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T. K. Isabek[1], M. S. Usenbekov[1], *A. M. Khamze[1], A. R. Abdiev [2]
[1]NJSC «Abylkas Saginov Karaganda Technical University» (Karaganda, Kazakhstan),
[2]«Kyrgyz State Technical University (KSTU) named after I. Razzakov» (Bishkek, Kyrgyzstan)

FORMATION OF METHANE COLLECTORS IN THE PROCESS OF UNDERMINING AND OVERMINING COAL SEAMS

Abstract. Mine methane, once viewed mainly as a safety concern, is now recognized as both a valuable energy resource and a significant greenhouse gas, particularly in regions such as the Karaganda Coal Basin. This study uses an integrated approach combining analysis of global methane drainage practices, rock mass movement and subsidence, gas emission modeling, and in-situ observations. Void volumes formed by bedding separation are estimated as the difference between theoretical and actual subsidence trough volumes and are considered potential methane reservoirs. The proposed model enables spatial assessment of void distribution and supports optimal placement of methane drainage boreholes in abandoned panels, improving methane recovery, reducing emissions, and enhancing environmental sustainability.

Key words*: coal seam, mine methane, goaf voids, bedding separation, abandoned panel, gas content, degasification, methane reservoir, gas accumulation, gas capture.*

Көмір қабаттарын астыңғы және үстіңгі өндіру процесінде метан коллекторларының қалыптасуы

Аңдатпа. Шахта метаны бұрын негізінен қауіпсіздік факторы ретінде қарастырылса, қазіргі уақытта ол құнды энергетикалық ресурс және маңызды парниктік газ ретінде танылады, әсіресе Қарағанды көмір бассейні сияқты өңірлерде. Бұл жұмыста кешенді тәсіл қолданылды: метанды дегазациялау бойынша әлемдік тәжірибені талдау, тау жыныстарының қозғалысы мен шөгуін зерттеу, газ бөлінуін модельдеу және натуралдық бақылаулар жүргізу. Қабаттардың ажырауынан пайда болатын қуыстар көлемі шөгу мульдасының теориялық және нақты көлемдерінің айырмасы ретінде анықталып, метанның ықтимал жиналу аймағы ретінде қарастырылады. Ұсынылған модель қуыстардың кеңістіктік таралуын бағалауға және игерілген панельдерде дегазациялық ұңғымаларды оңтайлы орналастыруды негіздеуге мүмкіндік береді. Бұл метанды өндіруді арттыруға, шығарындыларды азайтуға және көмір өндіру аймақтарының экологиялық тұрақтылығын жақсартуға ықпал етеді.

Түйінді сөздер: *көмір қабаты, шахталық метан, өндірілген кеңістік қуыстары, қабатаралық ажырау, тасталған панель, газ мөлшері, дегазация, метан жиналу резервуары, газ жиналу, газды жинау.*

Формирование метановых коллекторов при подработке и надработке угольных пластов

Аннотация. Метан шахт, ранее рассматривавшийся преимущественно как фактор безопасности, в настоящее время признан ценным энергетическим ресурсом и значительным парниковым газом, особенно в таких регионах, как Карагандинский угольный бассейн. В работе применяется комплексный подход, включающий анализ мирового опыта дегазации, изучение движения горных пород и оседания, моделирование газовыделения и натурные наблюдения. Объемы пустот, образующихся при расслоении пород, определяются как разность между теоретическим и фактическим объемами мульды оседания и рассматриваются как потенциальные резервуары метана. Предложенная модель позволяет оценивать пространственное распределение пустот и обосновывать оптимальное размещение дегазационных скважин в отработанных панелях, что способствует повышению извлечения метана, снижению выбросов и улучшению экологической устойчивости угледобывающих регионов.

Ключевые слова: *угольный пласт, шахтный метан, пустоты выработанного пространства, межслоевое расслоение, заброшенная панель, газоносность, дегазация, метановый коллектор, накопление газа, улавливание газа.*

Introduction

Coal mine methane (CMM) represents both a potential hazard and a valuable energy resource. During the undermining and overmining of coal seams, natural methane collectors form in the rock mass, including bedding separation voids, boundary cracks, and residual workings. These voids serve as primary sites for gas accumulation and provide promising targets for methane extraction. Accurate quantification of these void volumes is critical for improving mining safety, optimizing coal production, and developing effective strategies for industrial and domestic utilization of methane [1].

In recent decades, global attention to methane extraction from abandoned or partially mined areas has intensified due to environmental, economic, and energy considerations. Residual and abandoned coal seams, as well as worked-out mine sections, are major sources of methane accumulation and migration, posing risks to surface infrastructure and atmospheric balance. On average, one tonne of abandoned coal can contain 5–10 m³ or more of methane, highlighting the potential energy value of these otherwise inaccessible resources.

Modern methane recovery strategies integrate safety improvement, emission reduction, and energy utilization. They include extraction during mining, pre-drainage of coal seams, and recovery from abandoned workings. This study focuses on methane collector formation during undermining and overmining, proposing a dynamic model to estimate bedding separation volumes and gas accumulation based on mining and geological parameters [2].

This modeling approach provides a scientifically grounded framework for planning safe and efficient methane extraction, enabling better resource management in both active and abandoned coal mines while addressing ecological concerns and promoting sustainable energy use.

Analysis of rock mass movement and surface deformation processes during coal seam mining

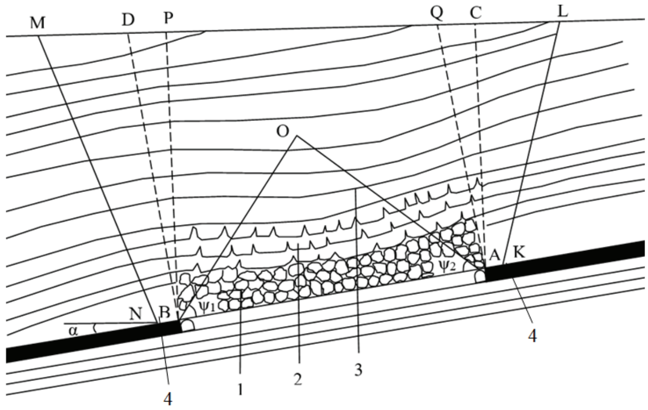
Coal seam extraction disrupts the natural equilibrium of the rock mass, resulting in its deformation and displacement. Immediately above the goaf of the coal seam, a caving zone is formed.

The portion of the rock mass subjected to deformations and movements under the influence of mining operations is referred to as the rock mass movement zone, while the section of the Earth's surface exhibiting subsidence and deformation is termed the subsidence trough. The boundary of the subsidence trough on the surface is defined by boundary angles [3].

Surface subsidence and deformation depend on mining and geological factors such as seam thickness, depth, dip angle, rock strength, overburden thickness, mining method, and extraction size.

The undermining coefficient is the ratio of the actual mined area to that required for full subsidence. Two types are distinguished: full undermining, where subsidence no longer increases, and partial undermining, where subsidence continues to grow with mining area expansion.

Ensuring methane extraction from abandoned mine panels through surface vertical boreholes requires determining optimal borehole locations based on the intersection of the most probable gas collectors. A model of void and fracture formation filled with gas can be constructed by analyzing patterns of rock mass movement during longwall mining in conjunction with variations in gas-dynamic parameters of coal seams. Based on established scientific data, at least four zones can be distinguished (Figure 1): caving zone, fractured zone, continuous bending zone (without loss of continuity), and abutment pressure zones [4].



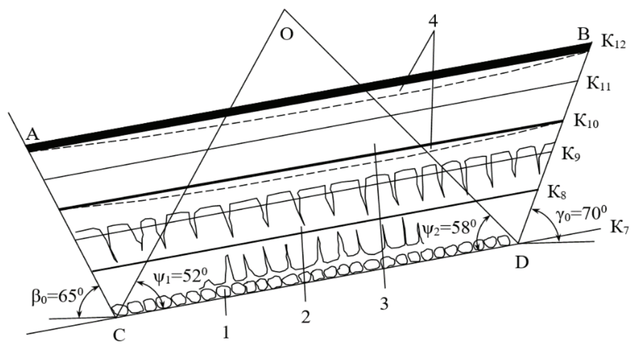
1 – caving zone (disordered collapse); 2 – fractured zone; 3 – continuous bending zone (no loss of continuity); 4 – NB and AK – abutment pressure zones; AOB – zone of full normal displacements; ψ_1, ψ_2 – full subsidence angles; MNKL – movement zone; DP and QC – surface sections most prone to tensile fractures; α – seam dip angle

1 – опырылу аймағы (тау жыныстарының ретсіз опырылуы); 2 – жарықшақтану аймағы; 3 – тұтастығы бұзылмайтын иілу аймағы; 4 – NB және AK – тіректік қысым аймақтары; AOB – толық қалыпты ығысулар аймағы; ψ_1, ψ_2 – толық шөгу бұрыштары; MNKL – тау жыныстары қозғалысының аймағы; DP және QC – жер бетінің созылу жарықшақтарының түзілуіне ең бейім учаскелері; α – көмір қабатының құлау бұрышы

1 – зона обрушения (хаотичное обрушение пород); 2 – зона трещинообразования; 3 – зона сплошного изгиба (без нарушения сплошности массива); 4 – NB и AK – зоны опорного давления; AOB – зона полных нормальных смещений; ψ_1, ψ_2 – углы полных оседаний; MNKL – зона сдвижения горных пород; DP и QC – участки земной поверхности, наиболее подверженные образованию трещин растяжения; α – угол падения угольного пласта

Figure 1. Zones of influence of a longwall face on the surrounding rock mass under full caving roof control.
Сурет 1. Төбесі толық құлатылып басқарылатын ұзын лава жағдайында қоршаған тау жыныстары массивіне ұзын лаваның әсер ету аймақтары.
Рис. 1. Зоны влияния очистного забоя на окружающий горный массив при полном обрушении кровли.

Based on concepts of rock mass movement mechanisms and coal seam gas dynamics, an analysis was performed of potential gas collector formation under conditions of mining seam K_7 at the Industrial section of the Karaganda Basin. The scenario considered involved extraction of the lower seam K_7, with coal pillars left in seams K_{10} and K_{12} (Figure 2). Calculations and analysis indicate that the height of the disordered caving zone for seam K_7 is 6.0 m, and it does not encompass any coal seams or interbeds.



1 – disordered caving zone, h_0 = 6 m; 2 – fracture formation zone, h_0 = 40 m; 3 – continuous bending zone of rock layers; 4 – bedding separation voids

1 – ретсіз опырылу аймағы, h_0 = 6 м; 2 – жарықшақтардың түзілу аймағы, h_0 = 40 м; 3 – тау жыныстары қабаттарының тұтас иілу аймағы; 4 – қабатаралық ажырау қуыстары

1 – зона беспорядочного обрушения, h_0 = 6 м; 2 – зона образования трещин, h_0 = 40 м; 3 – зона сплошного изгиба слоев горных пород; 4 – полости межслоевого расслоения

Figure 2. Schematic diagrams of rock mass movement.
Сурет 2. Тау жыныстары қозғалысының сызбалық схемалары.
Рис. 2. Схематические схемы движения горного массива.

Seams K_8 and K_9 fall within the 40-m-high fracture zone and release methane into the goaf of the K_7 longwall. Seams K_{10}, K_{11}, and K_{12} lie in the continuous bending zone without loss of continuity. The maximum subsidence in the region of full subsidence angles is concentrated toward the center of the longwall. The undermined seams K_{10} and K_{12}, entering the movement zone, experience unloading from mining pressure and deflect toward the goaf. Since the roof rock strength of seams K_{10} and K_{12} (5.2 and 4.5, respectively) is substantially higher than that of the coal seams, bedding separation voids may form at coal-rock contacts during layer deflection. These voids become filled with methane desorbing from the unloaded coal seams [5]. This desorption process continues until a new equilibrium is established in the coal-methane dynamic system following cessation of movement and restoration of mining pressure.

During overmining, underlying rocks bend toward the goaf and separate at lithological contacts, forming voids that fill with methane from the fractured seam. When stresses exceed rock strength, fractures develop, creating pathways that connect to the goaf and lead to gas release into the workings.

Mathematical Model of Dynamic Subsidence Trough for Undermined Rock Layers

Analysis of the movement mechanisms in undermined and overmined coal seams has revealed that the most probable gas collectors, from the perspective of potential extraction from abandoned panels, include:

- bedding separation voids at coal-rock contacts located within the continuous bending zone (without loss of continuity) of the rock mass, positioned beneath the center of the extraction panel;

- boundary voids formed at the edges of extraction panels within the movement zone bounded by boundary and full subsidence angles;

- stopped development workings and other unfilled mine workings.

Consider a plane problem of rock mass movement in the vertical ***xOz*** plane, perpendicular to the longwall face and passing through its center. The longwall is oriented parallel to the ***Oy*** axis. The subsidence of point ***A*** in the upper half-plane is analyzed under conditions of full undermining and complete roof caving.

The longwall moves from point O along the x-axis at velocity v, reaching point ***C*** after time t, covering distance ***vt***. Each extracted seam element causes a small surface subsidence, and total subsidence is the sum of all contributions. In Figure 3, segment ***Oa*** shows roof hanging over a stationary face, while ***bC*** shows hanging over the advancing face, corresponding to the horizontal displacement of the trough's inflection point relative to the extraction boundary or moving face.

The final subsidence value for a point located in the ***xOy*** plane can be determined according to Equation (1):

$$\eta(x.z) = \frac{2\eta_0}{L_z}\int_{d}^{vt-d} e^{-\frac{4\pi}{L_z^2}(\lambda - x)} . \qquad (1)$$

Performing variable substitution and integration using the Newton-Leibniz formula yields Equation (2):

$$\eta(x,z,t) = \frac{\eta_0}{2}\left\{\phi\left[\frac{5,013}{L_z}(vt-d-x)\right] - \right.$$
$$\left. - \phi\left[\frac{5,013}{L_z}(d-x)\right]\right\}, \qquad (2)$$

where η_0 is the maximum surface subsidence under full undermining (m);

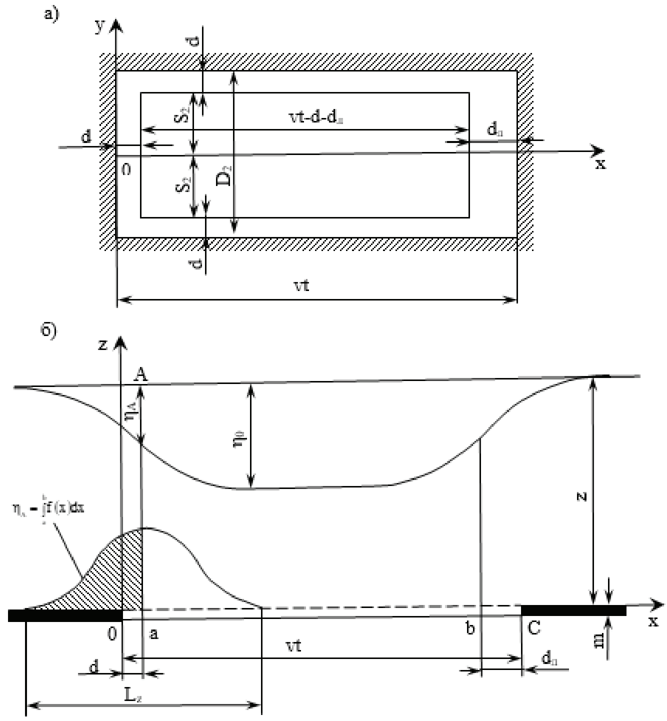
L_z is the half-length of the subsidence trough at horizon z (m);

x and ***y*** are coordinates of the point on the surface or within the rock mass where movement parameters are determined (m);

v is the longwall advance rate (m/month); t is the time at which the movement parameters at the point are evaluated (months; time zero corresponds to the start of the setup entry);

da is the main roof hanging at the advancing face over the extraction panel boundaries (m); d is the main roof hanging over the fixed boundary of the extraction panel (e. g., on the setup entry side) (m);

erf is the standard Gaussian error function [7].



a – plan view; b – vertical cross-section
а – жоспардағы көрініс; б – тік қима
а – вид в плане; б – вертикальный разрез

Figure 3. Schematic of dynamic subsidence trough formation.
Сурет 3. Динамикалық шөгу мульдасының қалыптасу сызбасы.
Рис. 3. Схема формирования динамической мульды оседания.

This expression represents the mathematical model of the dynamic subsidence trough formed on the Earth's surface or at horizon z at a given time instant. It enables determination of the subsidence magnitude at a point with coordinates ***x***, ***y***, ***z*** on the surface or within the rock mass at time ***t*** during longwall advance at velocity ***v***.

Determination of Bedding Separation Volumes under Undermining Conditions

Assume that a longwall panel A_1B_1 has been extracted at depth H (Figure 4) (the problem is solved for gently dipping seam conditions). Full undermining occurs along the ***y***-axis. It is known that main roof hanging occurs over the boundaries of the extraction panel, with the hanging magnitude d being a function of depth: ***d = f(H)***, expressed according to Equation (3):

$$d = H\frac{ctq\psi - ctq\delta_0}{2}. \qquad (3)$$

Since the surface movement zone along the principal cross-sections of the trough is bounded by boundary angles, the infinite limits in the latter expression can be replaced with finite ones. Thus, integration of Equation (3) is performed over the extraction boundaries extended by half the half-trough length, using the standard Gaussian integral function and

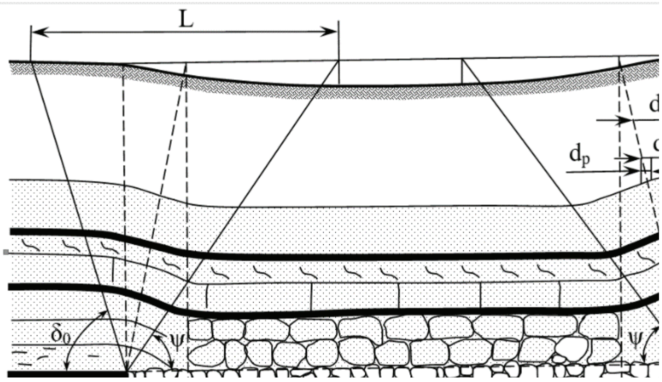


Figure 4. Schematic of bedding separation void formation above the boundaries of the longwall extraction panel.
Сурет 4. Ұзын лаванның өндіру панелі шекаралары үстінде қабатаралық қуыстардың қалыптасу сызбасы.
Рис. 4. Схема образования межслоевых пустот над границами очистной панели длинного забоя.

introducing boundary conditions S_1. After transformations, Equation (3) takes the form of Equation (4):

$$S_m = 2q_0mS_1. \quad (4)$$

Consequently, the area of the surface subsidence trough (in vertical cross-section) equals twice the product of the relative surface subsidence factor, the extracted seam thickness, and the calculated half-length of the extraction panel.

At contacts between undermined layers of different physico-mechanical properties, when a stronger, thicker layer (e. g., sandstone) overlies a weaker one (e. g., argillite or coal interbed), the most favorable conditions arise for bedding separation void formation and gas filling. The sandstone layer exhibits greater hanging d_s than the weaker layer d_l. In other words, the inequality holds (5):

$$d_s > d_l. \quad (5)$$

The subsidence curve equation for the upper line of the weaker layer is written as Equation (6):

$$\eta(x)_u = \frac{q_o m}{2}\left\{erf\left[\frac{5,013}{L}\left(\frac{D_1}{2} - d_c + x\right)\right] + \right.$$
$$\left. + erf\left[\frac{5,013}{L}\left(\frac{D_1}{2} - d_l - x\right)\right]\right\}. \quad (6)$$

The subsidence curve equation for the lower line of the upper layer (sandstone) is written as Equation (7):

$$\eta(x)_l = \frac{q_o m}{2}\left\{erf\left[\frac{5,013}{L}\left(\frac{D_1}{2} - d_п + x\right)\right] + \right.$$
$$\left. + erf\left[\frac{5,013}{L}\left(\frac{D_1}{2} - d_s - x\right)\right]\right\}. \quad (7)$$

Since the hanging magnitude equals the horizontal displacement of the subsidence curve inflection point relative to the longwall face, and considering condition (5), it is evident (Figure 4) that the curve described by Equation (6) is horizontally shifted relative to the curve in Equation (7) by the distance d_s between the upper and lower planes of the bedding separation void at the inflection point, calculated according to Equation (8):

$$d_{sep} = d_s - d_l. \quad (8)$$

The difference in subsidence is calculated according to Equation (9):

$$\eta(x)_u - \eta(x)_l = \eta(x)_{sep}, \quad (9)$$

where $\eta(x)_u$ в is the subsidence of a point on the upper line of the weaker layer (m);

$\eta(x)_l$ is the subsidence of a point on the lower line of the sandstone layer (m);

$\Delta\eta(x)$ represents the vertical dimension of the void in a cross-section at distance z from the origin.

Substituting the values of $\eta(x)_u$ and $\eta(x)_l$ into Equation (9) yields Equation (10):

$$\eta(x)_p = \frac{q_o m}{2}\left\{\begin{matrix} erf\left[\frac{5,013}{L_z}\left(\frac{D_1}{2} - d_c + x\right)\right] + erf\left[\frac{5,013}{L_z}\left(\frac{D_1}{2} - d_l - x\right)\right] - \\ -erf\left[\frac{5,013}{L_z}\left(\frac{D_1}{2} - d_п + x\right)\right] - erf\left[\frac{5,013}{L_z}\left(\frac{D_1}{2} - d_s - x\right)\right] \end{matrix}\right\}. \quad (10)$$

From Equation (6) it follows that the shape of bedding separation voids is determined by the bending pattern of layers above the extraction panel boundaries. Graphical construction of subsidence curves for the two layers using Equations (6) and (7) outlines the bedding separation void contour and shows that it has an S-shaped form in vertical cross-section.

The spatial problem is reduced to determining the volume of bedding separation voids as the difference between the subsidence trough volume without roof hanging and the actual trough volume with hanging, according to Equation (11):

$$V_{sep} = V_{d=0} - V_{tr}, \quad (11)$$

where $V_{d=0}$ is the surface subsidence trough volume without hanging (m³);

V_{tr} is the actual surface subsidence trough volume (m³).

The subsidence trough volume without hanging can be represented as a double integral of the subsidence trough equation for the spatial problem according to Equation (12):

$$V_{d=0} = \frac{q_o m}{4}\int_{-\left(\frac{D_1}{2}+\frac{L}{2}\right)}^{\frac{D_1}{2}+\frac{L}{2}}\int_{-\left(\frac{D_1}{2}+\frac{L}{2}\right)}^{\frac{D_1}{2}+\frac{L}{2}}\left\{erf\left[\frac{5,013}{L}\left(\frac{D_1}{2} + x\right)\right] + \right.$$
$$\left. + erf\left[\frac{5,013}{L}\left(\frac{D_1}{2} - x\right)\right]\right\} \times \left\{erf\left[\frac{5,013}{L}\left(\frac{D_2}{2} + y\right)\right] + \right.$$
$$\left. + erf\left[\frac{5,013}{L}\left(\frac{D_2}{2} - y\right)\right]\right\} dxdy. \quad (12)$$

Performing integration of Equation (12) analogously to the plane problem yields the surface subsidence trough volume without hanging according to Equation (13):

$$V_{d=0} = q_0 m D_1 D_2, \quad (13)$$

i. e., the subsidence trough volume without hanging equals the extracted mineral volume multiplied by the relative surface subsidence factor, since not the entire extracted seam portion participates in rock movement, but a reduced portion accounting for hanging by magnitude d.

In this case, the actual subsidence trough volume is determined according to Equation (14):

$$V_{tr} = \frac{q_0 m}{4} \int_{-(S_1+\frac{L}{2})}^{S_1+\frac{L}{2}} \int_{-(S_1+\frac{L}{2})}^{S_2+\frac{L}{2}} \left\{ erf\left[\frac{5,013}{L}(S_1+x)\right] + erf\left[\frac{5,013}{L}(S_1-x)\right] \right\} \times \left\{ erf\left[\frac{5,013}{L}(S_2+y)\right] + erf\left[\frac{5,013}{L}(S_2-y)\right] \right\} dxdy. \quad (14)$$

After integration, Equation (15) is obtained:

$$V_{tr} = 4q_0 m S_1 S_2. \quad (15)$$

Taking into account Equations (11) and (15), the sought bedding separation volume is written according to Equation (16):

$$V_{tr} = 2q_0 md(D_1 + D_2 + 2d). \quad (16)$$

The derived relationship shows that the volume of bedding separation voids formed in the rock mass at a stationary longwall face depends on the extraction panel dimensions, seam thickness, and main roof hanging magnitude. Under full undermining along the x- and y-axes, bedding separation voids are distributed along the perimeter of the extraction panel [8].

Performing integration analogously to the plane problem with respect to variable x, after variable substitution and imposition of boundary conditions, Equation (17) is obtained:

$$V_{tr} = 2q_0 m S_2(vt + d_a - d). \quad (17)$$

To determine bedding separation void volume above the extraction panel with an advancing face, the surface subsidence trough volume without hanging is calculated by integrating Equation (5) along the x- and y-axes within the surface movement zone. The subsidence trough volume in this case is calculated according to Equation (18):

$$V_{d=0} = q_0 mvtD_2. \quad (18)$$

From Equations (17) and (18) it is evident that the surface subsidence trough volume above the advancing face is time-variable and depends on the geometric dimensions of the extracted space. The latter, besides longwall length, depend on face advance rate and time elapsed since setup entry excavation. Accordingly, bedding separation void volume must also be time-variable. Representing bedding separation void volume as the difference between two subsidence trough volumes (without hanging and with hanging) yields Equation (19):

$$V_{sep} = V_{d=0} - V_{tr} = \frac{q_0 m}{vtD_2} + 2S_2(vt - d_a - d). \quad (19)$$

Since 2 $S_2 = D_2 - 2d$ (see Figure 4), V_p is expressed according to Equation (20):

$$V_{sep} = q_0 m(D_2 - 2d)(d_a + d) + 2dvyt, \quad (20)$$

or according to Equation (21):

$$V_{sep} = \frac{2q_0 m}{S_2(d_a + d)} + dvt. \quad (21)$$

Thus, bedding separation void volume depends on longwall length (size S_2), main roof hanging magnitudes, face position, and seam thickness [9]. Void volume for an advancing face increases over time due to progressive extension of extraction boundaries over gate roads (haulage and ventilation). Equation (21) enables a differentiated approach to establishing the spatial distribution of void volumes relative to extraction panel boundaries, namely:

$V_{dlf} = 2q_0 S_2 d_a$ – above the advancing longwall face (m³);

$V_{dse} = 2q_0 S_2 d$ – above the setup entry (installation roadway) (m³);

$V_{dd} = q_0 mdvt$ – above haulage and ventilation drift (m³).

In the presence of numerous gas-bearing satellite seams, the void and bedding separation volumes considered in this section constitute powerful collectors into which gas migrates from unloaded coal seams.

Conclusion

The study of rock mass behavior during undermining and overmining of coal seams has demonstrated that the formation of methane collectors is primarily controlled by the creation of bedding separation voids, boundary voids, and residual workings within the rock mass. These structures represent the most significant sites for potential methane accumulation in abandoned and partially mined panels.

A dynamic mathematical approach was developed to describe the temporal evolution of the subsidence trough and associated void volumes. By employing Gaussian integral-based representations of vertical displacements, the model enables quantitative assessment of bedding separation volumes as functions of longwall advance, seam thickness, and main roof hanging magnitudes. This methodology provides a robust framework for estimating the spatial distribution and capacity of methane collectors under complex mining conditions.

The results indicate that void formation and methane accumulation are highly sensitive to both the geometry of extraction panels and the dynamics of mining operations. In particular, the time-dependent advancement of the longwall face significantly influences the development and enlargement of voids, emphasizing the necessity of incorporating dynamic factors in planning methane recovery strategies.

Overall, the proposed approach bridges theoretical modeling of rock mass deformation with practical applications in methane resource management, offering a scientifically grounded basis for predicting gas storage capacity, optimizing extraction from abandoned panels, and ensuring safe and efficient utilization of coal mine methane.

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Information about the authors:
Isabek T. K., Doctor of Technical Sciences, Professor, Researcher of the Department of Mineral Deposit Development, NJSC «Abylkas Saginov Karaganda Technical University» (Karaganda, Kazakhstan), *t.isabek@ktu.edu.kz;* https://orcid.org/0000-0001-7718-933X
Usenbekov M. S., Candidate of Technical Sciences, Associate Professor of the Department of Mineral Deposit Development, NJSC «Abylkas Saginov Karaganda Technical University» (Karaganda, Kazakhstan), *m.usenbekov@ktu.edu.kz;* https://orcid.org/0000-0002-4209-3853
Khamze A. M., Master of Technical Sciences, Doctoral student of the GDD-25-1 group of the Department of Mineral Deposit Development, NJSC «Abylkas Saginov Karaganda Technical University» (Karaganda, Kazakhstan), *a.khamze@ktu.edu.kz;* https://orcid.org/0009-0006-7170-8438
Abdiev A. R., Doctor of Technical Sciences, Professor, Director of the Scientific and Technical Center named after Prof. Sh .A. Mambetov «Geoquantum» at Kyrgyz State Technical University named after I. Razzakov (Bishkek, Kyrgyzstan), *abdiev_arstan@mail.ru;* https://orcid.org/0000-0003-3409-5717

Авторлар туралы мәліметтер:
Исабек Т. К., техникалық ғылымдарының докторы, «Пайдалы қазбалар кенорындарын өндіру» кафедрасының профессор-зерттеушісі, КЕАҚ «Әбілқас Сағынов атындағы Қарағанды техникалық университеті» (Қарағанды қ., Қазақстан)
Усенбеков М. С., техникалық ғылымдарының кандидаты, доцент, «Пайдалы қазбалар кенорындарын өндіру» кафедрасының қауымдастырылған-профессоры, КЕАҚ «Әбілқас Сағынов атындағы Қарағанды техникалық университеті» (Қарағанды қ., Қазақстан)
Хамзе А. М., техникалық ғылымдарының магистрі, ГДД-25-1 тобының докторанты, «Пайдалы қазбалар кенорындарын өндіру» кафедрасы, КЕАҚ «Әбілқас Сағынов атындағы Қарағанды техникалық университеті» (Қарағанды қ., Қазақстан)
Абдиев А. Р., техника ғылымдарының докторы, профессор, Қырғыз мемлекеттік техникалық университеті ат. И. Раззаков жанындағы профессор Ш. А. Мамбетов атындағы «Геокватум» ғылыми-техникалық орталығының директоры (Бішкек қ., Қырғызстан)

Сведения об авторах:
Исабек Т. К., доктор техн. наук, профессор исследователь кафедры «Разработка месторождений полезных ископаемых», НАО «Карагандинский технический университет им. Абылкаса Сагинова» (г. Караганда, Казахстан)
Усенбеков М. С., кандидат техн. наук, ассоциированный профессор кафедры «Разработка месторождений полезных ископаемых», НАО «Карагандинский технический университет им. Абылкаса Сагинова» (г. Караганда, Казахстан)
Хамзе А. М., магистр техн. наук, докторант группы ГДД-25-1 кафедры «Разработка месторождений полезных ископаемых», НАО «Карагандинский технический университет им. Абылкаса Сагинова» (г. Караганда, Казахстан)
Абдиев А. Р., доктор техн. наук, профессор, директор Научно-технического центра им. проф. Ш. А. Мамбетова «Геоквантум» Кыргызского государственного технического университета им. И. Раззакова (г. Бишкек, Кыргызстан)