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Numerical simulation of interaction of methane filtration and rock massif deformation during mining of methane-bearing seams

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Abstract. This paper presents the results of the first stage of theoretical research and mathematical modeling of interaction of geomechanical and filtration processes in methane-bearing coal-seams when mining them in gravitational and non-uniform geotectonic stress fields. Comprehensive studies were carried out on the basis of numerical modeling of geomechanical and gas-dynamic processes with adjustment of the input parameters of the mathematical model based on the results of mine measurements. According to the results of numerical modeling, the features of the residual strength distribution of the coal seam to the original one, displacements, vertical and horizontal stresses, methane pressure in the rock mass at different coefficients of lateral pressure in the undisturbed geomassif and in the zone of influence of the gob are revealed. It also presents the results of computational experiments for determining the geomechanical and gas filtration parameters in the rock massif with different options of the boundary conditions and the spatial position of the workings.

1. Introduction

The problem solution of efficient and safe mining of methane-bearing coal seams is closely linked to the need for preliminary gas drainage of deposits. However, traditional gas drainage technologies are based on empirical dependencies and production experience, since there are no results of basic research on the interaction of geomechanical and filtration processes that would substantiate the transition of methane from the hydrate to gaseous state during the change of mining and geological conditions, natural stress field.

The problem solution of increasing the gas drainage efficiency in the absence of theoretical substantiation of the processes of rock pressure formation, changes in the coal seams permeability, porosity, fluids filtration, mechanical destruction of the coal matrix turned out to be very difficult. This is confirmed by the mining practice in the mines and the results of research. The article [1] presents the analysis results of the gas drainage efficiency of coal mines in Kuzbass for the period 2000-2011. It is established that the coefficient of efficiency of gas drainage is 28%. When using the combined ventilation scheme, this coefficient reaches 55%. The average degassing efficiency in Kuzbass mines is 30%, and in underground mining an average 18.6 m³ of methane is released per ton of coal produced, which is the limit for the operation of modern high-performance equipment.

The importance of the problem of theoretical and analytical research on the interaction of methane filtration processes and rock mass deformation during mining of methane-bearing seams in seismically active areas is due to the high risk of accidents and incidents, and restricted operation of high-performance gas equipment in coal mines. In the development faces of coal mine, up to 67% of the



working time is associated with the implementation of preventive measures for the gas drainage of coal seams and the provision of mine atmosphere parameters regulated by normative documents.

The aim of the research is to improve the safety and efficiency of the mining technology of high-gas-bearing coal seams in seismically active areas through the use of identified patterns of interaction of methane filtration and rock massif deformation.

To achieve the goal, comprehensive studies were conducted using the results of numerical simulation and mine measurements of parameters of geomechanical and gas-dynamic processes with adjustment of the input parameters of a mathematical model based on the results of a full-scale experiment.

The object of research is the processes of filtration and deformation in the rock massif of Kuzbass mines.

According to the analysis of literature sources and patents, the following promising directions for the development of methods and means of controlling the methane release and interacting geomechanical and filtration processes in the rock massif of coal mines were revealed [2-7]:

- the use of interval hydrofracturing of a seam with a distance between hydraulic fracture cracks of 10÷15 m;
- the use of interval hydrofracturing of a seam using Novec 1230 fluid;
- creation of antifiltration screens in the rock massif for sealing gas drainage wells;
- the use of a two-component composition to prevent ignition and explosion of methane-air mixtures;
- the use of rock pressure energy to increase the permeability of coal seams;
- the use of plasma-pulsed impact on the coal seam in order to increase its permeability.

To substantiate the parameters of these methods and means of increasing the gas recovery of methane-bearing seams, it is necessary to study the following processes in the rock massif:

- conditions for the clathrates transition into gaseous state: pressure, temperature, mechanical destruction, etc.;
- fluids movement through transport channels when rock massif is exposed to the external conditions;
- the mechanism for changing the permeability and porosity of coal under external influences;
- movement patterns of the gas-liquid medium in the rock massif when its permeability, porosity, temperature change.

Although at present in the technical literature these problems are solved by both analytical and empirical methods, the results useful for mining practice have not yet been obtained. Therefore, in the present work the computational experiments were carried out to identify the basic laws of these processes by jointly solution of geomechanical and filtration problems in accordance with the options graph (figure 1) using the author's complex of software [8–10].

2. Methods of research

To study the deformation processes, the mathematical model is constructed in the form of a boundary problem of the elasticity theory in the form of a system of differential equations: equilibrium equations, geometric equations of deformation and displacement, physical equations (Hooke's law) and kinematic boundary conditions.

To quantitatively predict the parameters of gas filtration processes, calculate the pressure and methane flow rate in a continuous gas-bearing gas-saturated coal-rock massif complicated by natural attenuation surfaces, the following equations are accepted: differential equations of discrete medium mechanics with variable boundary conditions and variation of stress fields under the influence of workings, the equations of multidimensional gas flow continuity, Darcy and Clapeyron equations in the movement of deep-earth methane along tectonic fractures and workings under the influence of artificial gas drainage are .

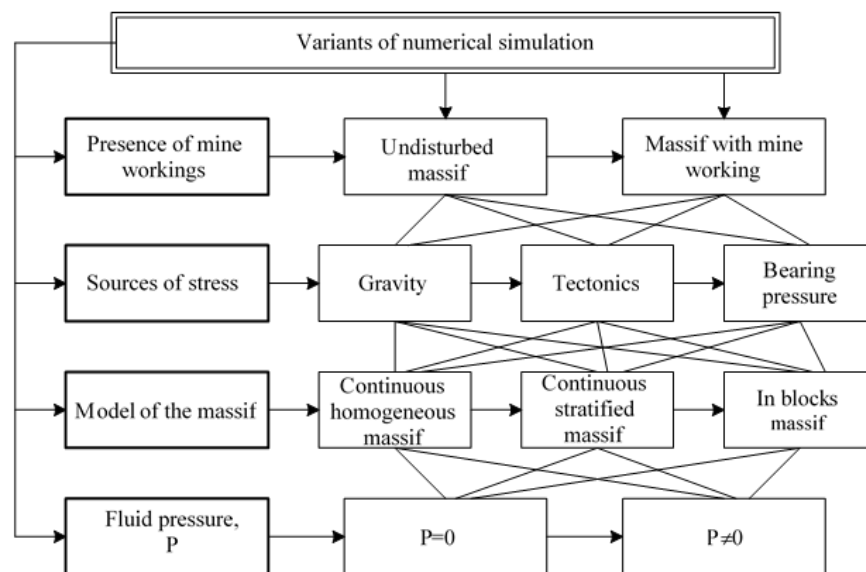


Figure 1. Options graph for computational experiments.

The experience of numerical simulation confirms that it is practically impossible to obtain predictable parameters and dependencies that are adequate to the real ones [11]. This is due both to the imperfection of mathematical models of gas filtration processes and the discrepancy between the measurement results of the natural methane content of coal seams, for example, the residual methane content in laboratory samples. Therefore, the algorithm of the developed mathematical model of nonlinear methane filtration in a hierarchically structured block coal and rock massif should ensure that the parameters of the model can be adjusted according to the results of field measurements, including data from automated digital monitoring of the mine atmosphere parameters.

For the numerical model, the following input data for the Polosukhinskaya mine (Kuzbass) were adopted: the mined seam 26a; seam thickness $m = 2.00$ m, maximum development depth $H=650$ m, face $L=200$ m, angle of dip $\alpha=8^\circ$, ultimate strength of coal under uniaxial compression $\sigma_{com}=8$ MPa, average density of rocks $\gamma=2500$ kg/m³, the length of the two-dimensional model is 1000 m; the number of rock layers and coal seams in the two-dimensional model 100.

3. Results and discussion

At the first stage, the calculation was performed in the gravitational and geotectonic fields of natural stresses. The boundary conditions on the sides of the model were taken in accordance with the value of the coefficient of lateral expansion λ according to the hypothesis of A.N. Dinnik [12].

The option of the vertical and horizontal stresses distribution in the undisturbed massif with different coefficients of horizontal stress is presented in figure 2.

According to the results of numerical simulation in a layered massif, taking into account the gravitational and geotectonic stress fields outside the zone of influence of mine workings, the following regularities of the distribution of displacements, stresses and deformations were revealed for various types of horizontal forces on the model's sides:

- when the lateral load is applied over a triangular diagram of the of horizontal forces distribution, the magnitudes of the horizontal displacements decrease in proportion to the lateral pressure coefficient, and the vertical displacements in the middle part of the model, on the contrary, increase;
- when the lateral load is applied to a model along the rectangular diagram of the horizontal forces distribution, the horizontal displacements along the height do not change much and depend proportionally on the lateral pressure coefficient, across the width of the model, the

horizontal displacements vary in proportion to the lateral pressure coefficient, vertical displacements are almost not affected by changes in lateral pressure coefficient.

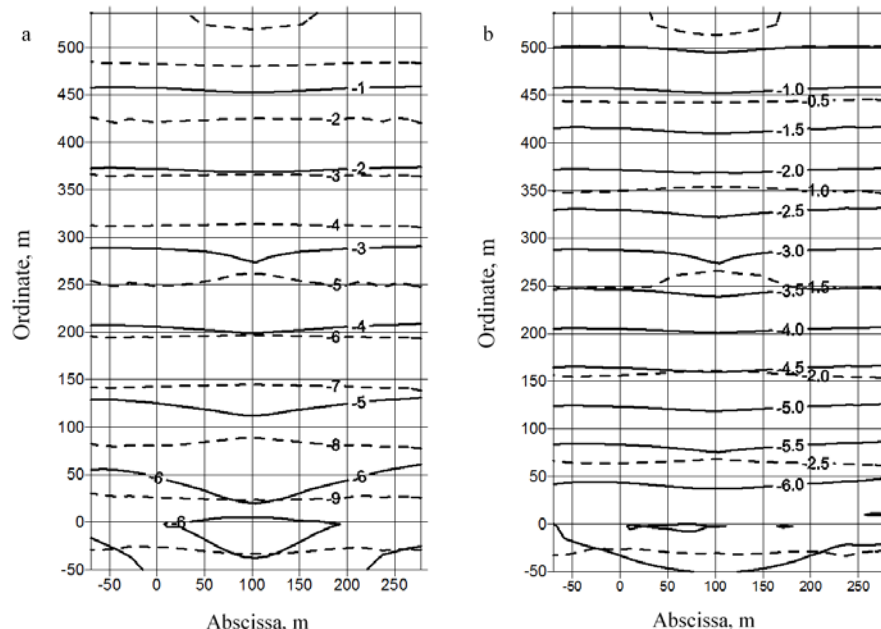


Figure 2. Distribution isolines of vertical (solid lines) and horizontal (dotted lines) stresses (MPa) in the undisturbed rock massif: a – horizontal stress ratio $\lambda = 1.5$;
b – coefficient of horizontal stress $\lambda = 0.5$.

For comparison, the simulation of the stress-strain state in the vicinity of the mine workings with a production length of 200 m and a variation of the lateral pressure coefficient λ in the range of 0.5-1.5 was conducted. Figure 3 shows one of the results of the stress distribution in the rock mass at a lateral pressure ratio $\lambda = 0.5$.

Based on the analysis of the results obtained, it was established that:

- the vertical displacements of the roof rocks of the moving face are located asymmetrically relative to the vertical axis of the developed space due to the creep of coal and rocks in time;
- the vector of horizontal displacements is directed towards the middle of the gob and towards the face, over the gob, the isolines of rocks displacements have the dome shape that corresponds to the results of field observations by many researchers [13, 14];
- the ratio of the height of the zone of cracking in the underworked rocks to the width of the open space is 0.35, which corresponds to the normative document [15].

The previously unknown pattern of the occurrence of high compressive vertical and horizontal stresses in the geotectonic stresses in the undermined coal seams at a distance of 80 and 180 m from the roof of the mined seam, which corresponds to the coordinates of the position of the undermined layers 30 and 29a, was revealed. The presence of such zones of volume compression during the processing of coal seams-satellites can lead to conditions favorable for the formation of gas reservoirs and commercial production of methane.

The comparative analysis of the distribution of vertical and horizontal stresses and strains confirms that large vertical compressive stresses (up to 28 MPa) and horizontal tensile stresses (up to 12 MPa) appear in the edge part of the mined seam. The coal disintegration, changes in permeability and porosity of the edge of the coal seam should take place in this zone, due to large tensile stresses, which in practice is confirmed by intense coal sloughing in the face and methane release.

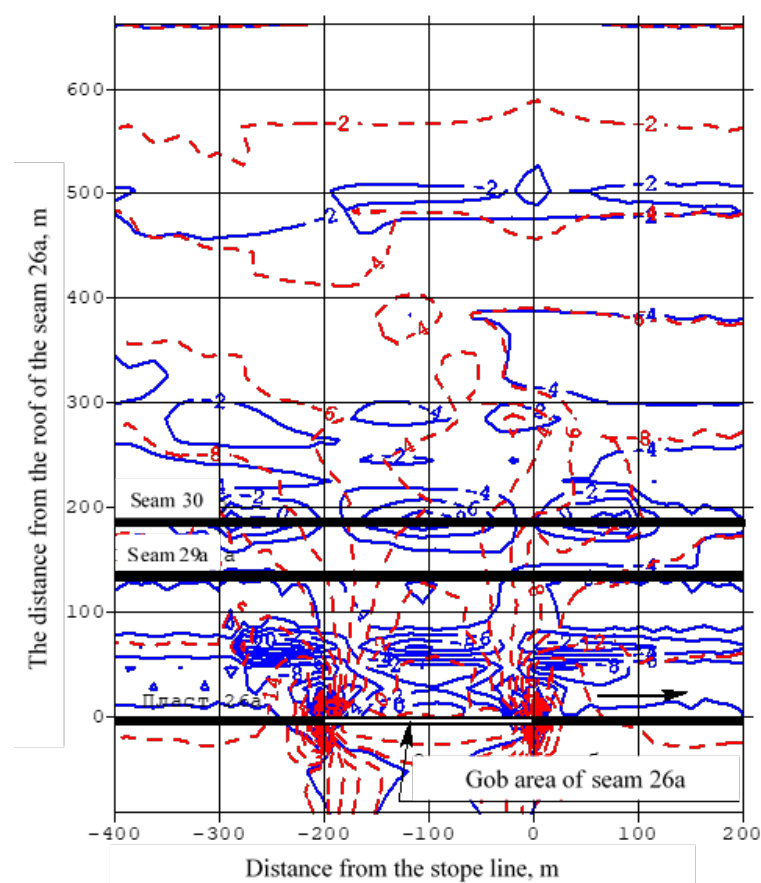


Figure 3. Distribution isolines of vertical (dashed lines) and horizontal (solid lines) stresses (MPa) in the zone of influence of the seam gob ($\lambda = 0.5$).

To solve the gas filtration problem, the software packages include modules for calculating the pressure of methane under the influence of gravitational and geotectonic stress fields. To adjust the input parameters of the mathematical model and assess the adequacy of the obtained simulation results, mine measurements of the parameters of the mine atmosphere were used. As an example, figure 4 shows graphs of methane concentration, confirming the non-uniformity and waviness of methane release [16].

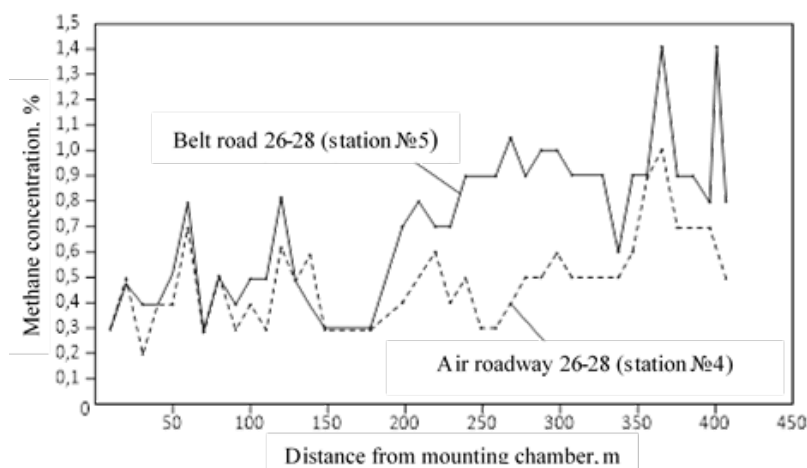


Figure 4. Dependency graph of methane concentration in outgoing jets on the distance to the installation chamber, excavation section 26-30, mine “Abashevskaya”, Kuzbass [15] (s. 4, s .5 – numbers of observation stations).

Computational experiments were carried out to determine the geomechanical and gas filtration parameters at different variants of the boundary conditions and the spatial position of the workings. One of the options for the distribution of methane pressure in the vicinity of the gob with different lateral pressure coefficients is shown in figure 5.

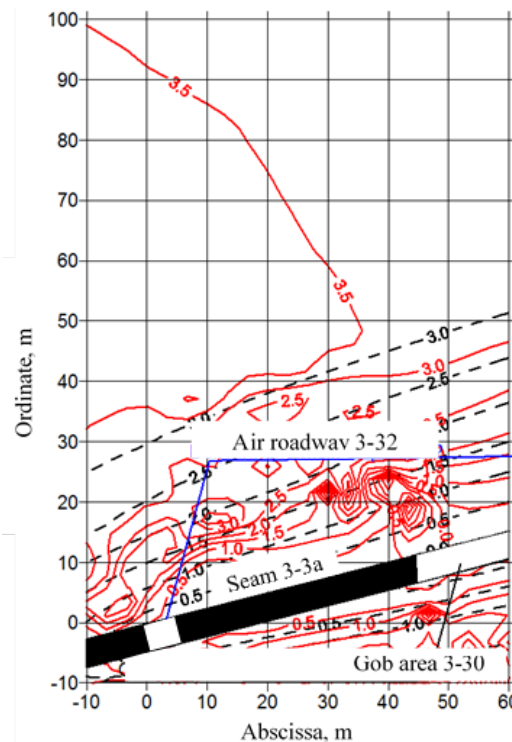


Figure 5. Distribution isolines of the of methane pressure (MPa) in a heterogeneous geomassif with the cumulative effect of the ventilation drift 3-32 and the gob of the extraction panel 3-30: dotted lines – methane pressure in the gravitational stress field ($\lambda = 0.5$); solid lines – methane pressure in the geotectonic stress field ($\lambda = 2.0$).

According to the results of numerical simulation it was established:

- the most significant change in the nature of the distribution of methane pressure in the geotectonic field occurs in the rocks of the bottom and roof of the mined seam;
- the influence of mine workings on the methane pressure in the roof of the seam can be traced up to 200 m, which corresponds to the height of the fracture zone $h = 35\text{--}40$ m, where m is the extracted thickness of the seam;
- the influence of the geotectonic stress field on changes in the pressure of methane as compared with the gravitational stress field was revealed at a distance of 130 m, that is, about 25–30 m;
- the distribution of methane pressure in the edge areas of the mined seam out and in the zone of influence of the coal pillar is extremely uneven, the most unevenness is observed when exposed to a geotectonic field;
- Near the gob the methane pressure is close to zero, and in the edge sections of the seam the methane pressure increases, which should be explained by the closure of cracks and the decrease in porosity of coal and rocks under the influence of prevailing horizontal stresses compared to the stresses in the gravitational field;
- The maximum gradient of methane pressure drop is fixed above and below the edge of the seam only in the geotectonic stress field.

4. Conclusions

The main scientific results, conclusions and recommendations are as follows. A set of problem-oriented software for quantitative prediction of parameters of deformation and filtration processes were developed and adapted for solving the set scientific problems.

The interaction regularities of methane filtration and deformation of the rock massif during the mining of methane-bearing seams in seismically active regions are revealed.

The conditions for the formation of hazardous zones in a gas-saturated geo-massif were determined on the basis of the criterion of rock destruction: in the extension zone, by tensile stresses exceeding the tensile strength of rocks under tension; in the compression zone, by the sum of the compressive stresses and methane pressure exceeding 70% of the initial strength of the rocks under compression.

Acknowledgments

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