FORMATION PECULIARITIES OF CAVING ZONES AS AERODYNAMIC ACTIVE BRANCHES OF MINE VENTILATION SYSTEMS IN PILLAR MINING OF COAL BEDS

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ABSTRACT

This paper considers the formation peculiarities of caving zones depending on specific mining, geological and technical conditions. The properties of rocks representing structures complicated by man-induced and naturally occurred cracks have been analyzed. When mined-out spaces are formed, the rock massif transforms into caving zones having other properties and characteristics differing from the initial ones and affecting the filtration processes. In mining conditions, such mined-out spaces represent a fractured and porous medium of various structures (irregular or partially regular) permeable for the motion of gas and air masses. This fractured and porous medium represents an aggregate of solid bodies of various shapes and sizes adjacent to each other with the space between them (large channels and fractures), internal voids and pores filled with air and gas masses moving in the direction as established by the head gradient. The mined-out spaces are considered as active branches of mine ventilation systems where air leaks are moving. A participant in gas exchange with mine workings is the so called active zone from which the air and gas mix can be fed to the working zone of the working area and affect the gas environment in workings. The size of this zone is determined by the development system and geomechanical parameters of undermined rocks that condition the caving increment of the immediate and main roof, the width and height of the caving arch, and the distance from the longwall to the beginning of the bearing pressure zone. To quantitatively assess possible leaks and gas content of working zones in case of emergency related to gas emissions from mined-out spaces, the methodology to determine the active zone volume has been developed and described in this paper. The permeability values of caving zone layers calculated with the obtained results allow identifying the consistent patterns of leak formation processes in the mined-out space.

INTRODUCTION

Glazed As the study results obtained by multiple scientists testify, mined-out spaces represent active branches of mine ventilation systems where air leaks are moving. Based on ventilation system laws, these branches in the simplest case can be considered parallel to the primary branches (Shamsurin, 1970; Ustinov and Kaliyev, 1973; Shevelev and Perepelitsa, 2010).

When longwalls move, a caving zone is left behind them, the formation of which is affected by various factors. The essence of the caving process can be described as follows. Rocks in a virgin ground are in a state of stressed equilibrium (Bogdanov, et al., 1972; Borisov, 1980; Baklashov, 1988). During second working, this equilibrium is disturbed and complicated geomechanical processes occur. The differences in the way of how mountain pressure

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manifests itself in the area of stopes have caused several hypotheses to appear that represent these processes. The fullest of them is the combined hypothesis of slabs and beams (Borisov, 1980).

According to it, the immediate roof has two operating modes: initial and steady state motion. The initial motion is expressed when the bottom hole distances itself from the pillar, with the increasing area of immediate roof exposure. Roof rocks gradually bend. Then the first caving of the immediate roof slab occurs. In the steady-state motion conditions, the rocks of the immediate roof that are suspended above the longwall bottom-hole in cantilever fashion cave area by area, regularly, after the powered support is moved. There are also two modes distinguished in the main roof operation. In the first mode, the gradual rock buckling causes the primary caving of the main roof. In the second mode, the main roof fracture occurs regularly with the established spacing after a number of primary cavings of immediate roof rocks. The primary and secondary caving of the main roof occur almost uncontrollably when there is no data regarding its parameters. The distance of regular artificial roof caving is referred to as the caving increment or spacing (Borisov, 1980; Proskuryakov, 1991).

Upwards from the boundary of the mined-out space in the undermined mass, three zones can be distinguished described by a various degree of rock disturbance: caving, buckling with disturbed continuity of layers in the form of cracks, and smooth buckling without continuity disturbance. Not all the volume of these zones participates in gas exchange with mine workings, but only the so called active zone from which the gas and air mix can be fed to the working area and affect the gas environment in minings (Popov, 1990; Puchkov, 1993; Puchkov and Kaledina, 1995; Ushakov and Kosarev, 1988; Ushakov, 2004).

The size of this zone is determined by the development type and geomechanical parameters of rocks undermined when forming the mined-out space that condition the caving increment of the immediate and main roof, the width and height of the caving arch, and the distance from the longwall to the beginning of the bearing pressure zone. The highest leakage rates are found in the caving zone that, in its turn, is divided into the zones of irregular and regular (block) caving (Miletich, 1962; Puchkov and Alekhiachev, 1964; Maslyayev and Lindenau, 1973; Patrushev and Dranitsyn, 1974; Kolesnichenko and Kolesnichenko, 1988).

The caving zone height in general represents the range from several meters to several tens of meters and, first of all, depends on such parameters as the formation depth, depth of individual roof layers, adhesion (or rupture strength) by layer contacts, rock compression and tensile strength. The same parameters define the propagation height of the fracture zone.

In various coal basins, the height of regular (irregular) caving zone does not exceed five or sixth times the depth. The height of the block caving is formed depending on the depth of layers located above the regular caving zone. The zone of fractures oriented normally to the stratum is limited by 30-35-fold deposit depth (Sergeyev, 1986). The propagation height of cracks parallel to the stratum is significantly higher. The buckling zone with no discontinuity is located above the fracture zone. In case of complete roof caving, the propagation of the impact zone with discontinuity of rock layers normally from the undermined formation is 30-35-fold depth of the deposit to be undermined depending on longwall advancing.

Above the fracture zone, roof rock moves in the form of consecutive buckling of layers with individual layers sliding normally to cross fractures. In roof rocks located at the distance of 10-fold formation depth from the mined-out space, the cracks with opening above 10 mm do not occur (Romn, 1985). Cracks are closed 50 m to 60 m behind the moving stope of the crack (Sergeyev, 1986).

**METHODOLOGY**

On The given data allow adopting the following assumptions of caving zone formation conditions (Fig. 1).

The mined-out space includes three conditional zones described by various structures of collapsed above lying rocks and, respectively, by various aerodynamic parameters that the air leak magnitude and paths depend on.

If there are easily caved rocks, the irregular caving zone consists of the system of rock blocks of various shapes irregularly located in the mined-out space. The average size of these blocks is 0.5 to 1.5 m to 2 m (Sergeyev, 1986).

The so-called transportation channels between these blocks are filled with smaller joints with typical diameter of 0.01 m to 0.05 m (Romn, 1985). When the strength characteristics and, respectively, the stability, increase, the average size of blocks can be increased to 2 m to 10 m. In individual cases, the
immediate roof hanged by the main roof caving increment with further co-joint caving (Borisov, 1980; Proskuryakov, 1991). When there are stable rocks in the immediate roof with large caving increment, the part of the irregular caving zone directly adjoining the longwall represents an open space not filled with rock blocks.

The volume of the mined-out space is limited on its sides with the walls of development workings, by the main roof from the top, and has an aerodynamic link with the longwall and adjoining workings in the front. Inside there are caved parts of immediate roof rocks with voids between them filled with the air and gas mix.

The block caving zone is represented by blocks caved consecutively with the caving increment having a significant range (5 m to 60 m). Because of the significant thickness of the above lying rocks, caving takes place by weakening planes located in parallel to the stratum with the interval from 2-4 m to 18-20 m (Borisov, 1980; Proskuryakov, 1991). The primary roof represented as a system of rock blocks with some increment and the caving width hangs above a specific volume of the mined-out space shaped before that as a result of the immediate roof caving.

The fracture zone is localized in the continuous rock medium made up by various lithological varieties. This medium can be considered in all caving zones as a multi-layer one with various mechanical properties within each layer (Romn, 1985).

In the main roof caving zone, the following fracture systems are distinguished relative to the stratum planes and second working boundaries: parallel to the stratum and perpendicular to the longwall; perpendicular to the stratum and parallel to the longwall; perpendicular to both stratum and longwall.

Crack opening for each direction in the general system can be defined based on calculation schemes. It should be based on the increment and width and the caving zone type. The calculation scheme for the fracture opening in irregular caving zones is represented in Fig. 2.

The calculation schemes for the fracture opening in block caving zones and fractures are represented in Fig. 3.
RESULTS

1. Irregular caving zone. The void volume of the mined-out space in the irregular caving zone before main roof caving is determined under the formula:

\[ V_{\text{mos}} = (L \times \sum a_i) \Omega \sum x_i \]  

(1)

Where \( \Omega \) = coefficient to consider the main roof buckling magnitude.

The formula includes the total main roof caving opening.
increment in the zone of the non-steady bearing pressure. In the steady bearing pressure zone, the void volume of the mined-out space will be gradually decreased exposed to the mountain pressure and after some time it will approach the natural porousness.

The coefficient Ω to consider the main roof buckling magnitude takes into account the maximum opening of fractures parallel to the stratum within the main roof thickens:

\[ \Omega = \frac{h_n - \sum \delta_i}{h_i} \tag{2} \]

Where \( n \) = number of layers making up the main roof.

Depending on the immediate roof thickness and the looseness coefficient, the cave rocks can fully fill the mined out space (pack the main roof) or fill this space only partially. If the main roof touches the upper boundary of the immediate roof caved rocks before caving, \( h_0 = 0 \). The value of \( h_0 > 0 \) if there is free space left between the caved rocks of the immediate roof and the main roof (Fig. 1). The caved rock will pack the main roof provided that:

\[ K_n h_i \geq (h_i + m) \Omega \tag{3} \]

After the main roof caving, the total volume of voids (transport channels) in the mined-out space will be calculated upon the condition of yield of the caved immediate roof under the following formula:

\[ V_{\text{mos cav}} = V_{\text{mos}} (1 - p) \tag{4} \]

Where \( p \) = relative yield of immediate roof caved rocks.

The relative yield of caved rocks of the intermediate roof will be calculated under the following formula:

\[ p = \frac{\Delta}{h_{\text{cav}} - h_o} \tag{5} \]

For practical calculations, the relative yield of caved rocks of the intermediate roof can be adopted as 0.08-0.1.

The absolute yield of caved rocks of the intermediate roof is understood as a shift along the vertical axis of the upper boundary of immediate roof caved rocks after being exposed to the loading from the caved main roof.

By assuming that the fracture opening has a straight geometry, their opening in the irregular caving zone in each \( i \)-th layer can be found as follows.

By assuming that the same opening for each fracture in the \( i \)-th layer is parallel to the stratum (axis X), we use the following formula:

\[ \delta_i = \frac{h_{\text{cav}}}{n_o} \tag{6} \]

The maximum values \( \psi_i \) and \( \chi_i \) for the irregular caving zone (Y and Z) for each caved \( i \)-th layer can be calculated under the following formulas:

\[ \psi_i = \frac{2 \delta m_i}{h_i}; \chi_i = \frac{2 \delta m_i}{a_i} \tag{7} \]

where \( a_i \) = caving width and increment of the \( i \)-th layer of the immediate roof, respectively;

\( m_i \) = caving thickness of the \( i \)-th layer of the immediate roof.

These formulas are of practical value when calculating the immediate roof in low-thickness formations which are comparable to the thickness of layers included in the irregular caving zone. In this case, caving is of more regular nature due to packing of above lying layers by caved blocks of immediate roof rocks.

2. Block caving zone. The main roof caving height is considered to the distance between the main roof block plane and the upper boundary of immediate roof caved rocks.

The total volume of transport channels between these blocks after main roof caving can be calculated based on the given assumptions on the caving zone structure under the following formulas:

1. For transportation channels parallel to the stratum and perpendicular to the longwall:

\[ V'_{2\text{mos}} = n_o' \left( \sum a_z \sum b_z \cdot \delta_z' \right) \tag{8} \]

2. For transportation channels perpendicular to the stratum and parallel to the longwall:

\[ V''_{2\text{mos}} = n_o'' \left( h_{\text{cav}} \sum a_z \cdot \psi_z' \right) \tag{9} \]

3. For transportation channels perpendicular to both stratum and longwall:

\[ V'''_{2\text{mos}} = n_o''' \left( h_{\text{cav}} \sum a_z \cdot \chi_z' \right) \tag{10} \]

where \( n_o', n_o''', n_o'''' \) = number of transportation channels (opened fractures) parallel to the stratum and perpendicular to the longwall, perpendicular to the stratum and parallel to the longwall, and perpendicular to both stratum and longwall, respectively.

In this respect, the total volume of transportation channels between blocks after main roof caving is:

\[ V_{2\text{mos cav}} = V'_{2\text{mos}} + V''_{2\text{mos}} + V'''_{2\text{mos}} \tag{11} \]
The above formulas are introduced based on the adopted caving scheme and an assumption that the maximum length of transportation channels oriented perpendicular to the longwall between main roof blocks can be adopted equal to the caving increment \( b_2 \) and the length of transportation channels oriented parallel to the longwall between main roof blocks can be stated as the caving width \( a_2 \) and the length of transportation channels oriented upwards between the main roof blocks as the main roof caving thickness \( h_2 \).

The total height of transportation channels can be regarded as varying within the absolute yield of the immediate roof (for channel parallel to the stratum) to the layer thickness of the caved main roof (for channel perpendicular to the stratum). The main roof caving height \( h_0 \) where the main roof starts interacting with the immediate roof during caving depends on the looseness coefficient of caved rocks that depends on their strength properties.

The width of transportation channels can be adopted based on the average opening of fractures parallel and perpendicular to the stratum.

The number of transportation channels in the block caving zone can be calculated based on the frequency of fractures parallel and perpendicular to the stratum and opened per length unit (density). The following expressions must be satisfied:

- prior to main roof caving:
  \[
  \sum (b_2 \cdot a_2) m \leq V_{1mos}
  \]  

- after main roof caving:
  \[
  n_i (\sum b_2 \cdot a_2 \cdot \delta_2^i) + n_i (\sum b_2 \cdot a_2 \cdot \gamma_2^i) + n_i (\sum a_2 \cdot b_2 \cdot \chi_2^i) \leq V_{2mos Cav}
  \]  

It can be adopted that the following formula is fair:

\[
\Delta + h_0 \]

The total maximum fracture opening after the main roof caving for fractures parallel to the stratum in the block caving zone will be the total caving height of the maximum roof and the absolute yield of the immediate roof.

The maximum opening of a single fracture in the \( i \)-th layer parallel to the stratum is found as follows:

\[
\delta_2^i = \frac{\Delta + h_0}{n_0}
\]

The average opening of fractures parallel and perpendicular to the stratum is defined as:

\[
\gamma_2^i = \frac{2 \delta_2^i}{a_2^i}, \quad \chi_2^i = \frac{2 \delta_2^i}{b_2^i}
\]

Taking into account the above assumptions on the formation features of structures of mined-out space zones, a physical and analytical model can be built for the air leak filtration zone in the mined-out space and calculations can be made to find the permeability coefficient of various caving zones.

**Discussion**

The permeability calculation for rocks within the
1. Rock permeability in each caving zone and fractures can be found in general as a total value for each zone. When there are reference data regarding the nature and structure of above-lying rock layers, the rock permeability before and after main roof caving is found for each layer within the zone based on the following assumptions. Zone boundaries are defined according to geological studies.

2. Leak paths by layers for which the rock permeability is found are spatially related to the spot where the calculated layer crosses the conditional line of splits corresponding to the main roof rock caving angle.

3. In the regular caving zone at the distance from the longwall within the boundary of the previous main roof caving increment, the rock permeability in general for the zone is adopted as a constant value before main roof caving since the own weight compaction is insignificant. After the main roof caving, the permeability is decreased because of the decreased volume of voids; however, it can be considered constant within the caving increment and width, taking into account the block structure of the above lying rocks. Since the irregular caving zone permeability must be determined before and after caving of the above lying rocks of the main roof, the caving sequence of layers of undermined rocks must be taken into account when setting a task for calculating the irregular caving zone permeability.

The following calculation options are possible:

1. Permeability is calculated within the longwall at the distance of the main roof caving increment for each of the caved layers separately, and the thickness of the caved layers has to be taken into account considering the excavated thickness and the main roof packing condition. The irregular caving zone permeability is calculated for the conditions before and after the main roof caving.

2. Permeability is calculated within the longwall at the distance of the main roof caving increment for the total thickness of caved rocks with respect to the excavated layer thickness and the volume of free space within the caving zone. After main roof caving for an entire layer of immediate roof, the permeability is calculated for the irregular caving packed zone.

3. Permeability is calculated for the irregular caving zone beyond the caving increment along the pillar axis for each of the caved layers separately and for the entire zone in general. In this case, the individual thickness of caved layers has to be considered with respect to the excavated layer thickness.

When setting a calculation task, it should be taken into account that the structure of various caving zones of mined-out spaces has unequal permeability for all direction, e.g., the caved massif is anisotropic to different extents.

Because of the chaotic laying of rock pieces having small and medium size in the irregular caving zone, the permeability in all directions (height, width and length of the mined-out space) before main roof caving slightly differs for any of the coordinate system directions. The anisotropy property of the massif irregular caving zone insignificantly increases after caving of the above-lying rocks due to packing during surcharging. As a rule, after packing, permeability insignificantly decreases along the vertical axis (Z axis) with relatively constant values along the axis lines of the pillar and the longwall (X and Y axes).

The anisotropy is typical of the block caving zone. The larger is the size of pieces, the more intensive anisotropy manifests itself. The differences of permeability values within the block caving zone mainly depend on the density of fractures in a specific direction before caving and in the direction of fractures after it.

The fracture zone is characterized by the highest anisotropism with a significantly lower permeability for all directions. The most significant permeability is found along the planes of fracture opening.

The massif anisotropism can be caused by both mining and geological characteristics of cave rocks, and by the thickness of the formation to be excavated on which the main roof packing height depends. This characteristic of the caving zone must be taken into account when calculating its total permeability.

**CONCLUSION**

Air and gas dynamic processes with participation of mined-out spaces are the most relevant factors affecting the aerologic situation in a coal mine working area that is hazardous because of methane emission. When applying pillar excavation methods with roof caving, a participant in gas exchange with mine workings is not the entire volume of caving zones, but the so called active zone from which the
air and gas mix can be fed to the working zone of the working area and affect the gas environment in workings. The size of this zone is determined by the development type, system and geomechanical parameters of undermined rocks when forming the mined-out space that condition the caving increment of the immediate and main roof, the width and height of the caving arch, and the distance from the longwall to the beginning of the bearing pressure zone.

The analytical methods of the air dynamic parameters calculation for the mined-out space and adjacent workings allow acquiring their quantitative dependencies on mining geological and technical factors, and assessing their changing dynamics in space and time.

According to the studies, the mined-out space includes three individual zones described by various structures of collapsed above lying rocks and, respectively, by various aerodynamic parameters that the air leak magnitude and paths depend on. To obtain reliable data, the calculation is done for the following zones of the mined-out space: irregular caving; regular (block) caving; fractures. The calculation must be done separately for the periods before and after main roof caving. For the calculation along the pillar axis, the zones have to be distinguished within the last main roof caving increment and beyond it at the distances several times exceeding the longwall length.

The primary practical advantage of the developed methodology to measure the active zone volume is an opportunity to get such results that are as close as possible to field (actual) results based on the minimal amount of available reference data. Such reference data include the immediate and main roof caving increment, the caving arch width and height, the distance from the longwall to the start of the bearing pressure zone, and the geological characteristics of above-lying rocks.

Since the primary requirements to safety in terms of gas are first of all intended to ensure efficient ventilation of working areas, the timely calculation of aerodynamic parameters of the mined-out space promotes reliable assessment of the aerological situation in stopes and represents one of its primary monitoring measures.

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