 5$ then the width is 3,2 m. The area of uniform compression where $Q^* < 0,4$ arises around the central bolts. Since the moment, each injection rock bolt is surrounded with a zone of completely impermeable rocks with more than 0.6 m diameter shown clearly in Fig. 7*c*.

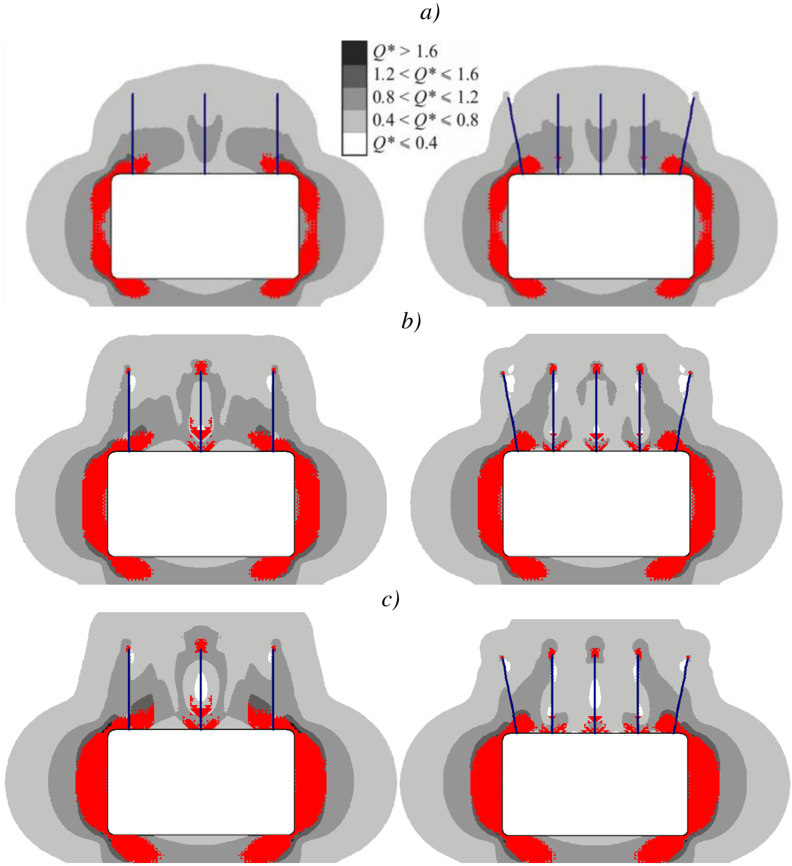

Fig. 6. Distribution of the Q^* parameter values and the inelastic deformation zone bolts are installed in the when 3 (left side) and 5 (right side) injection rock mine roof: *a* - = 4; *b* - *i* = 6; *c* - *i* = 10.

However, if $N_a = 3$ then highly permeable rocks (in our case, their permeability is more than 0,4 mD) occur between the impermeable areas. Three monolith polymer-reinforced rock-bolt supports are not linked; they are separated by zones of the fissured disturbed rocks where $0{,}4 < Q^* < 0{,}8$ and $k > 0{,}4$ mD.

In the second case when $N_a = 5$, almost impermeable rock-bolt arch is formed from five polymer-reinforced supports. Fig. 6 explains that the area with $Q^* < 0{,}8$ parameter values has spread towards the mine working walls occupying now greater share of the rock bolted mine roof. Owing to the increased value of minimum component of the principal stresses as well as the decreased maximum component, the stressed state of rocks went into uniform compression state and became stable. As a result, the system, consisting of five injection rock bolts, has formed the high-strength uniform arch blocking the potential for spontaneous failure.

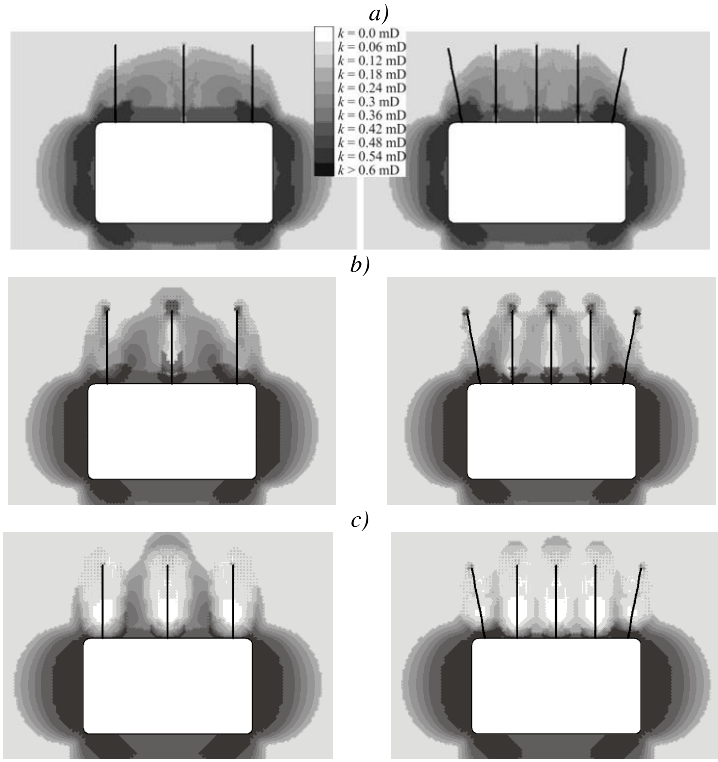

Fig. 7. Distribution of permeability coefficients values when 3 (left side) and 5 (right side) injection rock bolts are installed in the mine roof: *a* - $i = 4$; *b* - $i = 6$; *c* - $i = 10$

Fig. 8 and 9 demonstrate graphs of changes in P^* parameter as well as rock permeability coefficients within the mine roof at a 1.2 m distance from its surface concerning the two considered cases.

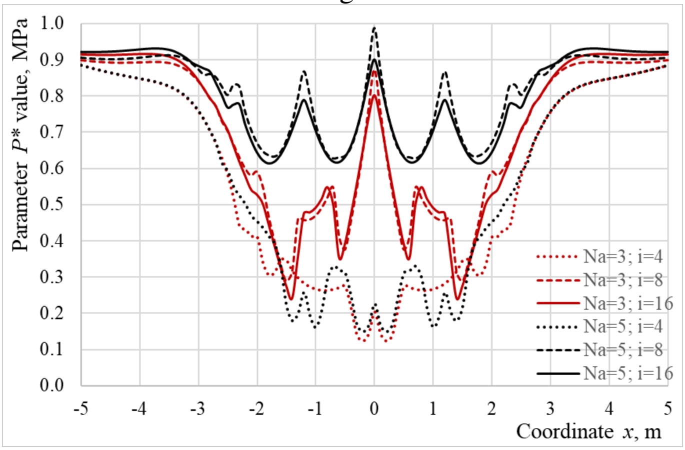

Fig. 8. Changes in P^* parameter values within the mine roof where 3 and 5 injection rock bolts are installed

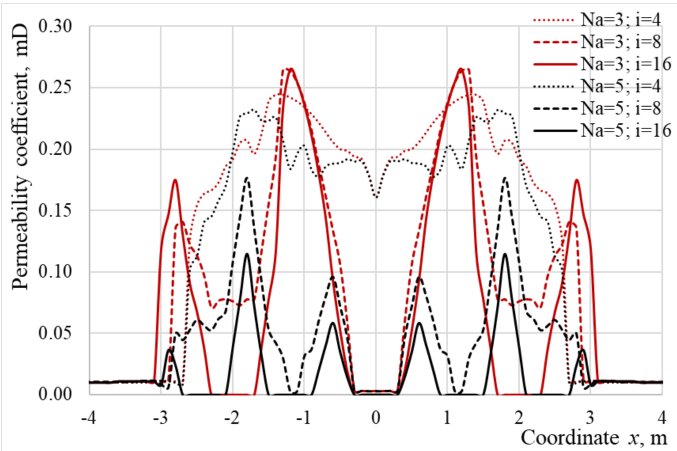

Fig. 9. Changes in the values of permeability coefficients within the mine roof where 3 and 5 injection rock bolts are installed

In the graphs, $x = 0$ coordinate corresponds to the central share of the mine working (i.e. location of the central rock bolt). Coordinates of the mine working walls are ±2,6 m. P^* parameter characterizes a probable rock failure mode: the closer P^* value to a unit is, the more stable near-contour rocks are. Graphs in Fig. 8 show that at the start of a delivery process, if $i = 4$, $P^* \approx 0{,}15$ for $N_a = 3$ and $N_a = 5$. Such low P^* values stipulates beginning of roof rock transition to unstable state. P^* values increase after the delivery is over and polymer is solidified ($i = 8$-16). If $N_a = 3$ then average P^*_{av} is 0,51; and minimum value is P^*_{min}- 0,24 within the mine working roof $x \in [-2{,}6; 2{,}6]$. If $N_a = 5$ then $P^*_{av} = 0{,}7$, and $P^*_{min} = 0{,}61$. The increased density of injection rock bolts results in 2,5 times increase of P^* parameter supporting the idea of roof stability improvement.

It follows from Fig. 9 that at the initial delivery stage (when $i = 4$), the values of filtration permeability k achieve 0,23 mD for both supporting schemes at a 1,2 m distance from the mine roof. After the polymer delivery and its solidifying ($i = 8$-16) when $N_a = 3$, k_{max} value increases up to 0,27 mD between the rock-bolt supports (for the assumed initial and boundary conditions). Deep in the rock mass at a 1,2 m distance from the mine roof, the average permeability value is 0.08 mD. If $N_a = 5$ then $k_{av} = 0{,}02$ mD, and $k_{\max} = 0{,}1$ mD. Increase in the density of injection rock bolts results in 4 time decrease of the average value of permeability coefficients within the mine roof.

Fig. 10 shows the areas where fracture space of the mine roof are packed with the polymer at different time steps for the considered supporting schemes.

Starting from the 6th time step, the delivery stops. The polymer continues its solidifying; its pressure drops gradually. A filtration process of a liquid polymer is restricted by the rock mass area with rather developed fracture network.

In terms of the assumed initial and boundary conditions, a diameter of one reinforced area is 1.5 m. Nevertheless, in the first case when $N_a = 3$, the areas are not interconnected (Fig. 10*c*, left side); hence, they cannot protect the mine working against failure, gas emission, and water inflow.

If sufficient number of injection rock bolts (five ones in the context of the case) are installed within the mine roof then reinforced arch with low permeability appears (Figs. 10b and 10c, right side). Such an arch is required for the mine working stability, and it becomes the barrier restricting water inflow and gas emission from the undermined rocks into the mine working.

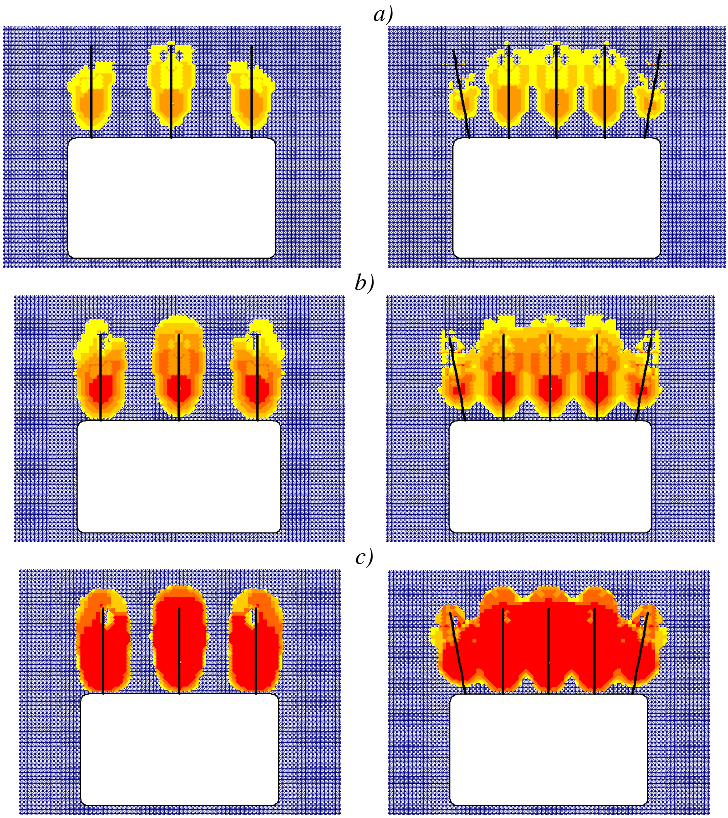

Fig. 10. Roof rock fracture packing with the polymer while installing 3 and 5 injection rock bolts: *a* - $i = 4$; *b* - $i = 6$; *c* - $i = 10$

4.3 Formation of a reinforced rock-bolts arch in the mine roof depending on the initial permeability of host rocks

Let us investigate how the initial permeability of host rocks affects the shape and dimensions of the polymer-reinforced region.

The abovementioned computations have been performed if $N_a = 3$ and initial natural rock permeability is $k_0 = 0{,}01$ mD. It is quite obvious fact that other k_0 values will vary the diameter of the reinforced area around the injection rock bolt (Fig. 11).

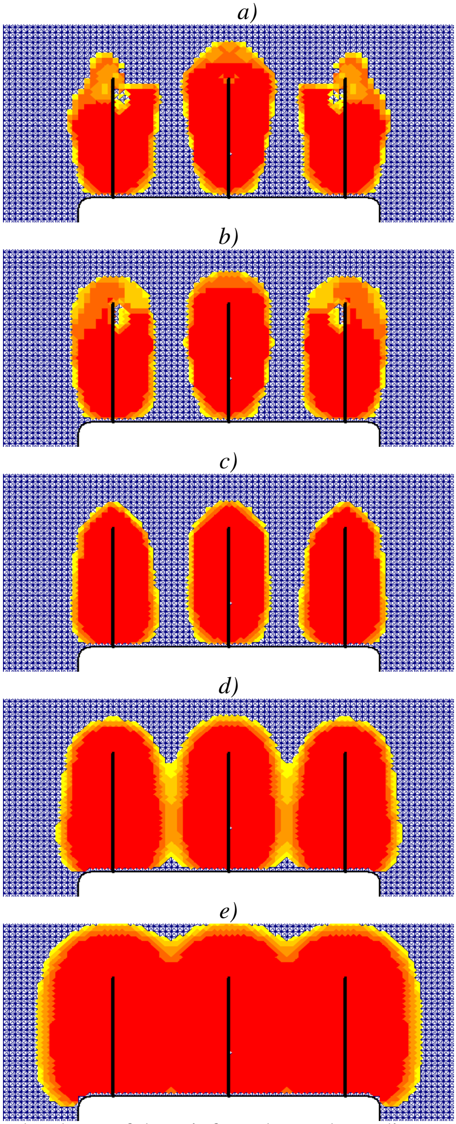

Fig. 11. Changes in the shape of the reinforced area depending on the values of initial permeability: *a* - k_0 = 0,001 mD; *b* - k_0 = 0,01 mD; *c* - k_0 = 0,1 mD; *d* - k_0 = 0,4 mD; e - k_0 = 1,0 mD

In the context of three first cases (Figs. 11*a-c*), the polymer-reinforced areas around the rock bolts are not interconnected; their diameters are almost similar (about 1,5 m). In terms of low initial permeability values (Figs. 11*a* and 11*b*), the upper share of rock-bolt supports is not shaped completely. Proper packing of a fracture space is possible only within the area, influenced by a mine working zone, restricted by the filtration region. If $k_0 > 0{,}1$ mD then the initial permeability starts influencing the reinforced areas diameter: if $k_0 = 0{,}4$ mD they contact (Fig. 11*d*); and if $k_0 = 1{,}0$ mD they form monolith arch (Fig. 11*e*).

Generally, quite typical increase in the dimensions of the reinforcing zone is observed along the increase in the initial rock permeability. Fig. 12 represents dependence of changes in the reinforced area upon the value of initial permeability of host rock for the mentioned conditions of the mine working driving.

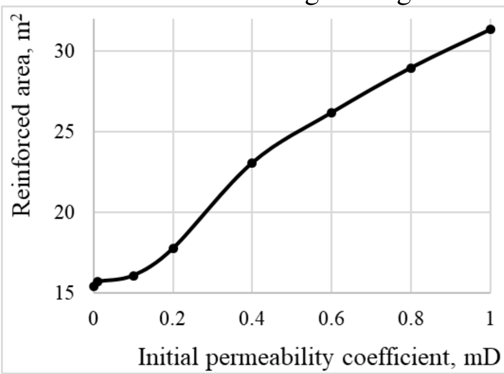

Fig. 12. Dependence of changes in the reinforced area upon the value of initial permeability of host rock

Hence, development of schemes for the mine working support with the help of injection rock bolts should involve following factors determining formation of a permeable zone for a polymer filtration: time from the moment of the mine face was removed; initial rock permeability; and density of injection rock bolts. Consequently, to optimize supporting schemes of the mine working by means of injection rock bolts under specific mining and geological conditions, it is quite expedient to perform early computations using the proposed numerical model.

5 The use of injection rock bolts in combination with steel rock bolts in difficult mining and geological conditions of coal mines in Ukraine

Let us consider a mine working with a cross-section of TSYS-17.7, which is located in disturbed rock near a tectonic fault. We will assume that filtration permeability coefficient $k_0 = 0.01$ mD in the zone of fault influence, and in the immediate vicinity of the dislocation plane $k_0 = 0.1$ mD.

To investigate how the order of installation of steel and injection rock bolts affects the quality of the mine working support, we will consider two cases:

1) at the mine face, at the 3rd time step i, 7 steel rock bolts 2.4 m long are installed; injection of polymer (8 injection rock bolts) is carried out with a lag of 5 m from the mine face, at $i = 10$ (27 h);

2) at the mine face, at $i = 3$, the polymer is injected in 8 injection rock bolts; and 7 steel rock bolts are installed with a lag of 5 m from the mine face, at the 10th time step.

5.1 Changes in the stress state and permeability of host rocks in the process of supporting the mine working

Fig. 13 demonstrates the results of calculating Q^* parameter values, zones of inelastic deformations (red color) and permeability coefficients before installing rock bolts.

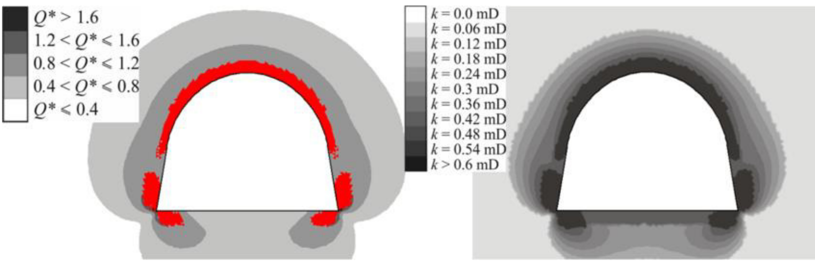

Fig. 13. Distributions of Q^* parameter values and inelastic deformation zones (left side); permeability coefficients (right side) at the time step $i = 2$, $k_0 = 0{,}01$ mD

Extraction of coal and rocks initiates the process of redistribution of the stress field in the host rocks. Since the rocks near the tectonic fault are weakened and disturbed, an area of increased difference of the stress tensor components (parameter Q^*) is already formed around the mine working at the second time step. The vault of the mine working is surrounded by a zone up to 1 m deep, where $0.8 < Q^* < 1,2$ (Fig. 13, left side). An inelastic deformation zone, shown in red, appears on the mine working contour, in which the process of fracturing leads to stratification and disintegration of near-contour rocks.

It can be seen (Fig. 13, right side) that the values of the permeability coefficients are not equal to zero even outside the zone of influence of the mine working (light gray color), since the host rocks are disturbed near the tectonic fault. The permeability values vary from 0,01 mD to 0,5 mD at a distance of 1.5 m to the mine working contour.

At the next time step (i=3), rock bolts are installed: in the first case, these are steel rock bolts, in the second case, these are injection rock bolts, through which the polymer is delivered into the fractured space of the host rocks. Let us compare the changes in stress fields and permeability around the mine working over time in these two cases.

Fig. 14 shows the distributions of Q^* parameter values and inelastic deformation zones; Fig. 15 shows distributions of permeability coefficients k for our two cases at different time steps. It can be seen that in both cases, the areas of increased Q^* parameter values around the mine working in the time interval from the 3rd to the 9th time step expand very slowly, almost imperceptibly, since the installation of the rock bolts hinders the process of further unloading of the host rocks from rock pressure.

Small areas are formed around the rock bolts, in which the rocks are in a state of uniform compression ($Q^* < 0,4$), similar to the state of undisturbed rocks. However, when steel rock bolts are installed, the area where the values of the Q^* parameter are very high ($Q^* > 1,2$) practically disappears (Fig. 14*a*, left side), since, firstly, there are one more steel rock bolts than injection ones. In addition, steel rock bolts come into operation almost instantly, already 30 s after they are installed, immediately after the quick-hardening fixer located in their bottom part has set.

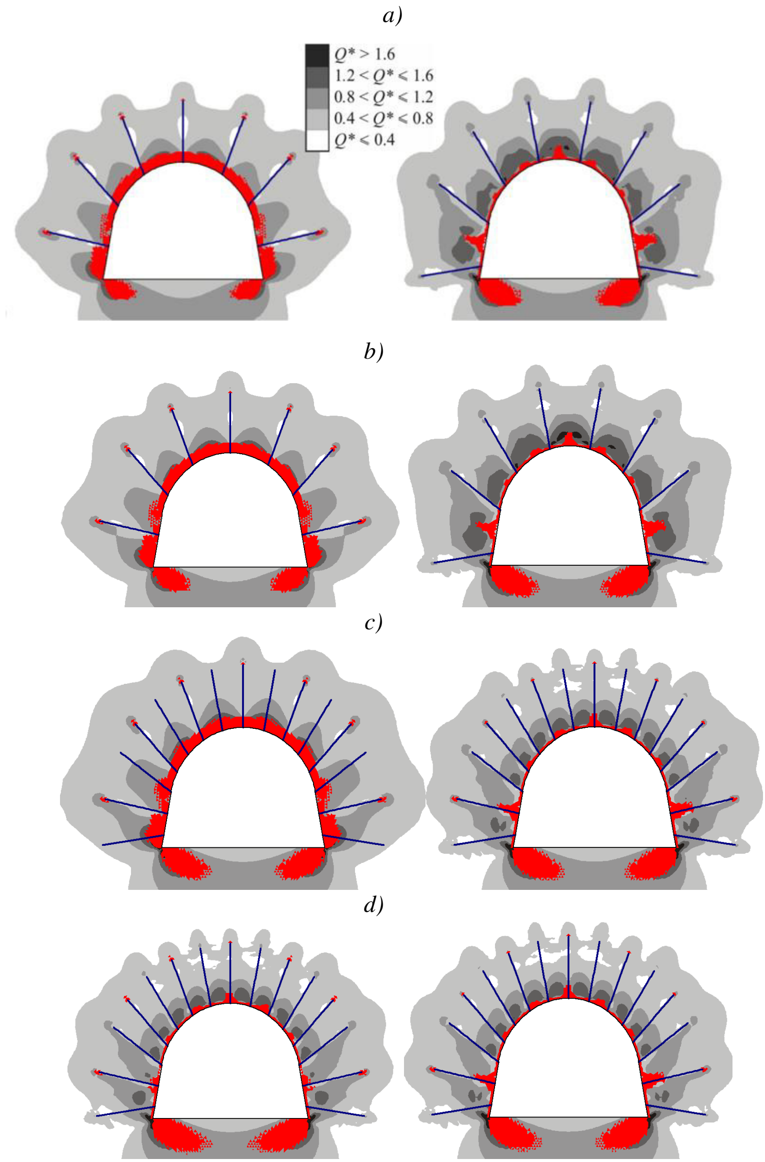

Fig. 14. Distribution of Q^* parameter values and inelastic deformation zones (red color) for the first calculation (left side) and the second calculation (right side) at the time steps: *a* - $i = 4$; *b* - $i = 6$; *c* - $i = 10$; *d* - $i = 20$

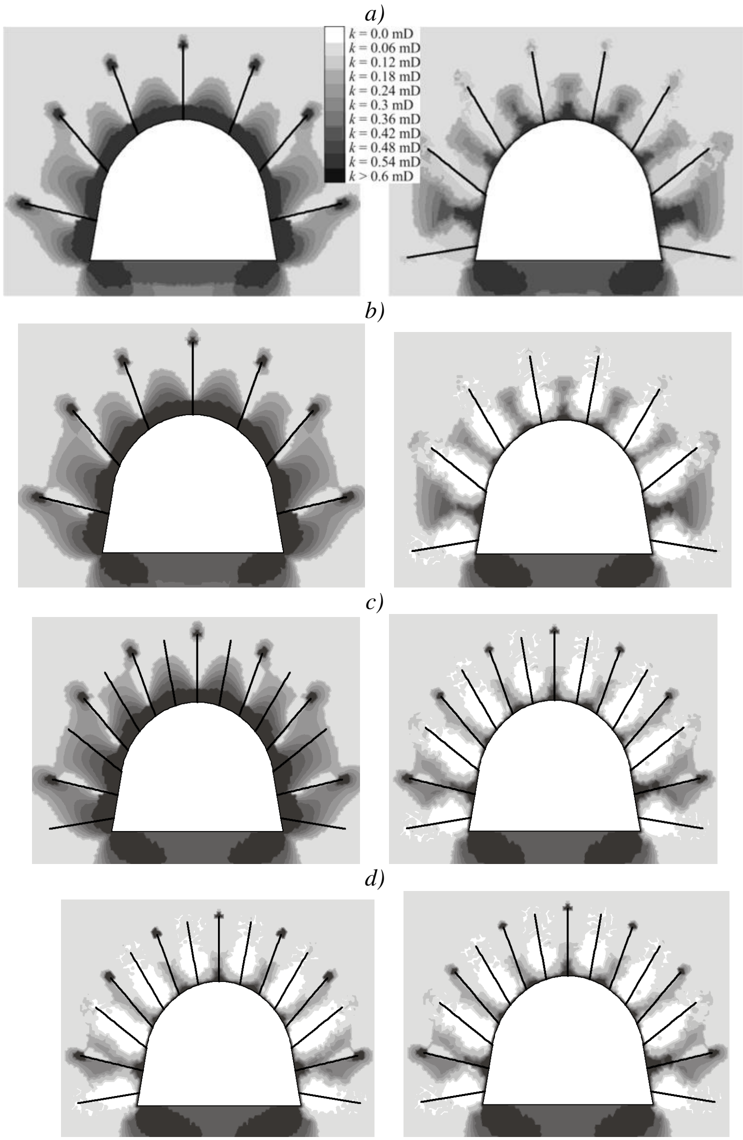

Fig. 15. Distribution of values of permeability coefficients for the first calculation (left side) and the second calculation (right side) at the time steps: *a* - $i = 4$; *b* - $i = 6$; *c* - $i = 10$; *d* - $i = 20$

Conversely, the metal pipe of the injection rock bolt, through which the polymer is delivered, comes into operation only after the delivery is completed and the polymer has solidified.

In the first calculation, when the steel bolts are installed first, the inelastic deformation zones do not decrease after steel rock bolts are installed during the time interval from the 3rd to the 9th time step. Steel bolts do not turn the disturbed rock into a monolith, they fix the state of the host rocks at the time of their installation and do not allow further unloading of the rock mass.

In the second calculation, after the completion of the polymer solidification process (Fig. 14*b*, right side), an region of reinforced rocks, the elasticity modulus and tensile strength of which have increased, is formed around the injection rock bolts. From this point in time, each injection rock bolt is surrounded by a zone of completely impermeable rocks with a diameter of 1,2-1,5 m, which is clearly seen in Fig. 15*b*, on the right side. In the near-contour area, where previously there was a zone of inelastic deformations, due to the binding of stratificated rocks by the polymer, they again acquired the properties of a monolith. However, with a low initial permeability k_0 = 0,01 mD and with a given number of injection rock bolts, there are rocks with high permeability (in this case reaching 0.3 mD) between the impermeable regions. Polymer-reinforced monolithic rock-bolt supports are not sufficiently interconnected, they are separated by areas of disturbed rocks, where $Q^* > 0,4$ и $k > 0,3$ mD.

At the 10th time step, which approximately corresponds to a five-meter lag behind the mine face, the rock bolts are installed again: in the first case, these are injection rock bolts; in the second, these are steel ones. After that, the disadvantages of suppjrting described above are neutralized. In the first case, the zone of inelastic deformations in the near-contour area disappears, and the stratified rocks become monolithic and strong again. Their permeability is significantly reduced. In the second case, the difference of the stress tensor components in the bolted area decreases. By the 20th time step, both the stress state of the host rocks and their permeability in the two considered cases become almost the same. In the mine roof, the area of uniform compression, where $Q^* < 0,4$, increases. Thus, steel and injection rock bolts complement each other very well, increasing the stability of the mine working and reducing the filtration permeability of the host rocks.

Let us construct graphs of the average values of the geomechanical parameters Q^* and P^*, as well as the rock permeability in the bolted area in the process of supporting the mine working for the two considered cases and in the absence of support for comparison, Figs. 16 and 17.

a *b*

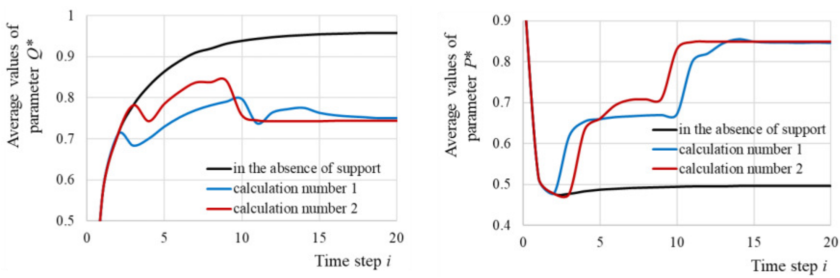

Fig. 16. Average values of the geomechanical parameters in the bolted area around the mine working: *a* -arameter Q^*; *b* - parameter P^*

Over time, the difference of the stress tensor components increases around the unsupported mine working, which leads to fracturing of varying degrees of intensity in the host rocks, Fig. 16*a*, black curve. If the values of this geomechanical parameter decrease, the mine working becomes more stable. The use of steel rock bolts for supporting in the initial time makes it possible to reduce the average value of the Q^* parameter in the bolted area by 12-15% compared to the unsupported mine working (Fig. 16*a*, the time from the 3rd to the 9th time step). If injection rock bolts are installed first, this parameter is reduced by 8-10%. As a result of the combined action of the steel and injection rock bolts, the average value of the Q^* parameter decreases by 22% (Fig. 16a, $i > 15$).

When the free surface is exposed during the excavation of rock and coal, as a result of unloading from rock pressure, the minimum component of the principal stress tensor (parameter P^*) decreases, and if the strength criterion is met, the process of rock destruction will begin. An increase in the value of the parameter P^* in a certain area of the rock mass will bring the state of this area closer to equal-component compression, and the probability of its destruction will decrease. In the period from the 3rd to the 9th time step, when the mine working is supported with only one type of supporting, steel rock bolts increase the average value of the P^* parameter in the bolted area by 30-35%, injection rock bolts increase this parameter by 31-43%, Fig. 16b. Steel rock bolts come into operation faster, and injection bolts, although they gain bearing capacity more slowly, strengthen the rock a little better. In general, by the 20th time step, the average value of the P^* parameter in both cases is increased by 70%, the possibility of near-edge rock destruction is excluded.

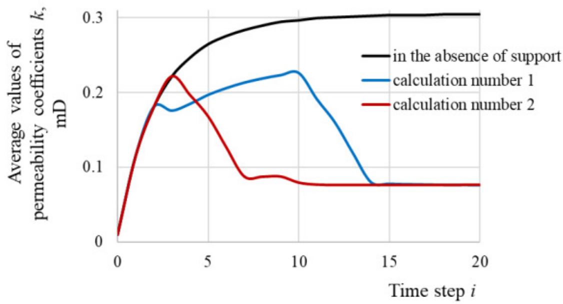

Fig. 17. Average values of rock permeability in the bolted area around the mine working

Fig. 5 shows that the reduction in filtration permeability is mainly due to injection rock bolts. This is because the foamed polymer under high pressure penetrates even into small cracks in the rock and, after it hardens, the possibility of fluid filtration in the consolidated region is excluded. In the first calculation, the average permeability in the bolted area is reduced by 75% compared to the unsupported mine working by the 14th time step. In the second calculation it is reduced by the same amount by the sixth step. If the polymer is injected into disturbed rocks closer to the mine face, then an impermeable shell arch around the mine working will form faster.

If we compare the results of the two calculations, we can see that injection rock bolts exclude the possibility of destruction of host rocks and more effectively reduce the permeability of disturbed rocks in the zone of influence of the tectonic fault. And steel rock bolts better restrain the expansion of the zone of increased difference of the stress tensor components. Therefore, in the case of heavily watered rocks or a high probability of methane breakthroughs into the mine working, it is better to install injection rock bolts and deliver the polymer into the disturbed rock as close as possible to the mine face. Then a water- and gas-proof shell arch around the mine working will be created in the immediate vicinity of the mine face, which will make it possible to quickly prevent emergency water inflows and gas emissions. If there is no such threat and the priority is to maintain the long-term stability of the mine working, then first of all it is necessary to install steel rock bolts with polymer fixing in the borehole. In the rocks fastened with steel bolts, the lateral thrust growths, their residual bearing capacity increases, and the rock displacement into the mine working is significantly reduced. The rock-bolts structure performs its function during the entire period of mine working maintenance.

5.2 Formation of a polymer-reinforced region around the mine working in various zones of tectonic fault

Fig. 18 shows the results of calculation of host rock regions, the fracture space of which is filled with polymer.

The polymer is delivered into the disturbed rock at the 3rd time step in the first calculation and at the 10th time step in the second one. The diameter of one hardened region is 1-1,5 m.

The chemical reaction when mixing the components of the polymer composition proceeds with an increase in its volume. Increasing in volume, the polymer creates additional pressure inside the fractured-pore space of the rock.

The foam composition penetrates under pressure even into small cracks in the rock mass, however, this process is limited by the size of the filtration area around the mine working.

The polymer-reinforced region is not fully formed around each injection rock bolt (Fig. 18*d*).

The bottoms of 6 out of the 8 installed injection rock bolts extend beyond the filtration area. In general, it can be seen that both the first and second supporting schemes by the 20th time step give almost the same result.

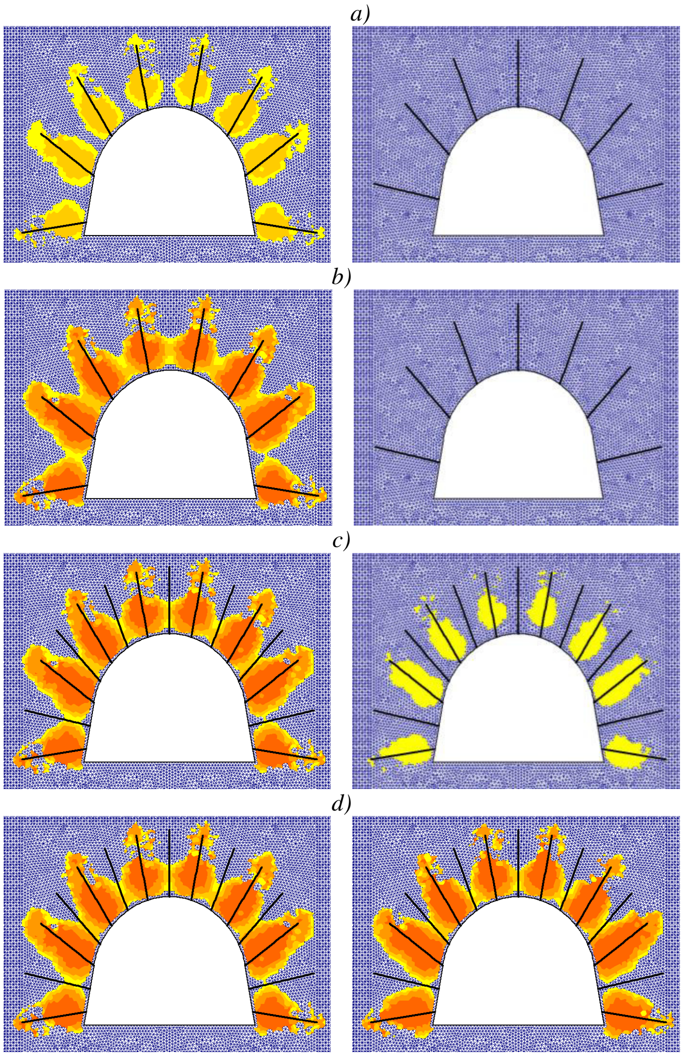

Fig. 18. Host rock regions, the fracture space of which is filled with polymer for the first calculation (left side) and the second calculation (right side) at the time points: *a* - $i = 4$; *b* - $i = 6$; *c* - $i = 10$; *d* - $i = 20$

Let us consider how the shape and area of the polymer-reinforced region will change at a higher initial permeability $k_0 = 0{,}1$ mD in the immediate vicinity of the dislocation plane, Fig. 19.

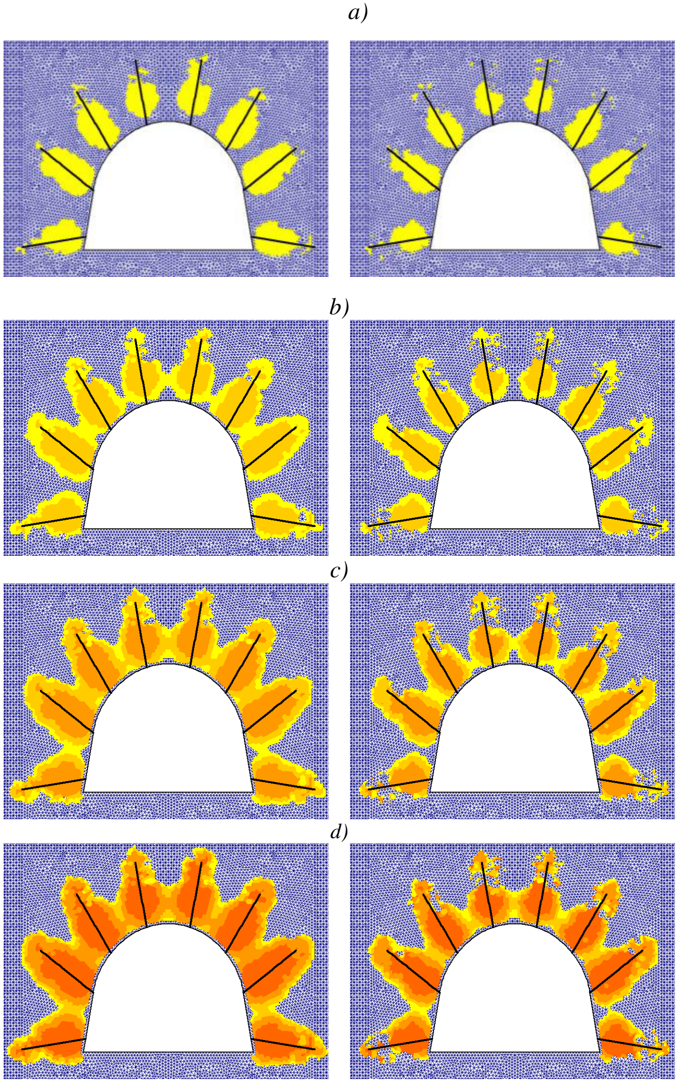

Fig. 19. Formation of polymer-reinforced regions when k_0 = 0.1 mD (left side) and k_0 = 0.01 mD (right side) at the time points: a -*t* = 5 min after the start of injection; *b*- - *t* = 10 min; *c* - *t* = 15 min; *d* - *t* = 20 min

At k_0 = 0,1 mD, the diameter of reinforced rocks increases, they are in closer contact with each other (Fig. 19, right side), forming a monolithic arch. Such an arch ensures the stability of the mine working and serves as a barrier that restrains water inflow and gas emission from the undermined rocks into the mine working.

In general, there is a regular increase in the size of the reinforced region with an increase in the initial rock permeability. The dependence of the change in the area of the hardened region on the initial permeability of the host rocks for the considered mining and geological conditions is shown in Fig. 20.

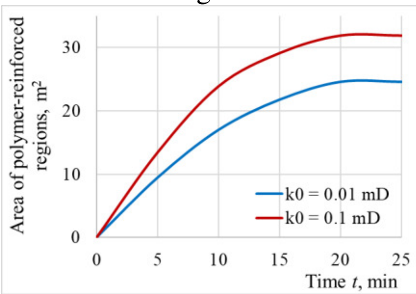

Fig. 20. Areas of the polymer-reinforced regions (in the plane of injection rock bolts installation) in various zones of the tectonic fault, at different values of the initial permeability k_0

When the mine working approaches the dislocation plane and the tectonic permeability increases from 0,01 to 0,1 mD, the diameter of the reinforced rocks around each injection rock bolt increases, they are in closer contact with each other, and the area of the polymer-reinforced region increases by 30%.

5.3 The use of steel and injection rock bolts in coal mines

Supporting technology with steel and injection rock bolts is successfully used in some coal mines of Ukraine when crossing large tectonic faults. For example, the Bogdanovsky fault (one of the largest faults in the Pavlogradsk-Petropavlovsk region) was crossed by a haulage crosscut at the Heroiv Kosmosu mine. The rock displacement amplitude in the work area is 195 m. The width of the disturbed zone is 36,6 m. Fig. 21 shows the supporting scheme.

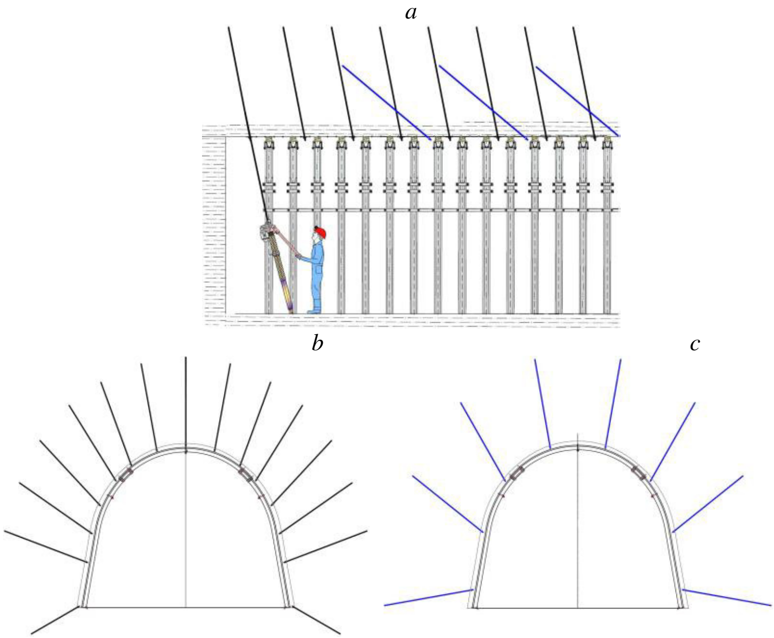

Fig. 21. The supporting scheme for the haulage crosscut: *a* - longitudinal section; *b* - cross section in row with steel rock bolts; *c* - cross section in row with injection rock bolts

The production plan provides for the operation of the haulage crosscut for 25 years. The haulage crosscut was supported with the frame support TSYS-17.7. Rock bolts were installed in the mine face. In order to strengthen the near-contour rocks, polymeric chemical compositions were injected using injection rock bolts with a lag of 5 m from the mine face.

The natural gas content in the coal seam is 8,7-25,2 m^3/t; at the crossing of the fault, the water inflow from 12 to 525 m^3/h was expected [17]. However, thanks to the measures taken when crossing this fault, the mine working remains stable, there are no breakthroughs of gas and water.

6 Conclusions

To study the mechanism of operation of injection rock bolts and the conditions for the formation of the rock-bolts arch around the mine working, a mathematical model of coupled processes of rock deformation and liquid polymer filtration in the disturbed area around the mine working was developed. The problem formulation takes into account the initial permeability of host rocks as well as the permeability due to the mine working driving; time of polymer delivery and hardening; and foaming effect of the polymeric composition in the process of mixing of its components. The changes in physicomechanical and filtration characteristics of rocks during the polymer solidification also were taken into account in the problem formulation as well as the fact that a metal delivery pipe starts operating as a reinforcing element after solidification of the polymeric composition is over.

It was demonstrated that the supporting scheme is important to form a rock-bolts arch. With sufficient density of injection rock bolts, the formed rock-bolts arch may serve as a barrier controlling both water inflow and gas emission from the undermined rocks into the mine working. This rock-bolts arch also ensures its stability. Dependence of changes in the reinforced area upon the value of initial permeability of the host rocks was derived. If the values of initial permeability are low then size of the rock-bolt supports and their shape are determined using only a value of the unloaded zone around the mine working.

Thus, the condition for the formation of a rock-bolts arch around the working with the help of injection rock bolts is the qualitative interaction between reinforced zones around each bolt, which is ensured by the following factors:

- the presence of a filtration area covering the entire zone of injection rock bolts installation with sufficiently high permeability;
- the value of the initial, tectonic rock permeability;
- the amount of time passed from the moment of mine face advance, because of its influence on technological rock permeability;
- the mine working support installed before injection rock bolts, because it also affects technological rock permeability;
- density of injection rock bolts sufficient for high-quality interaction of reinforced zones.

It was shown that steel and injection rock bolts complement each other very well, increasing the stability of the mine working and reducing the filtration permeability of the host rocks. Injection rock bolts exclude the possibility of destruction of host rocks and more effectively reduce the permeability of disturbed rocks in the zone of influence of the tectonic fault. And steel rock bolts better restrain the expansion of the zone of increased difference of the stress tensor components. Therefore, in the case of heavily watered rocks or a high probability of methane breakthroughs into the mine working, it is better to install injection rock bolts and deliver the polymer into the disturbed rock as close as possible to the mine face. Then a water- and gas-proof shell arch around the mine working will be created in the immediate vicinity of the mine face, which will make it possible to quickly prevent emergency water inflows and gas emissions. If there is no such threat and the priority is to maintain the long-term stability of the mine working, then first of all it is necessary to install steel rock bolts with polymer fixing in the borehole.

Supporting technology with steel and injection rock bolts is successfully used in the coal mines of Ukraine when crossing large tectonic faults.

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