UDC 622.831.325 DOI: https://doi.org/10.15407/geotm2024.170.133

ANALYSIS OF THE INFLUENCE OF INITIAL COAL SEAM PERMEABILITY ON THE HYDRAULIC EXTRUSION PROCESS

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Abstract. One of the methods for preventing coal and gas outbursts is hydraulic extrusion of the near-face part of a coal seam. Hydraulic extrusion is performed by high-pressure water injection into the coal seam through wells in faces of stopes and temporary roadways. This method differs from others in its high injection pressure and rate, as well as the short length of the filtering part of wells, which ensures the coal seam displacement into the roadway, coal unloading and degassing. But its effectiveness depends on a number of factors, including the natural coal seam permeability. In this regard, the purpose of this work is to analyse the influence of the natural, initial coal seam permeability on the course of the hydraulic extrusion process and its effectiveness. To achieve the goal, numerical simulation of time-dependent coupled processes of elastic-plastic rock deformation and liquid and gas filtration was performed, and distributions of geomechanical and filtration parameters in the near-face zone of a coal seam during hydraulic extrusion were obtained at different values of initial permeability.

The graphs of the time change of average permeability in the near-face zone of the coal seam show that its increase before the start of injection is caused by the roadway construction and the growth of the filtration area around it. When injection begins, a sharp increase in average permeability occurs due to the spread of the permeable area around the filtering parts of the wells. The average permeability increases for the second time at the end of the injection process, when the highly permeable areas around the filtering parts of the wells and at the roadway face are connected, after which water comes to the free coal surface. As it follows from the analysis of water pressure distributions in the fractured porous space of coal, lower natural permeability leads to a decrease in the area of increased water pressure around the filtering part of the wells; an increase in water pressure in this area; an increase in water pressure gradients, which affects its ability to expand cracks and promote their growth, as well as the dynamics of the hydraulic extrusion process. The efforts should help in selecting potential measures to prevent coal and gas outbursts depending on the initial coal seam permeability, as well as in assessing the technological parameters of hydraulic extrusion.

Keywords: coal and gas outburst, coal seam hydraulic extrusion, coupled processes, permeability, numerical simulation.

1. Introduction

Gas-dynamic phenomena in coal mines have high kinetic power and lead to poisoning of the mine atmosphere, equipment damage and human casualties [1–3]. They have become one of the most important subjects of research in the field of mining as the most destructive dynamic phenomenon.

The presence of water in the fractured porous space of coal significantly affects the course of gas-dynamic processes [4], therefore, methods related to water injection into the coal seam are used for coal and gas outburst prevention [5–10]. It was experimentally proven that with an increase in the water content in the fractured porous space of a coal seam, the intensity and probability of outbursts gradually decrease [11]. The ways that hydraulic measures eliminate the outburst risk are summarized as follows [4, 12]. Firstly, hydraulic measures increase the number of cracks and improve the permeability of coal seams, as well as the gas emission [13, 14]. Secondly, intensity of the process of gas sorption-desorption also depends on the water content in coal [5, 11, 15–18]. Under different conditions and at certain values of humidity, the mechanism of influence of water on the course of sorption-desorption processes changes. Thirdly, moisture saturation leads to a decrease in the rock strength and bearing capacity, changes the nature of their behaviour after reaching the limiting state [5, 19–23]. Water can enhance the capability of plastic deformation of coal and reduce the energy of its crushing. When the coal moisture is higher, it is more difficult to crush it and the possibility of outburst is reduced [24]. Injected water makes the coal moist, improving the mechanical properties of the coal, making the stress concentration zone and increasing the width of the pressure relief protection zone [12].

One of the methods for preventing coal and gas outbursts is hydraulic extrusion of the near-face part of a coal seam. Hydraulic extrusion is performed by high-pressure water injection into the coal seam through wells in faces of stopes and temporary roadways [6]. This method differs from other methods involving water injection in its high injection pressure and rate, as well as the short length of the filtering part of wells, which ensures the coal seam displacement into the roadway, coal unloading and degassing. But its effectiveness depends on a number of factors, including the natural coal seam permeability.

In this regard, the purpose of this work is to analyse the influence of the natural, initial coal seam permeability on the course of the hydraulic extrusion process and its effectiveness. Solving the equations describing water injection into gas-bearing coal seams is currently possible only using numerical methods [14, 25–29]. Therefore, to achieve this goal, the numerical simulation method was applied and the following tasks were solved:

1) to perform numerical simulation of coupled processes of a gas-bearing coal seam deformation and liquid and gas filtration during water injection into the coal seam through wells;

2) to investigate the influence of initial coal seam permeability on the distributions of geomechanical parameters in the roadway face;

3) to investigate the influence of initial coal seam permeability on the distributions of filtration parameters in the roadway face;

4) to investigate the influence of initial permeability on the efficiency of the hydraulic extrusion process.

2. Methods

To solve the problem, numerical simulation of time-dependent coupled processes of elastic-plastic rock deformation and liquid and gas filtration was performed [30–33]. For the mathematical description of the process of rock fracturing, the Coulomb-Mohr criterion was used [34, 35], which takes into account the possibility of fracturing due to both shear and detachment, and well describes the behavior of brittle rocks. The system of equations was solved using the finite element method [36–38], using software developed at the M.S. Poliakov Institute of Geotechnical Mechanics of the NAS of Ukraine.

On the outer borders of the considered area, the coal seam displacements perpendicular to these borders was prohibited. On the outer contour, the gas reservoir pressure $p_g = 8$ MPa was set, which corresponds to the depth of work $H = 1000$ m, and the water pressure in the fractured and porous space of the coal $p = 0.1$ MPa. The same water pressure $p = 0.1$ MPa was set on the inner contour (the roadway and wells). The gas pressure on the inner contour was also equal to atmospheric $p_g = 0.1$ MPa.

At the initial time point, stresses equal to geostatic pressure, gas reservoir pressure $p_g = 8$ MPa and water pressure $p = 0.1$ MPa were set in each finite element. At time steps corresponding to the period of water injection, the following boundary conditions were added:

$$\sigma_{yy}\big|_{\Omega 1(t_{inj})} = p_{\mathrm{inj}}\cos\alpha; \quad \sigma_{xx}\big|_{\Omega 1(t_{inj})} = p_{\mathrm{inj}}\sin\alpha; \quad p\big|_{\Omega 1(t_{inj})} = p_{inj},$$

where σ_{yy} – vertical stress, Pa; σ_{xx} – horizontal stress, Pa; Ω_1 – the filtering part of the wells; t_{ing} – time of water injection, s; p_{inj} – water injection pressure, Pa; α – well inclination angle, degrees.

At each time step, the influence of the change in the stress field on the formation of the permeable region around the roadway and the influence of fluid pressure on the stress distribution were taken into account. The water effect on the strength properties of coal was modelled by halving its natural strength in the water injection zone, which was determined by the criterion $p > 0.2$ MPa.

The parameters Q^*, which characterizes the principal stress difference, and P^*, which characterizes the unloading from rock pressure, were used to analyse the stress field:

$$Q^* = \frac{\sigma_1 - \sigma_3}{\gamma H}; \qquad P^* = \frac{\sigma_3}{\gamma H},$$

where σ_1, σ_3 – maximum and minimum components of the principal stress tensor, Pa; γ – averaged weight of the overlying rocks, N/m^3; H – mining depth, m

In this work, a horizontal section of a roadway, along a coal seam, with a width of 4.8 m was considered; in the face of this roadway two wells with a length of 3.5 m were drilled at a distance of 1 m from the corners. The diameter of the wells is 42 mm, the length of the filtering part is 0.3 m.

The finite element mesh for this problem is shown in Fig. 1.

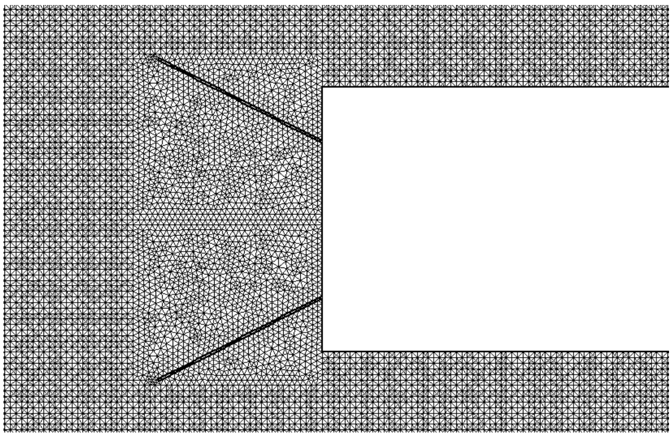


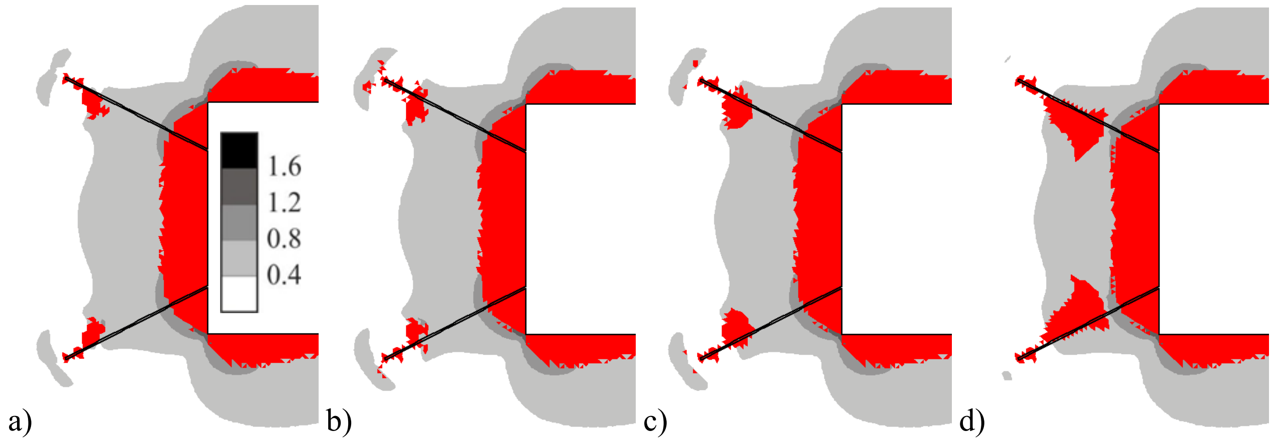
Figure 1 – Central fragment of the finite element mesh with the roadway face and injection wells in horizontal section

The duration of one time step is approximately 45 minutes.

3. Results and discussion

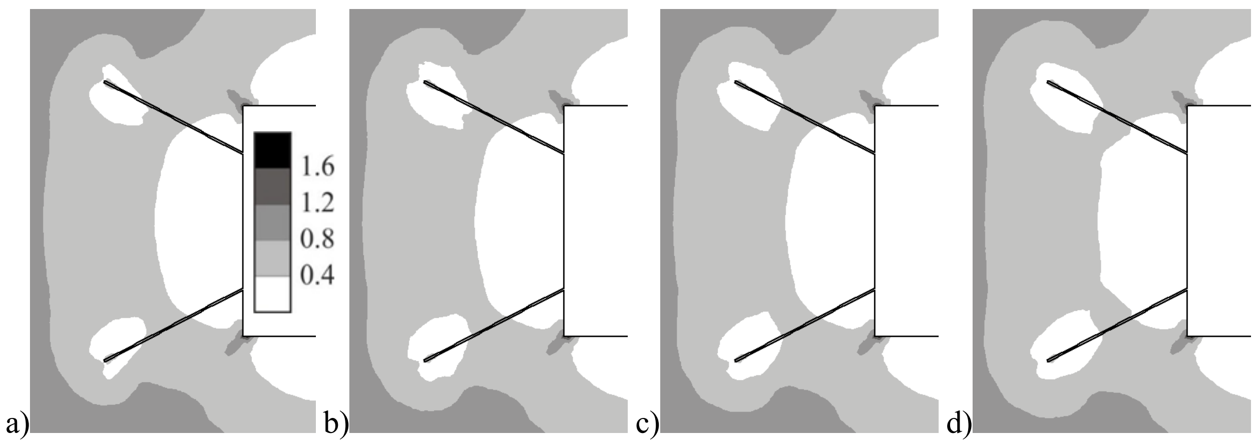
The simulation was carried out as follows. During the first 11 time steps, the stress field was redistributed after the regular face advance. Water injection under a given pressure p_{inj} = 30 MPa into the coal seam through the wells occurs from the 12th to the 13th time step.

In order to investigate whether the initial (natural or tectonic) permeability k_0 affects the course of deformation and filtration processes in the near-face zone of the coal seam during hydraulic extrusion, the cases were considered where $k_0 \to 0$; k_0 = 0.001 mD; k_0 = 0.01 mD and k_0 = 0.1 mD. Fig. 2 and 3 show the results of the calculation of geomechanical parameters Q^* and P^* in the near-face zone at the time step i = 14, more than two hours after the start of injection.



a) $k_0 \to 0$; b) k_0 = 0.001 mD; c) k_0 = 0.01 mD; d) k_0 = 0.1 mD

Figure 2 – Distribution of Q^* parameter values and the zone of inelastic deformations (red colour) in the near-face zone of the coal seam



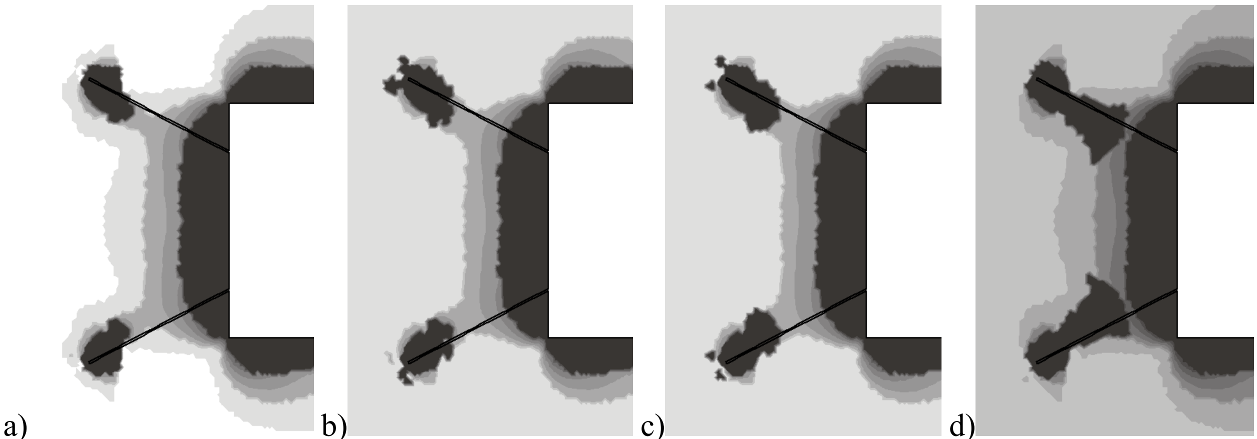
a) $k_0 \to 0$; b) k_0 = 0.001 mD; c) k_0 = 0.01 mD; d) k_0 = 0.1 mD

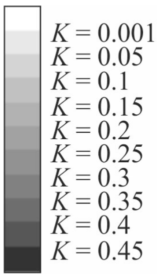
Figure 3 – Distribution of P^* parameter values in the near-face zone of the coal seam

We see that at this time in the coal seam around the roadway, a zone of increased principle stress difference has been formed, where the parameter $Q^* > 0.4$ and where the process of crack formation begins. The contour of the roadway is surrounded by a zone of inelastic deformations (Fig. 2), which leads to an increase in the near-contour coal seam fracturings, its delamination and disintegration. At the same time, the near-face zone of the coal seam is unloaded from rock pressure, Fig. 3. At time step $i = 14$, the depth of the zone unloaded from rock pressure, where $P^* < 0.4$, in the roadway face reaches 1.8 m in all cases.

Although the injection pressure in this series of calculations is quite small, we see that the area of inelastic deformation zones around the wells increases with an increase in the initial coal seam permeability k_0 (Fig. 2). In the case of high initial permeability and insufficient action of p_{inj}, filtration flows move towards the roadway face, along the shortest path along the wells, expanding the existing fracture system and weakening the coal. The filtering parts of the wells are surrounded by unloaded zones, where the parameter $P^* < 0.4$ (Fig. 3), and their area increases slightly with increasing k_0.

The permeability of the near-well zone of the coal seam during the injection process increases in each case considered, Fig. 4.





a) $k_0 \to 0$; b) $k_0 = 0.001$ mD; c) $k_0 = 0.01$ mD;
d) $k_0 = 0.1$ mD

Figure 4 – Filtration permeability k_0 in the near-face zone of the coal seam

Fig. 5 shows graphs of the change in average permeability in the near-face zone over time. We see that the main difference between the four graphs in Fig. 5 is due to different values of the initial permeability k_0. The increase in the average values of permeability coefficients by 0.046–0.053 mD in the period from 1st to 12th time step in each of the four cases is provided by the growth of the zone of inelastic deformations with high permeability at the roadway face. With the start of injection at the

12th time step, the increase in average permeability occurs due to the spread of the permeable zones around the filtering parts of the wells. The second sharp increase in average permeability is seen at the end of the injection process, after the 13th time step, when the high permeability areas around the filtering parts of the wells connect with the high permeability area at the roadway face, and water under high pressure moves along the wells in the direction of the roadway. It is this moment of merging of high permeability areas that is shown in Fig. 4a–4d.

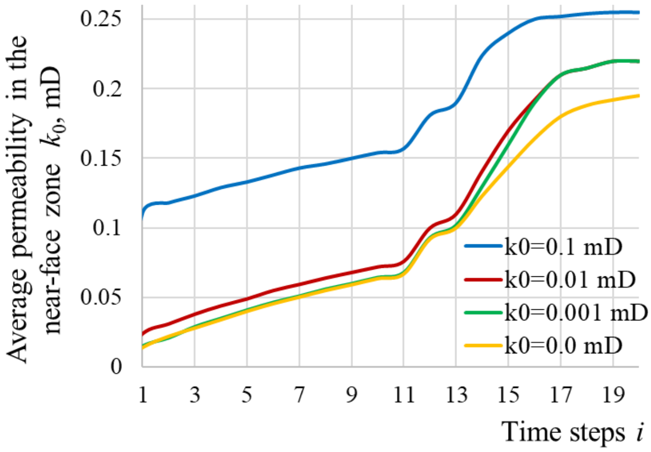


Figure 5 – Change in filtration permeability over time

After the 17th time step, the increase in permeability in the filtration area slows down, and the dynamic process of coal seam hydraulic extrusion is completed.

The distributions of the relative water pressure values p/p_{inj}, in the near-face zone of the coal seam with different initial permeability are shown in Fig. 6.

The analysis of water pressure distributions in the fractured porous space of coal shows that lower natural permeability leads to:

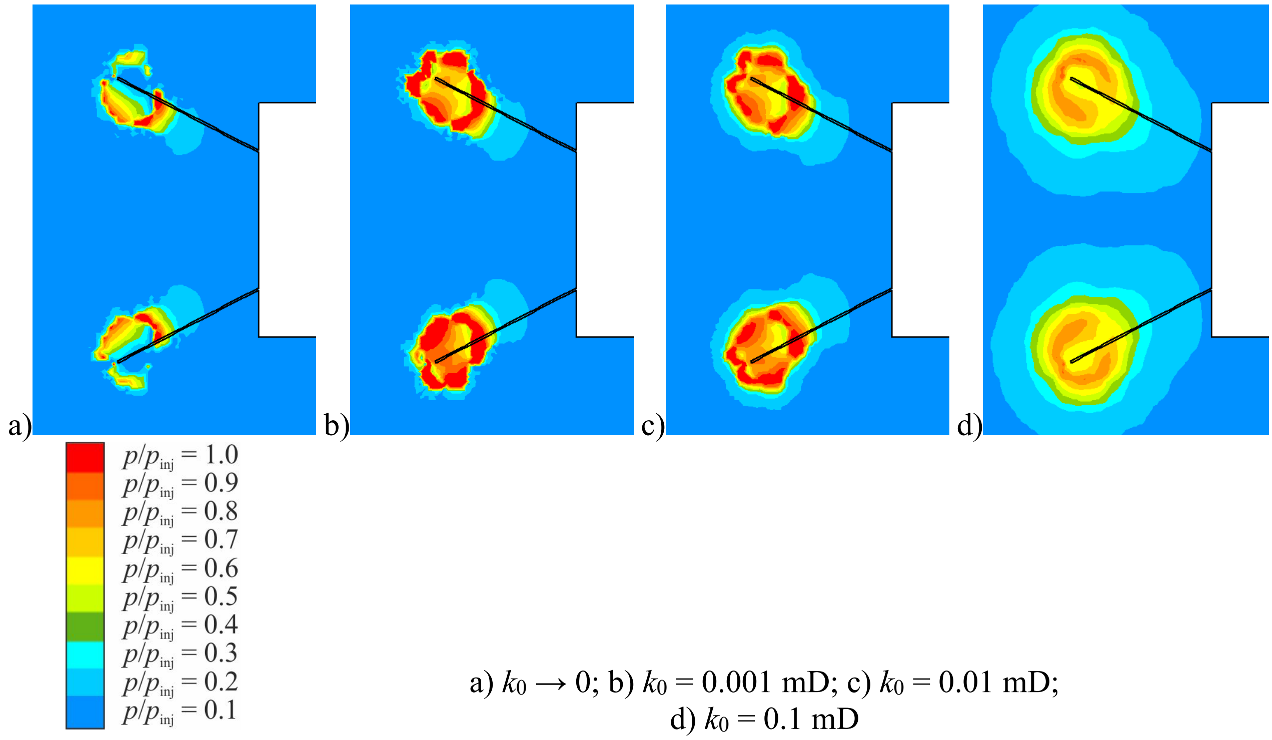
- a decrease in the area of the region of high water pressure around the filtering part of the well;

- an increase in water pressure in this region at $k_0 \to 0$; $k_0 = 0.001$ mD and $k_0 = 0.01$ mD (Fig. 6a–6c);

- an increase in water pressure gradients, which affects its ability to expand cracks and promote their growth, as well as the dynamics of the hydraulic extrusion process.

When k_0 values are high, the area of the region of increased water pressure is also large, Fig. 6d, and the water pressure inside it is low. In the case of $k_0 = 0.1$ mD, the maximum pressure around the filtering part of the wells does not exceed 0.7–0.8 p_{inj}. The water pressure gradients in this case will be very low, because the pressure drop occurs over a large area of the fractured porous space of the coal, Fig. 6d. Therefore, the water impact on the near-face zone of the coal seam will be slower, which complicates the implementation of hydraulic extrusion and reduces its efficiency.

Hydraulic extrusion is considered effective if the water pressure during injection decreases to the final value P_f, water comes to the free coal surface and the roadway face displacement reaches the standard value of $0.02 \cdot l_h$ (l_h is the hermetic sealing depth of injection wells) [6]. In our case, l_h = 3.2 m, therefore, the required face displacement is 0.064 m.



a) $k_0 \to 0$; b) k_0 = 0.001 mD; c) k_0 = 0.01 mD;
d) k_0 = 0.1 mD

Figure 6 – Distributions of the relative water pressure values p/p_{inj}, in the near-face zone of the coal seam

To investigate the effectiveness of the coal seam hydraulic extrusion for given injection parameters, given initial, mining and geological conditions, graphs of water inflow in the roadway face (Fig. 7) and its displacements (Fig. 8) at different time steps were constructed.

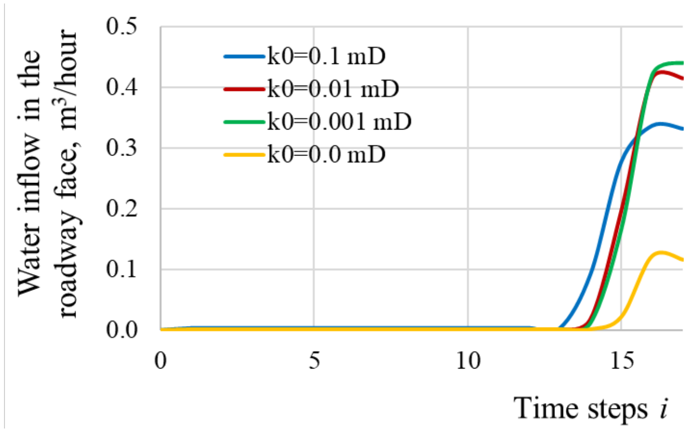
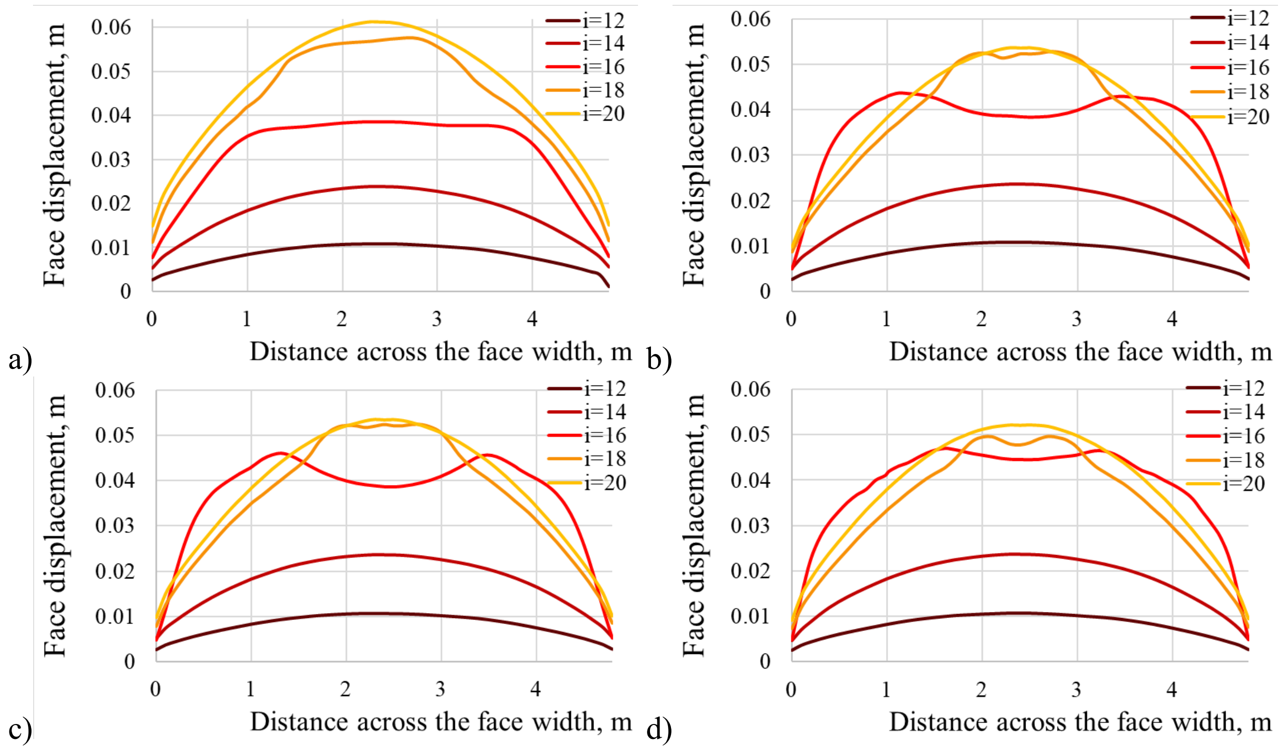


Figure 7 – Water inflows in the roadway face at different k_0

In our conditions, water comes to the face surface in all cases, but at different times and in different volumes. For k_0 = 0.1 mD this occurs at the 13th time step, for k_0 = 0.001 mD and k_0 = 0.01 mD at i = 14, for $k_0 \to 0$ at i = 15. As we can see, at the minimum k_0 the water inflow is the smallest (Fig. 7) and occurs later. Therefore, according to the criterion of the water coming to the roadway face, the coal seam hydraulic extrusion can be considered successful in all four cases.



a) $k_0 \to 0$; b) $k_0 = 0.001$ mD; c) $k_0 = 0.01$ mD; d) $k_0 = 0.1$ mD

Figure 8 – Displacements of the roadway face at different time steps

Under the condition of $p_{inj} = 30$ MPa, the roadway face displacements reach the control value of 6.4 cm only in the first case, when the initial permeability is minimal (Fig. 8a). An increase in initial permeability does not lead to an increase in the roadway face displacements (Fig. 8, 9). In Fig. 9, the curves $k_0 = 0.001$ mD and $k_0 = 0.01$ mD practically coincide.

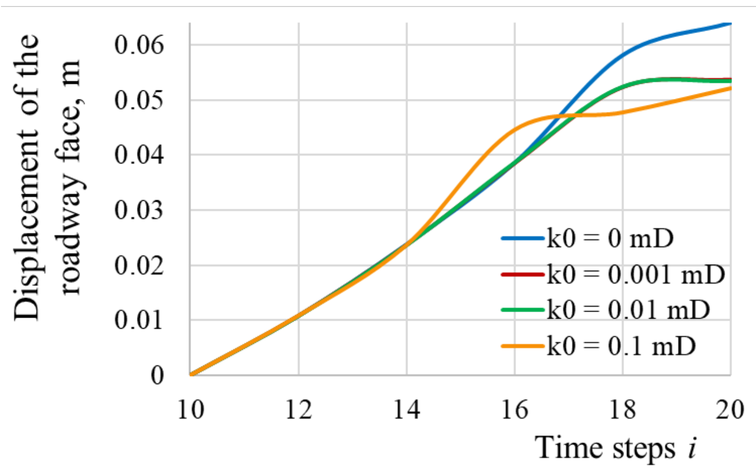


Figure 9 – Displacements of the central point of the roadway face at different k_0

According to the criterion of the coal seam displacement in the temporary roadways not less than $0.02 \cdot l_h$, the coal seam hydraulic extrusion can be considered successful only when $k_0 \rightarrow 0$ (under the conditions adopted in this simulation).

5. Conclusions

To study the influence of the initial coal seam permeability on the effectiveness of the coal and gas outbursts prevention measure, namely, hydraulic extrusion, numerical simulation of time-dependent coupled processes of elastic-plastic rock deformation and liquid and gas filtration was performed. As a result of the study, the following conclusions were made.

The graphs of the time change of average permeability in the near-face zone of the coal seam show that its increase before the start of injection is caused by the roadway construction and the growth of the filtration area around it. When injection begins, a sharp increase in average permeability occurs due to the spread of the permeable area around the filtering parts of the wells. The average permeability increases for the second time at the end of the injection process, when the highly permeable areas around the filtering parts of the wells and at the roadway face are connected, after which water comes to the free coal surface.

It follows from the analysis of water pressure distributions in the fractured porous space of coal that lower natural permeability leads to a decrease in the area of increased water pressure around the filtering part of the wells; an increase in water pressure in this area; an increase in water pressure gradients, which affects its ability to expand cracks and promote their growth, as well as the dynamics of the hydraulic extrusion process.

The efforts should help in selecting potential measures to prevent coal and gas outbursts depending on the initial coal seam permeability, as well as in assessing the technological parameters of hydraulic extrusion.

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АНАЛІЗ ВПЛИВУ ПОЧАТКОВОЇ ПРОНИКНОСТІ НА ПРОЦЕС ГІДРОВІДЖИМАННЯ ВУГІЛЬНОГО ПЛАСТА

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Анотація. Одним з методів запобігання викидів вугілля та газу є гідровіджимання привибійної частини пласта. Гідровіджимання здійснюється шляхом високонапірного нагнітання води у вугільний пласт через свердловини у вибоях очисних і підготовчих виробок. Цей метод відрізняється від інших високим тиском і темпом нагнітання, а також малою довжиною фільтруючої частини свердловини, що забезпечує висування у виробку привибійної частини вугільного пласта, її розвантаження і дегазацією. Але на його ефективність впливає ряд факторів, серед яких природна проникність вугільного пласта. У зв'язку з цим метою цієї роботи є аналіз впливу природної, початкової проникності вугільного пласта на перебіг процесу гідровіджимання і його ефективність. Для досягнення мети виконано чисельне моделювання залежних від часу зв'язаних процесів пружно-пластичного деформування породного масиву і фільтрації рідини і газу, отримано розподіли геомеханічних і фільтраційних параметрів в привибійній зоні вугільного пласта при різних значеннях початкової проникності.

Графіки зміни у часі середньої проникності в привибійній зоні вугільного пласта показують, що її зростання до початку нагнітання спричинене проведенням виробки і ростом області фільтрації в безпосередній близькості від вибою. З початком нагнітання різке збільшення середньої проникності відбувається вже за рахунок розповсюдження проникної зони навколо фільтруючих частин свердловин. Вдруге середня проникність підвищується наприкінці процесу нагнітання, коли з'єднуються високопроникні області навколо фільтруючих частин свердловин і у вибої виробки, після чого відбувається вихід води на вибій. З аналізу розподілів тиску води у тріщинно-поровому просторі вугілля, випливає, що менша природна проникність призводить до зменшення площі області підвищеного тиску води навколо фільтруючої частини свердловини; збільшення тиску води в цій області; зростання градієнтів тиску води, що впливає на її здатність розширювати тріщини та сприяти їх росту, а також на динаміку процесу гідровіджимання.

Результати наведеного аналізу повинні допомогти у виборі потенційних заходів для попередження викидів вугілля і газу в залежності від проникності вугільного пласта, а також в оцінці технологічних параметрів гідровіджимання.

Ключові слова: викид вугілля і газу, гідровіджимання вугільного пласта, зв'язані процеси, проникність, чисельне моделювання.