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EVALUATION OF COAL MINES' ROCK MASS GAS PERMEABILITY IN THE EQUIVALENT STRESS ZONE

Purpose. Based on a comparative analysis of the internal mechanism of shape change of rock samples, which were loaded in specified deformations mode, and geomechanical and gas-dynamic processes in coal mass, to establish a causal link between these phenomena. To qualitatively characterise their gas permeability as a function of the rock's volume expansion. To justify the possibility of using a full "stress-strain" diagram as a technogenic methane deposit formation model and its spatial localisation.

Methodology. Theoretical research is based on using the solid mechanic constitutive principles and results of studying the rock samples failure in the mode of specified strains.

Findings. The ability to use a full "stress-strain" diagram for detecting and localising methane reservoirs during the coal seams excavation was proved during the research. It was found that the compaction threshold coincides with the bearing pressure maximum in front of the longwall face. This area corresponds to the rock mass with minimal porosity and minimal filtration, which allows considering it as an envelope of an artificial gas deposit. Regularities that connect the three-dimensional equivalent stress state with the final gas permeability of the gas-saturated coal mass were obtained. These data allow creating a predictive numerical geomechanical model of methane migration paths.

Originality. The ability to use a full "stress-strain" diagram in the controlled strain mode for numerical modelling of gas permeability of a methane-saturated coal mass during the mining of coal seams and the determination of technogenic gas deposit boundaries are justified. Dependences of the current and final gas permeability on the rock's mechanical characteristics in a post-peak strain state are obtained.

Practical value. Functional dependencies based on geomechanical models are obtained that allow the identification and localisation of technogenic methane reservoirs in mines during coal seam excavation, with subsequent utilisation of the extracted gas. Furthermore, methane removal enhances mining safety by reducing the risk of gas dynamic phenomena while decreasing gas emissions into the atmosphere contributes to reducing the greenhouse effect.

Keywords: *coal mine, post-peak strain state, equivalent stress, gas permeability, methane reservoir, technogenic gas deposit*

Introduction. The political situation that has arisen in Ukraine due to the Russian aggression has led to significant problems in the country's energy sector. The artificially created global fuel crisis has resulted in a substantial increase in prices for all energy sources, including gas and coal. Ukraine's coal deposits contain billions of cubic meters of methane and can be considered as coalbed methane resources. Methane extraction from such deposits occurs in parallel with coal mining excavation, which imposes special requirements on the degasification process, identification of gas reservoirs, their localisation, and parameter assessment. This approach plays a crucial role in addressing the issue of methane emissions into the atmosphere, contributing to the greenhouse effect. One of the stages in their implementation is the reduction of greenhouse gas emissions, mainly coal mine methane. In the current stage of coal mining development in Ukraine, there are examples of using methane as a source of electrical and thermal energy, which significantly improves the ecological and energy state of the country. Therefore, identifying local methane accumulation zones during coal seam excavation and developing a methodology for their detection remain relevant scientific and technical tasks with significant practical importance.

Literature review. A practical solution for problems of coal mine methane extraction is required for the rock mass reservoir capabilities assessment, which is under conditions of intensive coal seam excavation. Another important task is determining the gas permeability of coal seams and the enclosing rocks. Research focused on investigating the reservoir properties of rock formations in coal mines is typically conducted in coal mining areas during regular operating mode and emergencies [1, 2]. To date, two directions can be distinguished among the known research results: establishing the permeability coefficient's dependence on the reservoir rocks' stress state and the fracture opening degree in them. Despite the apparent interdependence of these factors, specialised literature provides only fragmented data, mainly of a qualitative nature, linking stress in the massif to fracture opening degree.

The gas filtration velocity in porous rocks exhibits a stationary (laminar) character [3]. In such a system, it follows the well-known Darcy's law, the formula of which, for the conditions of the investigated situation, is expressed as follows

$$Q = \left(\frac{k \cdot S}{\mu}\right) grad(P), \quad \mu = \nu\rho, \tag{1}$$

where Q is filtration rate (m^3/day or sm^3/s); k – gas permeability factor (D); S – filtration flow's area (m^2); μ – dynamic viscosity of the fluid (Pa $\cdot$ s); ν – kinematic viscosity (m^2/s); ρ – density of the fluid (kg/m^3); *grad P* – pressure drop in the filtration path, which is equal to $\left(\frac{P_1 - P_2}{l}\right)$, where P_1 and P_2 are static pressure on the filtration flow path's limits, l – filtration path.

The combined influence of structure and stress state on the parameters of the reservoir rock in equation (1) is considered through the gas permeability factor, denoted as k. The permeability factor is determined by examining core samples of the fluid-filtering rocks through laboratory testing, in situ measurements, or calculation methods [4, 5].

During the research, the task was set to find a probable dependence between the gas permeability factor, k, and a certain integral absolute stress (σ) in the rock mass. In other words,

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the aim was to explicitly identify the dependency of $k = f(\sigma)$. Based on the results of the known research [6, 7], it is established that the permeability of the coal seam is not constant. Starting from the face, it continuously decreases within the mass, reaches a minimum at the maximum bearing pressure, and then gradually increases to the seam value. Thus, the concept of a "compaction threshold" was formulated as a hypothetical surface within the coal-bearing mass that separates the mined-out space from the intact rock mass, where the permeability of the surrounding rocks takes on the lowest values due to deformation. This allows considering the compaction threshold as one of the shielding surface characteristics of an artificial gas reservoir.

Unresolved aspects of the problem. The use of compaction threshold characteristics, as parameters for the barrier of an artificial deposit's characterise, allows one to find a fresh approach to addressing the spatial placement of such methane reservoirs within the mined mass. To achieve this, it is necessary to establish the regularities that characterise the manifestations of compaction threshold features, taking into account the volumetric stress-strain state of the gas-saturated mass and quantitative dependencies to determine the configuration and the deposit's barrier spatial location.

Research objective. The task of forming an artificial methane reservoir and its spatial localisation can be solved based on a comparative analysis of complete deformation diagrams of rock samples subjected to controlled-strain modes and the geomechanical and gas-dynamic processes in coal-bearing masses. This requires qualitatively characterising their gas permeability as a function of the rock formations' volumetric expansion.

Methodology. The research methodology consisted of two parts. The first part involved testing methods for rock samples for compression under the controlled-strain mode. The gas permeability factor was determined for the partially fractured sample at each deformation stage. This created the prerequisites for developing a gas flow model within the mined-out rock mass. In the second stage, analytical research was based on the solid deformed mechanic's basic principles using and the assumption that the equivalent stresses acting in a real gas-saturated rock mass are functionally related to its gas permeability. This stage involved using a full "stress-strain" diagram in the controlled strain mode and the equivalent stresses' distribution patterns computed in a three-dimensional equivalent stress state using the established failure criterion, with the theoretical research of Balandin being adopted as the basis.

Main research and results. The research results that consider the influence of the third component acting along the direction of the filtration flow on the gas permeability of rock samples under volumetric load are presented in [7, 8]. The research was conducted on both outburst-prone and outburst-safe sandstones. Graphs depicting the dependencies $k = f(\Delta\sigma = \sigma_1 - \sigma_3)$ were constructed based on the rock formations sample tests. In these tests, the lateral load (σ_3) was set equal to (σ_2) and fixed at 5, 10, 25, and 50 MPa, respectively.

Simultaneously, under the same loading conditions, full "stress-strain" diagrams of the samples were constructed in the mode of specified deformations [9]. The comparison of results from these tests allowed us to establish the relationship between gas permeability and stress and strain field components.

The analysis demonstrated that within the interval of $[0, R_{el}]$ the corresponding elastic area, triaxial compression leads to a reduction in gas permeability, as evidenced by a decrease in fluid filtration rate through the sample. Here, R_{el} represents the strength (elasticity) limit of the rock under uniaxial compression. With further loading and crossing the strength (elasticity) limit, the filtration rate and, consequently, gas permeability increase. During the deformation stage beyond the strength limit, the rate of gas permeability growth gradually decreases until reaching the residual strength, R_{res}, where the material's cohesion within the sample is completely lost, and its absolute value becomes constant. The nature of permeability changes during the transition of the deformed state of the rock from the elastic area to the plastic area allows us to formulate the following hypothesis: the technogenic reservoir's boundary lies within the undermined mass along the surface that separates elastically and plastically deformed rocks.

During the loading process within the range of stress states varying from long-term to residual strength, the deformation of the rock sample is accompanied by an increase in its volume. This phenomenon is known as dilation, which occurs with slight changes in the solid volume but results in a corresponding change in the filtration volume. Under natural conditions, this corresponds to the rock mass dilation and an increase in its porosity or filtration volume due to the formation of joints. The variation in porosity in the dilation zone can be determined using the volumetric strain coefficient $\Pi' = \dfrac{\Pi + (\theta - 1)}{\theta}$, where Π' and Π represent the initial porosity and porosity in the dilation zone, respectively, and θ is the relative volumetric strain.

In [10], a qualitative comparative assessment was performed for samples of both outburst-prone and outburst-safe sandstones, comparing the permeability coefficient (k) and their volumetric strain coefficient by overlaying the curves $k = f(C)$ and $\theta = f(C)$ in a coordinate system with a common abscissa axis (Fig. 1).

In this case, parameter C represents the ratio of the minimum load component applied to the sample following the Karman scheme to the maximum load component, specifically $C = \dfrac{\sigma_3}{\sigma_1}$. The red curve $k = f(C)$ was obtained from laboratory experiments, while the blue $\theta = f(C)$ was calculated.

As seen in Fig. 1, at the post-peak stage, the graphs for both types of samples (a and b) are nearly parallel, indicating that the volumetric strain coefficient of the rock and its gas permeability can be unambiguously related.

Based on the results of rock sample tests under uniaxial compression [9, 10], it was demonstrated that the equivalent stress coincides with the rock sample deformation curve under controlled strain mode.

The determined equivalent stress (σ_e) and the corresponding longitudinal (ε_1), transverse (ε_3) and volumetric (θ) strains provide comprehensive information about the rock's geomechanical state at that deformation stage for which these parameters are determined.

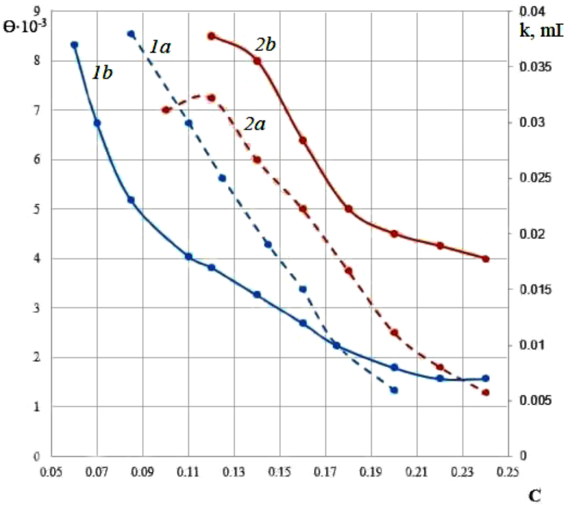

Fig. 1. Graphs of the filtration coefficient k (line 1) and residual volume Θ (line 2) dependence on parameter C:

a – for outburst-prone sandstones; b – for outburst-safe sandstones

Using the principle of stress states equivalence allows transferring the established regularities of permeability changes and the free methane accumulated zone formation to the real massif if the mining process is considered a sequential change of geomechanical states of its rocks during the coal face advance.

Depending on the nature of the problem being solved, the deformation process is divided into four stages. For each fixed load value, corresponding longitudinal ε_1 and transverse ε_2 strains are determined through measurements. Their combination gives the volumetric strain $\theta \approx \varepsilon_1 + 2\varepsilon_2$, which characterises the change in the sample's shape during the testing period.

The values of relative longitudinal strain ε_{1el} and ε_{1res} correspond to the limits of elastic and post-peak deformation, respectively.

Within the scope of the problem being solved, it is sufficient to analyse four stages of the complete deformation process, namely: elastic, compressive strength, post-peak, and equivoluminal flow.

In the first strain stage, elastic compression of the mineral skeleton of the rock is observed, as evidenced by the linear nature of the dependencies $\sigma_e(\varepsilon_1)$ and $\sigma_e(\varepsilon_3)$. The coefficient of transverse strain at this stage is less than 0.5 and remains constant throughout the deformation interval.

At the second strain stage, joints and pores are closed or reduced in size. As a result, the volume of the samples decreases, and the volumetric strain becomes a compaction strain. Experimental studies on the rocks' permeability also indicate that at the elastic strength, the permeability and porosity of these rocks reach their minimum values. These conditions correspond to the characteristics referred to as the compaction threshold in [6].

Experimental studies of the next stage involve the deformation of rock samples under multi-component volumetric load in the range from elastic to instantaneous strength. It has been observed that this deformation stage is associated with the highest rates of permeability increase [7, 8].

At the final stage, Poisson's ratio reaches 0.5, the tested sample changes its shape, but the volumetric strain returns to its initial state at the beginning of the tests.

At this stage, the process of unstable crack formation begins, which can continue without an increase in the external load. The sample volume increases from its minimum at the elastic strength to a value equal to the volume of the sample before applying the load, when the stress level can be compared to the compressive strength. An essential characteristic of the rock structuring at this stage is that until reaching the instantaneous strength boundary, the change in permeability in the direction of any of the principal stresses is the same.

The curves depicting the permeability coefficient dependence on the stress state components ($\sigma_1 > \sigma_2 = \sigma_3$) were adopted for analysis from the work by Ivanov, Feyt, & Yanovskaya (1979).

Despite the slight difference in the absolute values of the long-term and instantaneous strength boundaries, the size of the rock mass regions undergoing deformation due to mining at the discussed stage is quite large.

According to modern concepts of the geomechanical state of the undermined coal-bearing mass, such regions are interpreted as "zones of gradual yielding with the penetration of small cracks" and are adjacent to the shielding surface. The length of these regions in the vertical direction from the mined-out seam is estimated to be about 90–120 m_{seam}, which suggests that these areas constitute 60–80 % of the volume of the technogenic gas reservoir, and the methane trapped in these rocks represents the most significant portion of its reserves [7, 8]. Here, m_{seam} refers to the coal seam thickness.

The geomechanical processes at the third stage are irreversible, and the reduction in load-bearing capacity is accompanied by an increase in volume known as dilation. Along with this dilation, the permeability also increases, but the rate of its growth is lower compared to the previous strain stages.

In the real mass, similar deformation characteristics are observed in the intact rocks of the main roof and the rocks of the floor, which adjoin the mined-out space. It is precisely in this area where gas-collecting parts of surface-degassing boreholes are located.

In the final strain stage, beyond the post-peak boundary, the load-bearing capacity of the sample remains almost unchanged, and at the initial part of this stage, the sample volume does not change significantly. Such behaviour is typical in natural conditions for rock formations that have collapsed behind the coal face. According to different estimates, the collapsed zone extends to a height of 5–8 m_{seam} above the floor. Practically all the methane, both from these rocks and from the surrounding massif, is removed from the mine by ventilation means, and along with the extracted coal.

The step-by-step comparative analysis of the internal mechanism of shape change in rock samples along their full "stress-strain" diagram [10] allowed establishing cause-and-effect dependencies between geomechanical and gas-dynamic processes in coal-bearing mass and qualitatively characterising the general trends in permeability changes and volumetric expansion of these samples. The curves used for the comparative analysis were obtained experimentally and presented in [10]. The functional dependencies that reflect the quantitative interrelation between the investigated parameters are unknown. The mathematically implicit dependencies appear as follows

$$k = \nu(\sigma_1, \sigma_2, \sigma_3); \tag{2}$$

$$\theta = \varphi(\sigma_\perp), \tag{3}$$

where θ is volumetric strains; $\sigma_\perp$ – current total stress acting on the rock sample during its testing under uniaxial compression in a specified deformation mode.

The dependence (2) relates the gas permeability of a certain elementary volume of the coal-bearing mass to its stress state. Within the scope of the given problem, using the hypothesis of equivalent stress states allows for a comparative analysis of the system of equations (2 and 3) by transforming them into a single variable, which is the equivalent stress (σ_e). As a result, equation (3) takes the form $\theta = \varphi(\sigma_e)$. The volumetric stress state can be transformed into an equivalent state using dependencies established during the development of analytical strength theories, such as those by P. P. Balandin. According to this theory

$$\sigma_e = \frac{1}{2\varphi}\left[(\varphi-1)(\sigma_1+\sigma_2+\sigma_3) + \sqrt{(\varphi-1)(\sigma_1+\sigma_2+\sigma_3) + 2\varphi(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2}\,\right]. \tag{4}$$

In the equation φ is the brittleness coefficient, which is calculated using the formula $\varphi = \frac{R_t}{R_c}$, where R_t is uniaxial tensile strength; R_c – uniaxial compressive strength.

By means of mathematical calculations using criterion (4), expression (2) can be transformed into the form $k = \nu(\sigma_e)$, and the system of equations (2 and 3) into functions of a single variable. The recalculation based on experimental data used for curve construction showed that within the field of relative equivalent stresses, the mentioned curves are parallel, indicating regularity in gas filtration processes. Analysing these curves led to the following conclusions: the gas permeability of the rock in the elastic deformation stage decreases from a certain initial value corresponding to the geological conditions of the specific rock.

At the initial stage of deformation, its stress state is characterized by an increase in equivalent stresses from zero (undisturbed mass) to the rock compressive strength, R_{el}. In the subsequent stage of deformation, gas permeability increases, and the investigated curves intersect at a point with an ordinate of $\sigma_e = R_c$.

Furthermore, as the equivalent stress decreases to R_{res} for each specific rock type, the trends in permeability changes are maintained, and the curves converge. Essentially, at this stage, the behaviour of the curves reflects the variations in gas permeability of rock samples during uniaxial compression tests under controlled strain mode.

Thus, if the rock seam permeability and its values at the bifurcation points ($\sigma_e = R_{el}$, $\sigma_e = R_{res}$) are known, the evaluation of the undermined mass as a gas reservoir can be performed based on the results of uniaxial compression tests on the respective rocks.

The graphs in Fig. 1 indicate a clear dependence between volumetric strain, as a characteristic of the coal-bearing mass stress state, and its gas permeability throughout the interval of stress state changes from the moment of applying the load to complete failure. The step-by-step analysis of the rock samples' deformation process in correlation with their gas permeability provides grounds to consider the existence of a functional dependency that links gas permeability and volumetric strain within the intervals between the specified points

$$k = f(\theta). \tag{5}$$

These functions are defined within the interval of 0 to R_{el} values of the equivalent stress σ_e. The functions are continuous, odd, and non-periodic, and they do not have vertical asymptotes in their domain. The range of values extends from their minimums at the point $\sigma_e = R_{el}$ to their maximums at the point $\sigma_e = R_{res}$. Function (5) intersects the x-axis at points $\sigma_e = 0$ and $\sigma_e = R_c$, while the function $k = \nu(\sigma_e)$, as well as $k = \nu(\sigma_1, \sigma_2, \sigma_3)$ makes sense only in the region of their positive values.

Both functions monotonically decrease from the origin of the coordinates to the first critical point $\sigma_e = R_{el}$ and monotonically increase in the interval $[R_{el}, R_{res}]$. Within the range of equivalent stress values $[0, R_c]$, both functions are concave, and over the entire interval $[R_c, R_{res}]$they are convex. The point of inflection for both functions is $\sigma_e = R_c$. Thus, the critical points for both functions are $\sigma_e = 0$, $\sigma_e = R_{el}$, $\sigma_e = R_c$, and $\sigma_e = R_{res}$, which coincide with the critical points determined earlier.

Let us consider the behaviour of functions (5) within the intervals of their values, bounded by critical points.

In the interval $[0, R_{el}]$, the values of σ_e characterise the stress state of the elastic strain coal-bearing mass containing the technogenic deposit. It is established that in the zones of supporting pressure, the permeability decreases from natural to minimum values exponentially [7, 8]

$$k = a \exp(-d \cdot \sigma_e). \tag{6}$$

The constant coefficients (a and d) that appear in function (6) can be determined if the values of the rock permeability are known at the interval boundaries, specifically at points $\sigma_e = 0$ and $\sigma_e = R_{el}$. At $\sigma_e = 0$, and at the point $\sigma_e = R_{el}$, the function (6) takes values corresponding to the rock permeability at the elastic strength, denoted as $a = k_{el}$. Taking this into account, expression (6) will have the following form

$$k_{el} = k_{int} \exp(-d \cdot R_{el}),$$

where k_{int} is rock permeability in the intact mass. It follows

$$-d = \frac{\ln k_{el} - \ln k_{\text{int}}}{R_{el}}. \tag{7}$$

The rock volumetric strain can be determined experimentally or calculated using the following expression

$$\theta = \varepsilon_{el} + 2\varepsilon_n = \sigma_e \left(\frac{1}{E_{l.t.}} + \frac{2}{E_{tr.v.}} \right), \tag{8}$$

where $E_{l.t.}$ is modulus of longitudinal elasticity; $E_{tr.v.}$ – modulus of transverse elasticity.

After taking the logarithm of both sides of equation (7) and substituting the value of σ_e, determined from expression (9), the desired dependence is obtained. It links the change in the rock permeability in the bearing pressure zone to the stress state, which is expressed through its geomechanical characteristic θ

$$\ln k = \ln k_{\text{int}} - \theta \frac{\ln k_{\text{int}} - \ln k_{el}}{R_{el}} \left(\frac{1}{E_{l.t.}} + \frac{2}{E_{tr.v.}} \right),$$

or

$$\ln k = \ln k_{\text{int}} - \theta \frac{\ln \frac{k_{\text{int}}}{k_{el}}}{R_{el}} \left(\frac{1}{E_{l.t.}} + \frac{2}{E_{tr.v.}} \right)$$

as follows

$$\ln k = \ln k_{int} - \psi\theta. \tag{9}$$

Taking into account the fact that the rock compressive strength under uniaxial compression R_{el} at the elastic strain boundary is practically equal to the compressive strength R_c, that is $R_{el} = R_c$, it can be concluded that $k_{el} = k_c$. Then, the similarity coefficient is determined by the equation

$$\psi = \frac{\ln \frac{k_{\text{int}}}{k_c}}{R_c} \left(\frac{1}{E_{l.t.}} + \frac{2}{E_{tr.v.}} \right). \tag{10}$$

The following conclusions can be drawn by analysing the dependency (10). The functions exhibit similarity with a constant similarity coefficient ψ. The parameters involved in the ψ coefficient can be determined experimentally. To determine the permeability of any region in the rock mass surrounding the technogenic deposit, it is sufficient to know the values of its permeability k_{int} in the intact mass and k_{el} on the elastic strength, as well as the characteristics of post-peak strain under uniaxial compression of the constituting rock mass.

During the research, the most important results include establishing the boundaries of the technogenic gas deposit in particular and identifying the specific areas along this boundary where methane leaks from the deposit, including to the surface. The boundary's coordinates define the deposit configuration in the space of the mined-out coal mass, enabling the estimation of its reserves and the justification of methods for methane extraction from this mass. The condition indicating that a certain elementary region of the coal mass constitutes the boundary (shell) of the technogenic deposit is formulated as follows

$$R_{el} = mR_c, \tag{11}$$

where R_c is compressive strength, which is determined during uniaxial compression tests; m is the structural factor.

The elementary volumes coordinates, where the stress state corresponds to the condition in (11), determine the positions of the boundaries of the technogenic gas deposit in the space of the mined-out coal mass. The reserves of the technogenic gas deposit consist of methane present in gas-bearing rocks within the deposit. Using the dependence (9), it is possible to estimate the magnitude of methane inflow from the surrounding mass into the technogenic deposit or, conversely, its outflow from the deposit. This allows for the adjustment of the deposit's overall gas balance [10].

The gas collector within its established boundaries includes three interacting zones: caving rocks, fast gas, and slow gas. The boundary of the caved rocks zone can be determined with sufficient accuracy using numerical modelling of the initial and steady steps of roof collapse according to the methodology provided, for example, in [9]. At the same time, the permeability of this zone can be determined based on the results of longitudinal depression surveys [1, 2]. Research results on the rock's permeability under a volumetric stress state indicate that the boundary between the slow and fast gas zones intersects those parts of the rock mass where the rocks are at the point of instantaneous strength [7, 8]. In the numerical model of the rock mass, these areas will correspond to finite elements that satisfy condition (11).

Analysing the behaviour of the $\ln(k)$ curve as a function of equivalent stress (σ_e), we can consider that within the range of R_{el} (elastic strength) to R_{res} (residual strength), it can be adequately approximated by a linear dependence

$$\ln k = a + d\sigma_e, \qquad (12)$$

where a and d are constant coefficients.

The values of the constant coefficients in equation (12) can be determined using known permeability values at the boundaries of the mentioned range

$$a = \ln k_{el}; \quad d = \frac{\ln \dfrac{k_c}{k_{el}}}{R_c}.$$

Given that the deformation within the range $R_{el} = mR_c$ follows Hooke's law, the volumetric strain can be determined from expression (8). By substituting expressions (8 and 10) into (12), we obtain the dependence for determining the permeability of rocks in the slow gas filtration zone

$$\theta = \theta^* \frac{R_c - \sigma_e}{R_c - R_{res}}; \quad \ln \frac{k_{\text{int}}}{k} = \psi\theta^* \frac{R_c - \sigma_e}{R_c - R_{res}};$$

$$\frac{k_{\text{int}}}{k} = \exp\left(\psi\theta^* \frac{R_c - \sigma_e}{R_c - R_{res}}\right);$$

$$k = k_{\text{int}} \exp\left(\psi\theta^* \frac{R_c - \sigma_e}{R_c - R_{res}}\right)^{-1}.$$

At $\sigma_e = R_c$, we obtain a permeability coefficient equal to the permeability of the intact rock layer, i. e., $k = k_{int}$. And at $\sigma_e = R_{res}$, we obtain the value of the gas permeability factor $k = k_{int}\psi\theta^*$, where θ^* denotes the value of the volumetric strain at the residual strength boundary.

The change in the stress-strain state within the range of equivalent stresses $[R_c, R_{res}]$ is characteristic of the part of the undermined mass surrounding the region of caving rocks (rapid gas release). The extraction technologies of mine methane from the surface involve locating gas-collecting parts of surface-degassing boreholes in these areas of the coal-bearing mass. The dependence linking the volumetric strain (θ) of the rock with the current value of its equivalent stress σ_e within the specified interval can be expressed as follows

$$\theta = \theta^* \frac{(R_c - \sigma_e)}{R_c - R_{res}}.$$

The values of R_c, R_{res}, σ_e and θ^* can be determined experimentally and analytically for a specific stress state.

For the limit values of σ_e ($\sigma_e = R_c$ and $\sigma_e = R_{res}$), the value of k^* is within the range $1 \le k^* \le k_{res}$. The graph of the dependence of the relative permeability coefficient k^* on the magnitude of equivalent stresses (σ_e) is approximated by a power law (or L-curves), which can be expressed as follows (Fig. 2) $k^* = a\sigma_e^b$, where $a = 4.88$, $b = -0.83$.

The reservoir parameters of the undermined gas-saturated coal mass are determined based on its geomechanical characteristics, established through a full "stress-strain" diagram of samples subjected to uniaxial compression under controlled strain mode, and the permeability values of these rocks at bifurcation points. These parameters can be determined using approved methods on standard equipment.

Future research should include consideration of the potential for crack formation caused by harmonic loads under the action of harmonic loads that arise in the form of elastic impulses during the coal seam destruction by cutting tools [11].

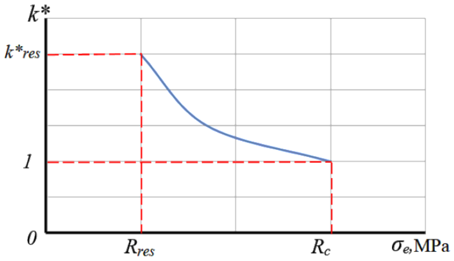

Fig. 2. The graph of the dependence of the relative permeability coefficient on the magnitude of equivalent stresses

Conclusions.

1. The ability to use a full "stress-strain" diagram for identifying methane reservoirs in the undermined coal-bearing mass was proved.

2. It has been proven that deformation occurs under controlled strain mode during the relatively slow advancement of the coal face in the coal-bearing mass. Ahead of the face, at a certain distance from the excavation, a maximum bearing pressure is formed, which is referred to as the "compaction threshold" concerning gas filtration. This area corresponds to the minimum values of porosity and, consequently, filtration, allowing it to be considered the envelope of a local gas reservoir.

3. The reservoir parameters of the undermined gas-saturated coal-bearing mass are determined based on its geomechanical characteristics. They are established through the full "stress-strain" diagram for subjected to uniaxial stress under controlled strain mode, and the permeability values of these rocks at bifurcation points. These parameters can be determined using standard equipment and approved methodologies.

4. It has been proven that the ratio of logarithms of the relative magnitudes of the current and final permeability of the gas-saturated coal mass is directly proportional to its three-dimensional equivalent stress state and strength characteristics of the post-peak strain state. These data allow creating a predictive numerical geomechanical model of the methane migration paths.

5. Further research is related to constructing and investigating a geomechanical model for specific mining and geological conditions and delineating local gas reservoir boundaries.

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Оцінка газопроникності породних масивів вугільних шахт у полі еквівалентних напружень

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Мета. На основі порівняльного аналізу внутрішнього механізму формозміни породних зразків, що навантажуються в режимі заданих деформацій, і геомеханічними та газодинамічними процесами у вуглепородних масивах встановити причинно-наслідкові зв'язки між цими явищами, якісно охарактеризувати газову проникність масивів як функцію об'ємного розширення гірських порід. Обгрунтувати можливість використання повних діаграм деформування породних зразків у якості моделі формування техногенного метанового родовища та його просторової локалізації.

Методика. Теоретичні дослідження базуються на використанні основних положень механіки твердого деформованого тіла й результатах лабораторних досліджень процесу руйнування породних зразків у режимі заданих деформацій.

Результати. У результаті досліджень доведена спроможність використання повної діаграми руйнування зразків гірських порід для виявлення й локалізації колекторів метану при відпрацюванні вугільних пластів. Виявлено, що поріг ущільнення співпадає з максимумом опорного тиску попереду вибою лави. Цій площині відповідає мінімальна пористість породного масиву й мінімум фільтрації, що дозволяє розглядати її як оболонку штучного газового родовища. Отримані закономірності, що пов'язують тривимірний еквівалентний напружений стан з остаточною газовою проникністю газонасиченого вуглепородного масиву, що дозволяє створити прогнозну числову геомеханічну модель колекторських шляхів міграції метану.

Наукова новизна. Уперше обгрунтована спроможність використання повних діаграм руйнування породних зразків у режимі контрольованих деформацій для математичного моделювання газової проникності насиченого метаном вуглепородного масиву при відпрацюванні вугільних пластів і визначення границь техногенного газового родовища. Отримані залежності поточної та остаточної газової проникності від механічних характеристик порід у стані позамежного деформування.

Практична значимість. Полягає в отриманні функціональних залежностей, що на основі геомеханічних моделей дозволяють виявити й локалізувати техногенні колектори метану в шахтах при відпрацюванні вугільних пластів із подальшим використанням видобутого газу. Окрім того, видалення метану підвищує безпеку виконання гірничих процесів завдяки зниженню ризику газодинамічних проявів гірського тиску, а зменшення викидів газу в атмосферу сприяє зниженню парникового ефекту.

Ключові слова: *вугільна шахта, позамежне деформування, еквівалентні напруження, газова проникність, колектори метану, техногенне газове родовище*

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