Numerical simulation of the stress state of the layered gas-bearing rocks in the bottom of mine working

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Abstract. The mathematical model has been developed for the coupled processes of the rock massif deformation and gas filtration in a disturbed area around mine working, in the bottom of which there are hard and soft gas-bearing rocks. When solving the problem, the finite element method was used. The calculation results of the displacements, stresses and pressures of methane in the studied area are represented in the paper. It is shown that the difference in the physical and mechanical properties of the bottom rocks of mine working causes the non-uniform distribution of geomechanics and filtration parameters. In more strong sandstone, the stresses concentration increases. Therewith, an intensive process of fractures formation takes place in the argillite and the coal. Methane from the upper part of the gas-bearing sandstone is filtered into the mine working, the destruction of the coal interlayer is accompanied by release of methane and its accumulation under the layer of a strong sandstone. The development of a zone of inelastic deformations leads to the destruction of sandstone. In case of brittle destruction, with the formation of fractures of a certain length, a breakthrough of methane may occur out of the bottom into mine working.

1 Introduction

The analysis of the deep Donbas mines work shows that a significant part of the preparatory mine workings is in unsatisfactory state caused by the intensive bottom rocks swelling [1]. The upheaving of the bottom in the preparatory mine workings sometimes reaches 1.5 m, depending on the technology of their fastening and geometrical dimensions [2]. The sudden destructions of bottom rocks occur when one or more layers of hard rocks lie over more pliable rocks. The mechanism of deforming the strong rock layers is in the elastic bending into the cavity of mine working with the subsequent fault and the formation of a longitudinal fracture along the mine working. The destruction occurs either near the boundaries of mine working, or in its central part, which is confirmed by the study of cases of bottom rocks sudden destruction [3, 4]. The growth of fractures is the main factor leading to the deformation and destruction of the rock massif around the mine working. To describe this process, a number of models of fractures initiation and development have been

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developed [5, 6]. If the fractures which are formed in the bottom reach the gas-bearing strata, a breakthrough of methane occurs into mine working, which leads to an excessive gasification of the mine environment, miners' injury, and an increase in the cost for maintaining the mine working.

To prevent such negative consequences, it is necessary to comprehensively study the connected processes of the layered gas-bearing rocks deformation and methane filtration, which is possible only with the use of numerical methods. In this regard, the purpose of the work is the computational modelling of the stress state of the rock massif around the mine working provided the alternation of strong and soft gas-bearing rocks in its bottom.

2 Methods

The coupled processes of the rock massif deformation and gas filtration in a disturbed area are described by a system of equations [7-9]:

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

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

$$k = \begin{cases} 0 \text{ for } Q^* < 0.7; P^* > 0.25; \\ k_{min} \text{ for } 0.7 < Q^* < 0.8; \\ e^{0.26Q^* - 4.65} \text{ for } Q^* > 0.8; P^* > 0.1; \\ k_{max} \text{ for } Q^* > 0.8; P^* < 0.1, \end{cases}$$

where c_g – the damping coefficient, kg/(m^3·s); u_i – the displacements, m; $\sigma_{ij,j}$ – the derivatives of the stress tensor components along x, y, Pa/m; $X_i(t)$ – the projections of the external forces acting on the volume unit of a solid body, N/m^3; $P_i(t)$ – the projections of forces due to gas pressure in the porous fractured space, N/m^3; p – the gas pressure, Pa; k – the permeability coefficients, D; m – porosity; μ – gas viscosity, Pa·s; $q(t)$ – the gas release function; $Q^* = (\sigma_1 - \sigma_3)/\gamma H$ – the parameter characterizing the diversity of the stress field components; $P^* = \sigma_3/\gamma H$ – the parameter characterizing the unloading of rocks from the rock pressure; σ_1, σ_3 – maximum and minimum components of the principal stress tensor; γ – the averaged weight of the overlying mine rocks, N/m^3; H – the mining depth, m.

The problem is solved in an elastic-plastic formulation. For the mathematical description of the process of rocks changeover into a disturbed state, the Mohr-Coulomb failure theory is applied. The initial and boundary conditions for the task set:

$$\sigma_{yy}\big|_{t=0} = \gamma H; \quad \sigma_{xx}\big|_{t=0} = \lambda \gamma H; \quad u_x\big|_{t=0} = 0; \quad u_y\big|_{t=0} = 0; \quad p\big|_{t=0} = p_0;$$

$$u_x\big|_{\Omega_1} = 0; \quad u_y\big|_{\Omega_2} = 0; \quad p\big|_{\Omega_1 \text{ and } \Omega_2} = p_0; \quad p\big|_{\Omega_{3(t)}} = p_0; \quad p\big|_{\Omega_4} = 0.1\,\text{MPa};$$

where λ – the side thrust coefficient; p_0 – the methane pressure in the virgin massif, MPa; Ω_1 – the vertical boundaries of the outer contour; Ω_2 – the horizontal boundaries of the outer contour; $\Omega_{3(t)}$ – the time-varying boundary of the filtering area; Ω_4 – the internal contour (mine working).

The problem is solved by the finite element method.

Let us consider the mine working with an arch section of 15 m^2 (width 5.2 m, height 3.7 m), in the bottom of which the sandstone with a thickness of 1.0 m and the coal

interlayer with a thickness of 0.4 m occur, Figure 1. The host rock is argillite. The properties of rocks are represented in Table 1.
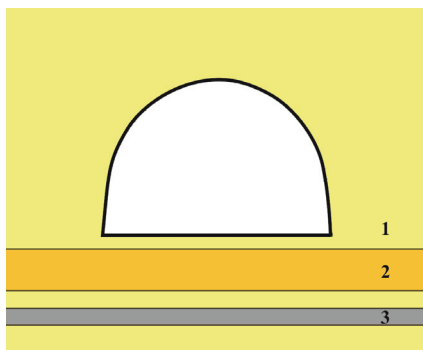

Fig. 1. The scheme of the rock layers' location in the bottom of mine working: 1 – argillite; 2 – sandstone; 3 – coal.

Table 1. Mechanical parameters of rock.

Rock	Axial compressive strength, σ_c, MPa	Deformation modulus, E, MPa	Poisson's ratio of rock mass	Cohesion, C, MPa	Friction angle, deg	Gas content, m^3/t
Argillite	25	$11 \cdot 10^3$	0.32	7.5	28	-
Sandstone	46	$18 \cdot 10^3$	0.35	12	35	7
Coal	16	$3 \cdot 10^3$	0.25	4.5	32	15

3 Results and discussion

As a result of modeling, the stresses fields have been obtained, the values of geomechanics parameters Q^* and P^*, and the inelastic deformations zone at different time iterations, Figure 2. The mine working development initiates the process of the stresses field redistribution in the host rocks. An area of increased diversity of the stresses field components begins to form around the mine working. At the first time station in the border areas of the mine working bottom, $Q^*<1.2$, Figure 2a, in the central sandstone part – $Q^*<0.7$, Figure 3; the parameter P^* values in the central part of sandstone exceed 0.1, Figure 4, which indicates the elastic deformation.

Over time, the area of diversity of the stresses field components increases in size with a gradual increase in the parameter Q^* values and a decrease in the parameter P^*, Figure 2b, 2c, 3, 4. The difference in the physical and mechanical properties of the bottom rocks in mine working causes the non-uniform distribution of geomechanics parameters: in the more strong sandstone, the stresses concentration increases, in its central part $1.2<Q^*<1.6$, in border parts – $Q^*>1.6$. At the same time in the argillite and in the coal $Q^*<1.0$, Figure 3b.

The mine working contour is surrounded by the zone of inelastic deformations, shown in red in Figure 2, in which the process of fractures formation leads to stratification and destruction of border rocks.

The further redistribution of the stresses field, Figure 2d, leads to the fulfilment of the criterion of the Mohr-Coulomb failure theory and the destruction of coal and argillite under the layer of sandstone in the mine working bottom. In the border and central areas of the sandstone, the values of parameter $Q^*>1.4$, Figure 3. Here, the development of the inelastic deformations zone begins, which leads to its destruction. Such destruction may occur in the form of the formation of fractures with the appropriate depth.

The graphs of vertical displacements of rocks in the mine working bottom, Figure 5, show that the different rock layers move in a non-uniform manner. That is, the deformation of the rocks in the mine working bottom occurs with an increase in the volume of geomaterial, causing the processes of stratification and fractures formation.
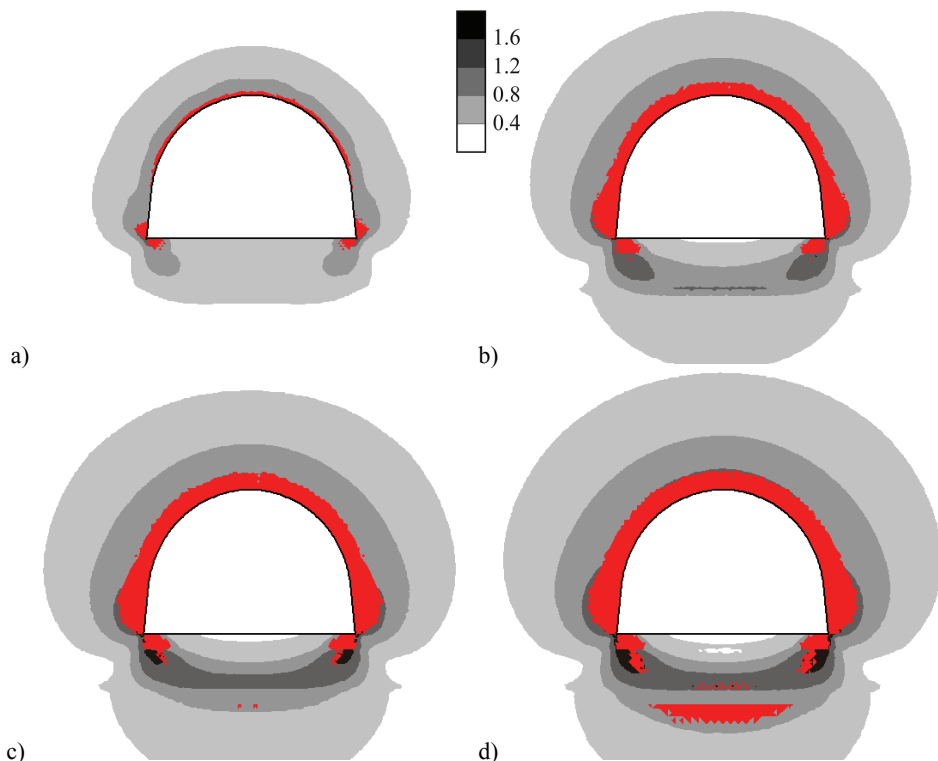

Fig. 2. The distribution of parameter Q^* values and inelastic deformation zones at different time stations: a – t =1 day; b – t =3 days; c – t =5 days; d – t =10 days.
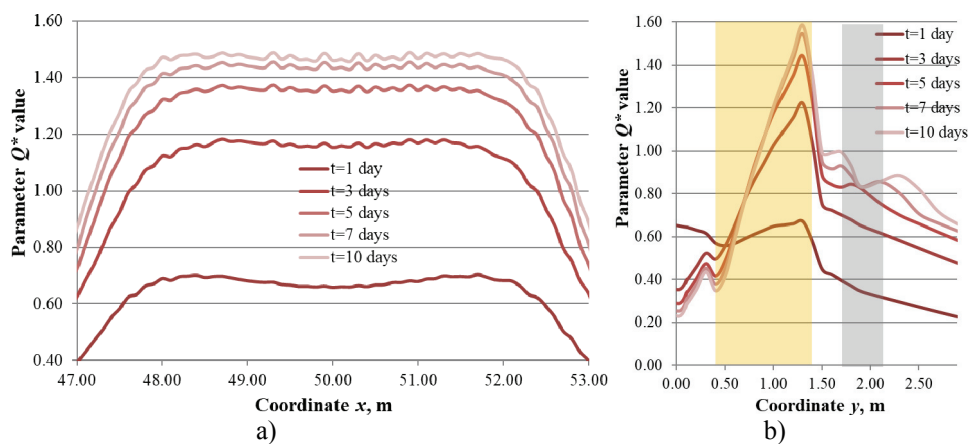

Fig. 3. Changing the parameter Q^* values in the mine working bottom: a – along a horizontal axis passing through the sandstone; b – along a vertical axis passing through the mine working centre.

The influence of increase in the mine rocks volume on the filtration permeability growth was considered when calculating the parameters of methane filtration in the disturbed area

around the mine working. The change in the relative gas pressure (p/p_0) at different time iterations is shown in Figure 6.
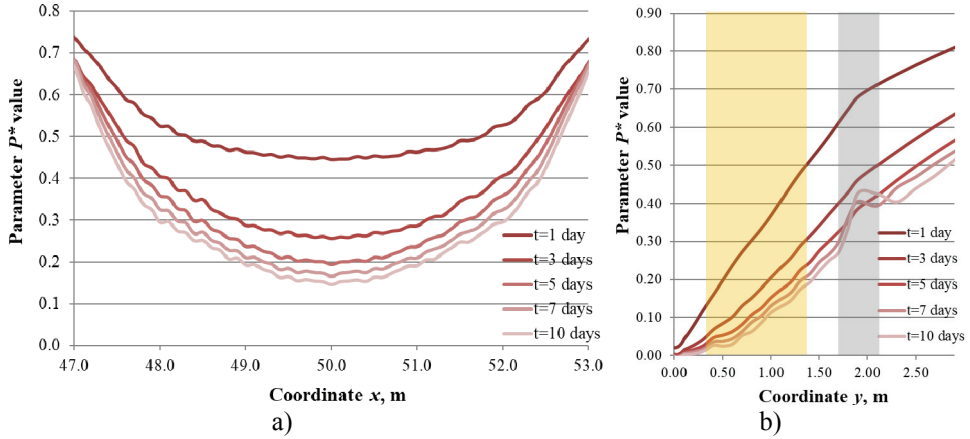

a) b)

Fig. 4. Changing the parameter P^* values in the mine working bottom: a – along a horizontal axis passing through the sandstone; b – along a vertical axis passing through the mine working centre.
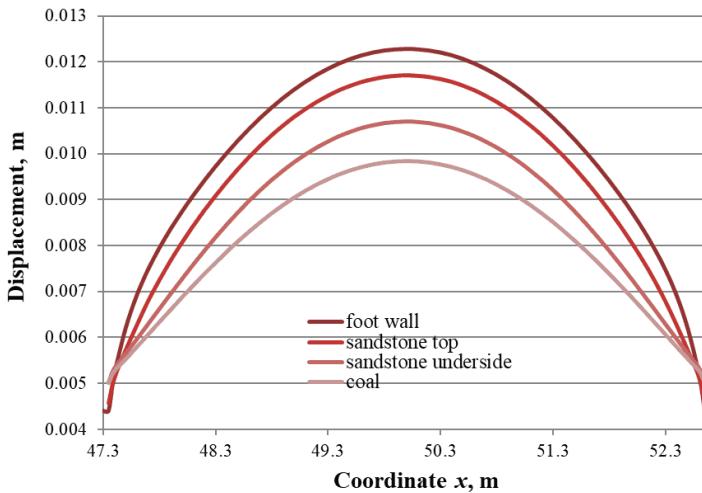

Fig. 5. The vertical displacements of rock layers at $t = 10$ days.

Beginning from the 3rd day, the gas pressure in the upper part of the gas-bearing sandstone decreases, Figure 6b. This indicates that methane is moved from the areas with a higher pressure to an area where the pressure is minimal – into the mine working environment. Thus, the process of methane filtration occurs.

The destruction of coal (Fig. 2d) is accompanied by the release of methane and its accumulation under the layer of strong sandstone (areas $p/p_0 > 1.0$), Figure 6d.

In the considered time interval, the area of decreased pressure ($p/p_0 < 1.0$) does not affect the coal interlayer, which is located under the sandstone. Methane from this source of gas release does not penetrate into the mine working, as it is prevented by non-permeable lower part of the sandstone. Subsequently, in the case of a gradual expansion of the permeable area in the mine working bottom, the process of filtration will continue in a quasi-stationary mode. And with the brittle destruction of the sandstone, there will be a breakthrough of methane out of the bottom into mine working.
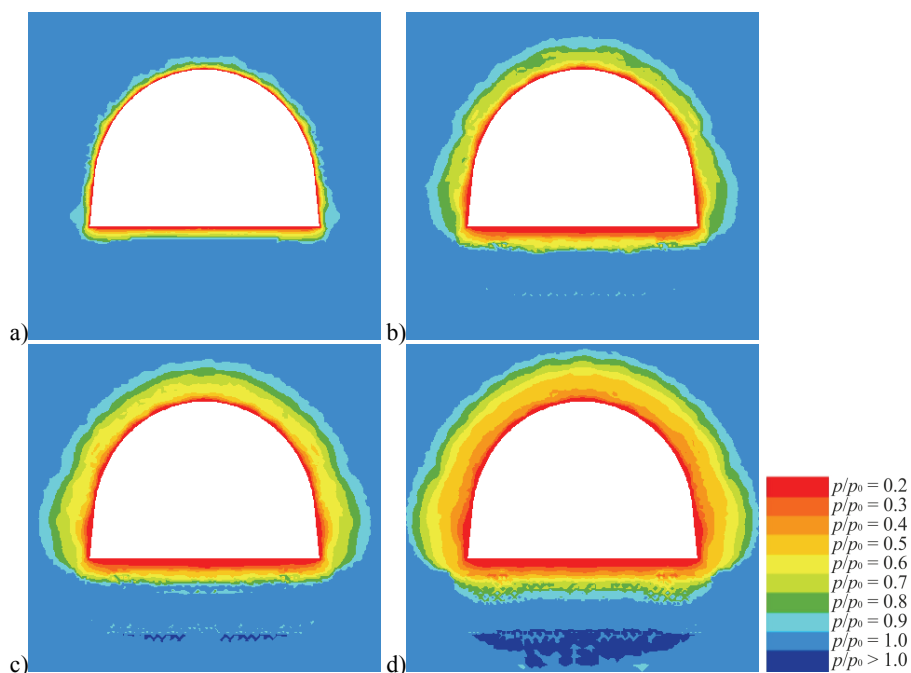
Fig. 6. The relative gas pressure at different time stations: a – t =1 day; b – t =3 days; c – t =5 days; d – t =10 days.

Conclusions

The mathematical model has been developed for the coupled processes of the rock massif deformation and gas filtration in a disturbed area around mine working, in the bottom of which there are hard and soft gas-bearing rocks. By means of the finite element method, the fields of displacements, stresses, permeability coefficients and methane pressure in the studied area have been calculated.

It is shown that the difference in the physical and mechanical properties of the bottom rocks of mine working causes the non-uniform distribution of geomechanics parameters. In more strong sandstone, the stresses concentration increases in its central and border parts. Therewith, an intensive process of fractures formation takes place in the argillite and the coal. Methane from the upper part of the gas-bearing sandstone is filtered into the mine working, the destruction of the coal interlayer is accompanied by release of methane and its accumulation under the layer of a strong sandstone.

At a certain point of time, the development of a zone of inelastic deformations leads to the destruction of sandstone. Such destruction may occur in the form of the formation of fractures to a depth of sandstone thickness. In case of brittle destruction of the sandstone, there may occur a breakthrough of methane out of the bottom into mine working. With a gradual expansion of the permeable area in the mine working bottom, the process of filtration will continue in a quasi-stationary mode.

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