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DETERMINING THE PARAMETERS OF STRATIFICATION CAVITY IN ROCK MASS TO EXTRACT MINE METHANE

Purpose. Substantiation of the stress-strain parameters of a rock mass state to identify potential mine methane accumulation in the roof rocks of the extraction pillar.

Methodology. Characterization of stratification cavity in rock mass for mine methane extraction relied upon analytical studies. The research is based on a method by Professor O.V. Savostyanov to calculate a stress-strain state of rocks. The method has been implemented in *GeoDenamics Lite* software. The use of the method helps obtain both geometrical and physical parameters of load characteristics for typical rock layers from the coal seam up to the surface. The abovementioned makes it possible to identify areas of rock stratification, coal bench being flaked away, and the number of rock layers after stratification. Mining and geological conditions of the coal seam occurrence and mining technology are the output data for the research.

Findings. Analysis of geometrical and physical parameters of load characteristics on the roof rocks of a coal seam has supported the fact that abnormal pressure areas propagate within the rock mass. The listed parameters vary from a seam up to the surface normally both towards the rock mass and towards the mined-out area along with the stope advance. The abovementioned helps define parameters of stratification cavity formation within the roof rocks of an extraction pillar since the cavities may accumulate mine methane.

Originality. Dependencies of the changes in rock layer subsidence height have been derived based upon formation dynamics of the mined-out longwall volume. Regularities of changes in volumes of rock formation stratification cavities have been identified depending upon the strength and thickness of the rock layers; closeness to mining area; and stope advance velocity as well as its length.

Practical value. Based upon the method by Professor O.V. Savostyanov, an algorithm has been proposed to define possible mine methane accumulations after mining operations within the extraction pillar are completed. Hence, the areas of methane accumulation will be considered in future as extra sources of fuel material. At the same time, it has been proposed to complement operation mode of a mining enterprise with biogas plants if the produced mine mixture is poor. A technological scheme for the combined *mine methane-biogas* extraction has been provided.

Keywords: *stope, mine methane, coal seam, stress-strain state, stratification cavity*

Introduction. The current conditions of Ukrainian coal industry progress motivate to make new technical and technological decisions as for the mineral mining. Consequently, implementation of a gasification geotechnology helps mine the coal concentrated within very thin seams as well as within the abandoned reserves which powered extraction is far from being expedient. At the same time, it should be mentioned that a significant share of mine fields is mined out either completely or partially, which results in liquidation of the coal enterprises. In this context, the basic problems, connected with methane emission from operating or abandoned mines, are not solved; in such a way, negative climate consequence occurs. Moreover, in 2020, the European Commission provided a separate EU strategy to reduce methane emissions. The strategy matches purposes of the European Green Deal to achieve climate neutrality by 2050. In addition, the measures will favour EU efforts as for decarbonisation by 2030, and climate neutrality by 2050. Also, in the field of heat engineering and power industry, the EU sets a goal to achieve zero environmental pollution [1].

It is possible to mitigate both technogenic and environmental load on depressive mining regions while implementing efficient and rational techniques to use resource and energy potential of coal enterprises [2, 3]. The authors believe that the

techniques may rely on the operating principles of mining energy and chemical complex whose activities are focused on the idea to produce in the closed cycle energy raw materials in the form of gas and biogas mixtures, and thermal power. Methane is the basic gas mixture which can be applied on the basis of a coal mine.

There are three types of methane localization within the rock mass: free methane in rocks and their fissures; the adsorbed gas in dispersed organic matter and coal layers; and gas dissolved in water-saturated sandstone [4, 5]. Underground mining operations shape technogenic cavities being potential areas for methane accumulation. At the same time, mine methane may accumulate within the areas even if coal extraction is completed [6]. Hence, the topical scientific and practical challenge is to identify methane locations while coal mining and/or completing.

Literature review. After mining is over, the disturbed rock mass, the unexploited coal seams and layers, the left coal pillars, and the mined-out area and mine workings release methane for decades. Methane amounts from decommissioned mines are 2–3 times more than the gas amounts released from operating mines. Release of methane from the abandoned mines in 2020 was 17 % of the global methane emission; according to the forecast, the indicator will increase up to 24 % in 2050 [7, 8].

The majority of Ukrainian mines are closed down using a ‘wet’ method. In this regard, methane flow rate in gas pipe-

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lines increases. The pipelines are in the mine workings entering surface. Nonavailability of aerodynamic connection with the gas pipelines results in the uncontrolled methane migration to the surface. The abovementioned results in greenhouse gas emissions into the atmosphere and its accumulation in the basements of residential buildings thus creating an explosive concentration [9, 10].

The world practices know numerous projects for methane extraction from the abandoned mines proving that its use is technically possible and economically feasible.

For instance, Germany has implemented thirty-five projects to extract methane from the closed-down mines. There were ninety-four plants generating electricity and thermal power. Within the projects, more than 500 MWh of electric energy and 75 MWh of heat are produced annually. France has implemented five projects on methane extraction from the closed-down mines. Five power plants with the installed 9 MW capacity generate electric energy. Annual methane production is almost 26 million cubic meters. Great Britain implemented thirteen projects for mine gas use. At twelve of them, electric energy with the installed 78 MW capacity is generated. One project concerned pipeline injection. Almost 58 % of methane emissions are utilized from the decommissioned mines [11, 12].

In view of the significant methane amount in the closed-down mines, its extensive concentration in mine atmosphere, and potential danger in terms of the uncontrolled release to the surface, methane extraction from technogenic volume of coal mines and use make a promising tendency which can mitigate financial, environmental, and social load in the process of mining enterprise liquidation.

To extract gas from technogenically undermined rock masses as well as from the subsoil volume of the closed-down mines, both the global and national practices apply either gas pipelines laid during liquidation of mine workings entering the surface or gas-drainage wells drilled to methane accumulations [13].

It should be mentioned that mine methane extraction and use are economically feasible if the following factors are available:

- quantity and quality of the gas;
- a clear picture of the methane accumulation availability and location;
- possibility to control water inflow;
- reliable isolation of mine workings entering the surface;
- aerodynamic connection between mine workings, and gas pipelines or wells;
- infrastructure to apply the gas.

Production technologies and opportunities for development of unconventional hydrocarbon resources became more urgent from year to year [14, 15]. However, experience supports the idea that the most efficient way for mine methane use as fuel is its combination with other sources of carbon energy (i.e. coal, natural gas, and biogas). In this context, utilization of poor methane mixtures in the Western Donbas mines, either terminating their activities or having already stopped them, is a promising tendency. However, we consider it to be understudied.

Thus, the **purpose** is substantiation of the rock mass stress-strain state parameters to identify potential mine methane accumulations in the roof rocks of extraction pillar.

Methods. Algorithm of the research. Analysis of geomechanical processes within a rock formation where mining operations take place or were performed needs comprehensive and qualitative characteristic of stress-strain state of the rock mass. The available methods calculating stress-strain rock state fail to involve completely specificity of rock mass structure and technological parameters of mining. The majority of calculation methods help solve some applied problems, for instance, determination of wall rock convergence, load on the powered support, roof caving interval and others.

To identify geomechanical stratification parameters of rock formation within the mining area, closely connected with the behaviour of the layered mass, consisting of sedimentary rocks, in the context of thin coal seam extraction, the paper applies a method by Professor O. V. Savostyanov to calculate a stress-strain state of rocks [16] implemented in GeoDenamics Lite software. Mining and geological data on stratigraphic section and technological parameters of mining are the basic indicators to perform the analytical studies. Coal formation around a stope is divided into rock layers in terms of lithological difference with their numeration from the coal seam up to the surface.

A calculation procedure of stratification parameters of the coal formation takes two stages.

Stage one determines geometry of load characteristics (a , d_0 , f_1 , f_2 , l_s , and l_r) for typical rock layers from the coal seam up to the surface. Values of free subsidence of the rock layer are boundary conditions for the problem solving since in terms of them no response is observed above the mined-out area of the longwall; the mass from the undermined rock formation is transferred to a reference pressure zone. Boundary span of rock layers is identified; in this context, maximum subsidence corresponds to the given values and geometry corresponds to the set ones. While determining physical parameters of a load characteristic, calculation is performed from the surface down to the coal seam being mined. In addition, the boundary conditions are limited by maximum subsidence of the rock layers. To simplify the challenge, points of rock layers are singled out within the mined-out area. The points are based upon the harder layers influencing the shear parameters.

Identification of geometrical and physical parameters is stipulated by the availability of hard rock layers determining a displacement process. Further parameters of distribution of responses and normal loads within the bench of rock layers are defined; the next step is calculation of (B_1 , B_2 , B_3) coefficients which depend upon the parameters of load characteristics.

A stress-strain state of rocks within formation is identified according to the key stresses (G_1G_2) and according to uniaxial compressive strength (SPR). Conditions of roof rock destruction in a layer, resulting from a bending moment, arise perpendicularly to stratification due to separation stress [17, 18]. In accordance with the accepted model and the design scheme, stresses in different sections of a rock layer are defined in addition to lateral force Q_x and bending moment M_x . In this context, horizontal shifts help identify parameters of vertical fissure formation as well as rock layer subsidence of the undermined rock mass. Field measurements have made it possible to define that $\varepsilon > 5$ mm/m deformation factor results in vertical fissuring in the rock mass layers [19].

The software involves a block to test the layers for stratification. The test criteria are shearing and disconnecting stresses within the rock layers generated by lateral forces Q , bending moment, and proper rock weight.

Rock stratification will take place if disconnecting rock strength is perpendicular to $G_{sep.} > R_{sep.}$ stratification or if shearing rock strength is parallel to $\tau_{ben.} > R_{sh}$ stratification. Calculations are applied for the given sections to identify rock stratification areas, thickness of a bench being flaked away, and the number of rock layers after stratification.

Output data formation for the research. The parameters of stratification cavity shaping and methane accumulation in the mined-out rock mass have been substantiated for extraction operations within longwall 712 of C_7 seam in M.I. Stashkov mine (DTEK Pavlohradvuhillia PJSC). Mines of the company are in a densely populated industrial area with the developed infrastructure. The fact stipulates expansion of the demand for energy. It should be mentioned that natural methane content of the seams, developed by DTEK Pavlohradvuhillia PJSC mines, varies in a large range from 4.7–22.6 m³/t of roof rocks to 1.8–2.2 m³/t of foot rocks. Approximate prospective reserves of gaseous hydrocarbons are 1.5 billion cubic meters [20].

Table 1

Output data for the study

Layer	H , m	h , m	h_l , m	Rock type
1	206	202	4	aleurite
2	202	194	8	sandstone
3	194	174	20	sandstone
4	174	162	12	aleurite
5	162	147	15	argillite
6	147	113	34	aleurite
7	113	67	46	argillite
8	67	0	67	sandstone
General data				

$\gamma = 2.18 \text{ t/m}^3$; $m = 1.12 \text{ m}$; $V = 1; 3; 5 \text{ m/day}$; $a = 0.1$; $LL = 80 \text{ m}$; $T = 150\text{--}300 \text{ days}$; $Y_0 = 0.79 \text{ mm}$; $d_2 = 1230$; $K_2 = 1.54 \cdot 10^6 \text{ t/m}^2$; $d_3 = 690$; $K_3 = 1.47 \cdot 10^6 \text{ t/m}^2$; $W = 30 \%$; $\Delta = 0.7$; $N = 2$; $No = 3; 7$; and 1 are sandstones

Table 2

Geometrical and physical parameters of loads on rock layers around longwall 712 while mining C_7 seam

Layer number top to down	Geometry, m			
	A	d_0	b_2	f_2
8	86.5	55.7	78.1	184.4
7	80.9	53.4	61.5	157.6
6	40.4	25.2	33.8	77.0
3	31.4	20.9	21.7	52.3
2	15.2	11.6	12	26.8
	Physical parameters, MPa			
	S_1	S_2	Z_2	T_2
8	20.7	20.2	–	0.6
7	23.4	22.5	–	1.5
6	27.2	24.3	–	2
3	31.1	29.8	–	3.4
2	29.5	16.2	–	3.1

Stress-strain parameters of the rock formation have been determined according to the mining and geological indicators of a stratigraphic section of 3354 well (Fig. 1).

In terms of lithological difference, rock formation is divided into layers. If thick bridge rocks are not available, then the division is performed from a coal seam being mined up to the surface. If bridge rocks are available, then layers are divided from a seam to a hard rock layer. Output data, characterizing the formation, divided into rock layers, are entered into GeoDynamics Lite software in the form of data array.

Fig. 1 demonstrates a scheme of the initial data preparation in terms of a typical stratigraphic section of rock mass according to 3354 well of 712 longwall of C_7 seam in M. I. Stashkov mine.

Data arrays on the rock occurrence depth, thickness, and physicommechanical characteristics are ordered and tabulated for convenience. The analysis is performed on two sections (Fig. 1, A–A section): I–I being perpendicular to a stope in the central longwall share; II–II being in the mined-out area at a distance from the stope and in parallel with it. Due to changes in rock deformation modulus (E_n) within the mined-out area and rigidity factor of the system (β), the calculations take into consideration the stope advance velocity and time. For example, in the context of I–I section, the time is taken to be equal to zero; in the context of II–II section, the time is taken into account from the moment of mining termination within the section.

Table 1 shows output data for the analysis to identify stratification parameters of coal formation above 712 longwall of C_7 seam in M. I. Stashkov mine.

In the table, a layer No is the order number of a rock layer shaping rock strata bottom-up above the stope; H and h are distances from the surface down to foot and roof, m; h_l is layer thickness, m; γ is average density of the layers, t/m^3 ; m is thickness of the seam being mined, m; V is stope advance velocity, m/day; a is seam inclination, rad; LL is distance from the section to the stope boundary, m; T is time after mining, days; Y_0 is boundary roof fault, mm; d_2 , K_2 , d_3 , and K_3 are deformation moduli for each lithological difference, t/m^2 ; W is rock moisture, %; Δ is friction coefficient; N is the number of hard layers, pieces stipulating shift within the rock mass, pieces.

Results and discussion. The calculations in the GeoDynamics Lite environment have helped identify geometrical and physical parameters of load characteristics on roof rock layers taking into consideration mining and geological conditions as well as technological parameters of C_7 coal seam mining of 712 longwall, which terminated its operation. Table 2 contains the data.

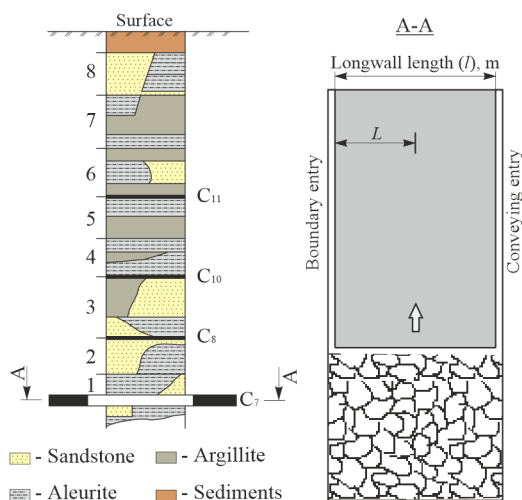


Fig. 1. Scheme of initial data preparation in terms of a typical stratigraphic section of rock mass according to 3354 well of 712 longwall of C_7 seam

While analysing the geometrical and physical parameters of loads on rock layers, one should mention the fact that the abnormal pressure zones expand within the rock mass containing C_7 seam. Changes in the parameters take place from the seam up to the surface normally towards the mined-out area along with the stope advance.

Fig. 2 explains distribution of loads on the rock layers and cavity shaping at a C_8 level above longwall 712 while mining a thin coal seam C_7 .

In the process of coal seam C_7 mining with average 3 m/day velocity of a longwall advance, at the level of C_8 seam reference pressure zone is formed $K = 7.5 \text{ m}$ apart from the stope to the cavity shaping boundary above the mined-out area of longwall 712 (Fig. 2). While analysing data in Fig. 2, one should note that along with the stope advance, stratification cavities above the longwall mined-out area are shaped normally 9–14 m apart from C_7 seam at the level of C_8 seam; at 15–26 m distance at the level of C_{10} seam; and at 17–28 m distance at the level of C_{11} seam normally up to the surface.

Fig. 3 demonstrates dependencies of changes in the volumes of rock formation stratification cavities upon the longwall length at the level of C_8 , C_{10} and C_{11} coal seams. The data help identify approximate amounts of the accumulated mine gas.

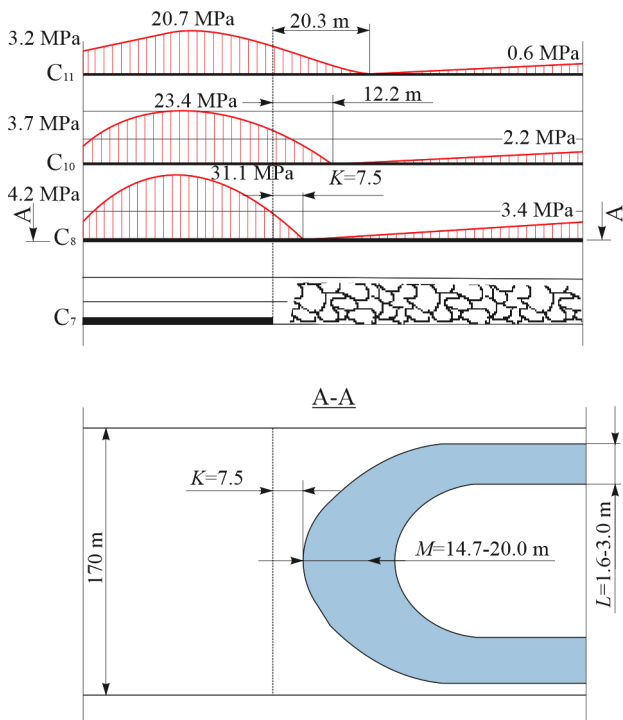


Fig. 2. Distribution of loads on the rock layers and cavity shaping at a C_8 level above longwall 712 while mining coal seam C_7 ; A–A is a section of the stratification cavity

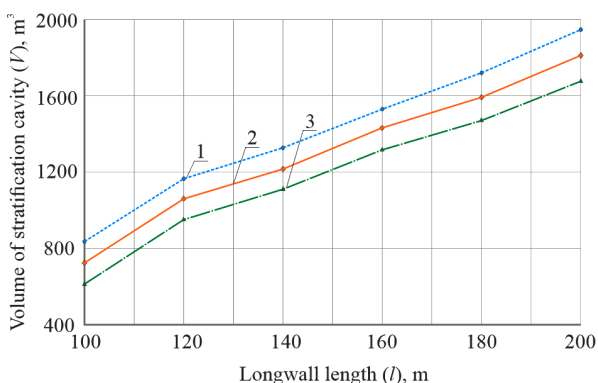


Fig. 3. Dependencies of the volumes of rock formation stratification cavities upon the longwall length at the level of C_8 (1); C_{10} (2); C_{11} (3) coal seams

The highest stratification cavity is shaped at the level of C_8 seam between hard rock layer 3 and layer 2 being the main roof of a coal seam C_7 being mined (Fig. 1). Under the conditions, cavity occurrence depends upon difference in rock strength, rock layer thickness, closeness to mining operations, and velocity of a stope advance stipulating the distinction between shear velocities of rock layers.

Fig. 4 shows subsidence parameters of layers 3 and 2 depending upon the advance velocity of the considered stope.

Dynamics of the mined-out area of longwall shaping determines both velocity and parameters of stratification cavity formation. For instance, longwall stope advance increases parameters of the mined-out area. In this context, the stratification cavity closes. After mining is terminated within coal seam C_7 and extraction pillar length is 685 m, a cavity height at the level of C_8 cannot be more than $h_{s.c.} = 181$ on average; in this context, its volume is $V_{s.c.} = 1879 \text{ m}^3$. According to a mining technique, parameters of stratification cavities within a percarbonic formation of longwall 712 vary according to linear dependence over three ranges: cavity height may be $h_{s.c.} = 155\text{--}278 \text{ mm}$; and cavity volume may be $V_{s.c.} = 517\text{--}1879 \text{ m}^3$. Ac-

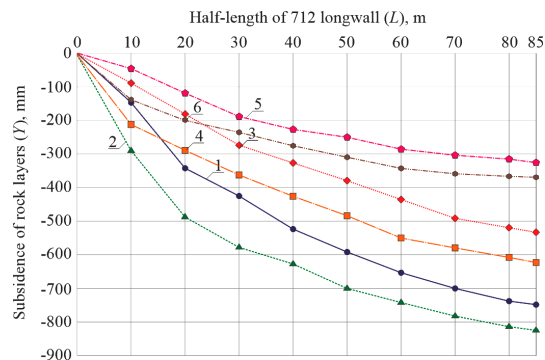


Fig. 4. Changes in subsidence height of rock layer subsidence within the stratification cavity at C_8 seam level in terms of half the length of longwall 712 depending upon its advance velocity:

1, 3, 5 – hard rock layer subsidence cases (Table 1) at 1, 3, 5 m/day velocities, respectively; 2, 4, 6 – subsidence cases of rock layer 2 (the main roof, Table 1) at 1, 3, 5 m/day velocities, respectively

celeration of stope advance results in the increased stratification cavity height above the mined-out area; in turn, its width decreases under the impact of shift of reference pressure zone boundary towards the mined-out area.

Analytical studies on a stress-strain rock state around longwall 712 of C_7 level in M. I. Stashkov mine have helped identify regularities to shape the areas of stratification cavity shaping above the mined-out area of a stope. The areas are in the distressing rock mass zone while being a potential place for methane accumulation. According to the calculations and the available mining schedule for C_7 level, cavity parameters above the mined-out area will achieve 8.9–40.2 thousand cubic meters and 443–836 mm height of the cavity.

After mining termination in the mine side or by the enterprise on the whole, such methane accumulation areas become an additional source of fuel raw materials. Methane from the rock formation cavities may be extracted from mine workings. However, significant length of underground line, required to degas subsurface technogenic space of the closed-down mine, results in numerous air inleakages while reducing methane content of the degassing mixture. Taking into consideration occurrence depth of stratification zones, methane extraction sites are proposed to operate through vertical wells or inclined and horizontal wells.

As it has been mentioned, the most efficient way to use the extracted mine methane is its application as a fuel combined with other energy sources. Consequently, prospects for further research are substantiation of the combined technique parameters to utilize mine methane while using biogas plants mounted within the surface complex of a coal mine. Fig. 5 represents general view of the technological scheme of underground and surface parts of the combined complex utilizing mine methane and biogas.

The technique prefers thin off grade coal seams as well as exhausted mines or stagnate mines having methane accumulation localizations.

Utilization process of mine methane begins with its withdrawal from the stratification cavities of rock mass 1 above the mined-out area of stope 3 through production wells 2. Then the gas is directed to an accumulation tank 4. A mixture, obtained by a biogas plant 5 is also directed to the accumulation tank. The gas mixtures are forwarded to a complex purifying them 6. The purified combination may be utilized and used as a chemical raw material and/or motor oil for car engines or in cogeneration plants 7.

Implementation of the combined technique for gas mixture utilization will provide extension of the resource base using recoverable energy raw materials of mining enterprises with the minimization of environmental impact and manufacturing of power products and chemicals.

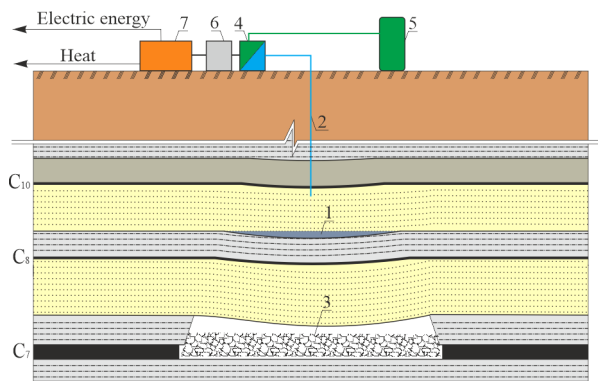


Fig. 5. Technological scheme of the combined method for mine methane and biogas utilization:

1 – rock mass stratification cavity above the mined-out area of 172 longwall; 2 – production well; 3 – the mined-out area of the longwall; 4 – accumulation tank for mine methane and biogas; 5 – biogas plant; 6 – complex to purify as mixtures; 7 – cogeneration plant

Conclusion. Based upon the research carried out in terms of 712 longwall operation in M. I. Stashkov mine, which terminated its activities, geometrical and physical parameters of load characteristics on roof rocks were substantiated taking into consideration mining and geological conditions of coal seam C_7 extraction. The abovementioned has helped identify parameters of rock mass stratification zone shaping above the extraction pillars which may be potential areas of mine methane localization.

At the same time, mining and processing of methane containing gases from rock formations of the closed-down enterprises are important components in the process of technogenic mine space utilization from the viewpoint of environmental friendliness and economic efficiency.

Implementation of the combined technique for mine methane and biogas utilization will expand energy potential of mining enterprise, and form its new chemical facilities. In turn, formation of the comprehensive approach will make it possible to prepare ‘poor’ mine methane mixture; generate electricity and thermal energy; and manufacture fuel gas and fertilizers while processing organic waste.

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Визначення параметрів порожнини розшарування в гірському масиві для видобутку шахтного метану

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Мета. Обґрунтування параметрів напружено-деформованого стану гірського масиву для визначення можливих локалізацій скопчення шахтного метану в породах покрівлі виїмкового стовпа.

Методика. Визначення параметрів порожнини розшарування в гірському масиві для видобутку шахтного метану ґрунтувалось на основі проведення аналітичних досліджень. Основою даних досліджень слугував метод розрахунку напружено-деформованого стану гірських порід, розроблений проф. О. В. Савостьяновим, що реалізований у програмному забезпеченні «GeoDenamics Lite». Застосування даного методу передбачає отримання геометричних і фізичних параметрів епюр навантажень для характерних породних шарів від вугільного пласта до земної поверхні. Це дозволяє встановити місця розшарування порід, потужність пачки, що відшаровується та кількість породних шарів після розшарування. Вихідними даними для досліджень слугують гірничо-геологічні умови залягання вугільного пласта й технологічні параметри ведення очисних робіт.

Результати. При аналізі геометричних і фізичних параметрів епюр навантажень на шари порід покрівлі вугільного пласта підтверджено факт розширення зон аномального тиску в гірському масиві. Характер зміни зазначених параметрів підтверджено від пласта до денної поверхні за нормаллю як у бік масиву, так і у бік виробленого простору в міру посування очисного вибою. Це дозво-

ляє визначити параметри формування порожнин розшарування в породах покрівлі виїмкового стовпа, що можуть слугувати локалізаціями скопчення шахтного метану.

Наукова новизна. Отримані залежності зміни висоти опускання породних шарів на основі динаміки формування виробленого простору лави. Встановлені закономірності зміни об'ємів порожнин розшарування породної товщі, що обумовлено міцністю й потужністю породних шарів, близькістю до зони ведення очисних робіт і швидкістю посування очисного вибою та його довжиною.

Практична значимість. Запропоновано, на основі методу проф. Савостьянова О. В., алгоритм визначення можливих локалізацій скопчення шахтного метану після завершення видобувних робіт у межах виїмкового стовпа. Це дозволяє в подальшому розглядати такі області накопичення метану як додаткове джерело паливної сировини. Водночас, запропоновано, за умови «бідності» отриманої шахтної суміші, у режим роботи гірничодобувного підприємства включати роботу біогазових установок. Запропонована технологічна схема комбінованого способу видобутку шахтного метану й біогазу

Ключові слова: очисний вибій, шахтний метан, вугільний пласт, напружено-деформований стан, порожнина розшарування

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