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DETERMINING STABILITY CONDITIONS FOR HAULAGE DRIFTS PROTECTED BY COAL PILLARS

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The aim of this research is to study the stability of haulage drifts and the manifestations of rock pressure in them lengthwise the working area when protecting them with coal pillars.

To assess the stability of workings, field experiments were conducted to study the manifestations of rock pressure in the haulage drifts of a steep coal seam. It has been registered that as the breakage face progresses, the displacement of roof rocks on the contour of the drift linearly increases with an increase in the length of the working area.

The deformation properties of coal pillars were studied taking into consideration the extent of the convergence of the roof and soil. This paper reports a theoretical model that describes the destruction of the above-drift coal pillars when unloading the coal-bearing massif that hosts the workings.

It has been determined that the equilibrium state of coal pillars is ensured when the specific deformation and stress potentials are equal before the occurrence of main cracks of destruction. As the relative deformation of coal pillars increases at compression, when this equality is broken, the specific energy intensity of destruction increases. It is noted that at a distance exceeding $l>10$ m behind the breakage face, the occurrence of the main cracks of destruction is followed by a stability loss in the coal pillars. As a result of external forces, the change in the volume and shape of the coal pillars causes the intensification of the process of convergence of lateral rocks on the contour of haulage drifts lengthwise the working area and leads, with a certain degree of probability, to a deterioration in the stability of workings.

The results of this study could be used to justify the choice of technique to protect haulage drifts. This would allow the timely development of minefield reserves thereby improving the safety of operations. It is recommended that the technique of protecting haulage drifts by coal pillars should be abandoned

Keywords: rock pressure, haulage drift, coal pillar, deformations, coal-bearing massif, roof

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1. Introduction

The safety and efficiency of coal mine operations are largely determined by the state of workings in the working area. At the same time, normal operating conditions for breakage faces during the development of steep seams can be provided only when the operational condition of haulage drifts is ensured.

When a floor technique to prepare steep coal seams is used, mining operations lead to collapses of lateral rocks that happen every year due to changing mining and geological conditions. The current technique to protect the sections of preparatory workings by coal pillars does not always provide reliable protection of haulage drifts adjacent to the working area against harmful manifestations of rock pressure. When the stratified rock mass collapses, the workings' roof is deformed while the area of their cross-section is reduced, which does not meet the requirements set by the Safety Regulations (SR). The underlying causes of such a situation are related to the increase in the depth of mining operations, the deterioration of rock and geological conditions, and the intensification of rock pressure manifestations.

In order to ensure the operational condition of sections' preparatory workings in emergency areas, a large volume of repair work is required (the labor-intensive repair operations include 85–90 people/shifts per 1,000 tons of average daily production). These activities imply the re-strengthening of workings, the replacement of the roof's deformed elements lengthwise the working area, and cannot be mechanized. Some mines have to repair up to 40 % of the total length of preparatory workings annually.

Ensuring the stability of haulage drifts over their entire service time is a prerequisite for guaranteeing high coal production rates. Therefore, in order to maintain the sections' preparatory workings in the operational state, a protection technique is important. When working out steep coal seams, the techniques used to protect sections' preparatory workings should ensure their operational condition within the working area.

Thus, it is a relevant task to justify and select the technique to protect the sections' preparatory workings under changing rock-geological conditions based on the patterns of rock pressure manifestations in a coal-bearing massif. The proper solution to this problem would affect the safety of mine operations, the timely development of reserves in working areas, as well as the technical-economic indicators of a coal enterprise's performance.

2. Literature review and problem statement

By now, many coal mines that develop steep seams have abandoned the use of pillar-free technology to operate working areas. To ensure high coal mining performance indicators, a protection technique that is currently used in sections' preparatory workings involves coal pillars.

Study [1] reports the results of investigating the movement of rocks in the development of steep coal seams. It is shown that the floor technique of preparation is accompanied by a consistent separation of layers from the rock mass located above the coal-bearing massif hosting workings. This is the reason for the worsening stability of haulage drifts and for the destruction of protective coal pillars.

Paper [2] proposes the use of coal pillars with a height of 8 m to protect the haulage drifts. However, the application of pillars of this size in the existing procedure of working out the seams, including conjoined layers, contributes to the formation of areas of elevated rock pressure (AERP) on adjacent layers. In fact, the effect of eliminating emissions during the advanced development of protective layers is significantly reduced or completely neutralized in such zones, as noted in work [3]. Indeed, this increases the likelihood of gas dynamics and the risk of drift blockages.

The transition of mining operations to large depths increases the intensity of rock pressure manifestations, which necessitates maintaining large-scale pillars (larger than 8–10 m) for the protection of workings. Attempts to establish changes in the intensity of rock pressure manifestations along the length of maintained workings depending on the size of the protective pillars were reported in paper [4]. However, the results did not make it possible to determine the type of dependence that establishes the effect of the size of coal pillars on the stability of workings.

It should be noted that the use of coal pillars that are 10 to 15 m high for the protection of workings increases the concentration of stresses in the lateral rocks and expands the area of their harmful influence. Moreover, the wider the pillar, the greater the distance over which AERP spreads in the rocks of the roof and soil, which was established in work [5].

In order to ensure the stability of workings, the authors of [6] considered the patterns of loading the pillars and determining their carrying capacity as a safety facility. By analyzing and measuring under field conditions, they determined actual stresses affecting the pillars at the time of their destruction. This solution makes it possible to predict the state of coal pillars; however, there are unsolved issues of ensuring the stability of workings in a working area, especially behind the breakage face (in the worked-out space).

An earlier study [7] found that the stresses in the roof and soil of a coal seam are concentrated in the area of the location of the protective pillar. Given this, the destruction of the lateral rocks and their swelling is always more intense on the part of the pillar, which is confirmed in practice. This geomechanical situation contributes to the sudden collapse of lateral rocks above the drift and their chaotic movement into the working.

Our analysis of research into the stability of mining workings makes it possible to assert the expediency of studying the manifestations of rock pressure in the haulage drifts and the patterns of side rock displacements on the contour of a working protected by coal pillars. A proper understanding of the involved geomechanical processes could help prepare reasonable decisions to ensure the stability of sections' preparatory workings in deep mines developing steep coal seams.

3. The aim and objectives of the study

The aim of this study is to determine the conditions of the stability of haulage drifts and the manifestations of rock pressure in them lengthwise a working area when a technique of protection with coal pillars is used.

To accomplish the aim, the following tasks have been set:

– to perform field observations of the convergence of lateral rocks on the contour of haulage drifts and establish the dependence of the roof displacements lengthwise a working area;

– to investigate the deformation properties of the above-drift coal pillars and determine their impact on the stability of mining workings lengthwise a working area.

4. Materials and methods to study the stability of haulage drifts protected by coal pillars

In studying the stability of the sections' preparatory workings and patterns in the deformation of the above-drift coal pillars, the object of research is studying the processes of ensuring the stability of lateral rocks in a haulage drift. Quantitative evaluation often involves the use of rock displacement values on the contour of a working, which makes it possible to justify its stability along the length of the working area.

To study the stability of haulage drifts protected by coal pillars, we experimentally investigated the breakage faces of seams l_5 and l_6 at a 1,146 m horizon in the mine «Central» at the «State Enterprise Toretskugol» (Toretsk, Ukraine).

The haulage drift of seam l_5 was protected by coal pillars whose size in terms of a seam rise is b_p=8 m; in terms of a seam advance, l_p=5 m, where b_p, l_p are, respectively, the height and width of the pillar, m. The area of the cross-section of a preparatory working at the joint between a breakage face and a drift was S=8.5 m^2. The distance between the frames of the arch support (AP-3) with a wooden clamp is 0.8 m. The drift was made with the help of drilling and blasting operations (DBO). The drift pass rate is V_d=11 m/month, the speed of breakage operations is V_{br}=9 m/month. Mine face with a ledge ceiling. The technique to manage the face roof is a complete collapse.

Coal seam l_5 with a capacity of m=0.6 m has a drop angle α=59°. The elasticity module is E=0.33·10^{10} N/m^2. In the immediate roof, there is stable shale, with a capacity of m=1.7–2.5 m. The main roof is represented by the shale of medium stability, the capacity of m>10.0 m. In the immediate soil, there is shale with a capacity of m=2.0 m. In the main soil, there is sandstone, the capacity of m=10.0 m.

The haulage drift of seam l_6 was protected by coal pillars whose size is b_p =8 m, l_p=5 m. The area of the cross-section of the drift was S=8.2 m^2, the distance between the frames of the arch support (AP-3) with a wooden clamp was 0.8 m. The drift was made with the help of DBO. The drift pass rate is V_d=12 m/month; the speed of the breakage operations is V_{br}=8 m/month. Mine face with a ledge ceiling. The technique to manage the face roof is a complete collapse.

Coal seam l_6 with a capacity of m=0.62 m has a drop angle α=59°. The elasticity module is E=0.3·10^{10} N/m. In the immediate roof, there is stable shale, with a capacity of m=1.1 m. The main roof is represented by shale, the capacity of m to 10.0 m. In the immediate soil, there is shale with a capacity of m=0.8–2.5 m; in the main roof, there is shale, the capacity of m=2.5–4.4 m.

The advance of the drift for seams l_5 and l_6 at the time of our study was, respectively, L_{ad}=110 m and L_{ad}=105 m.

Special measuring stations were installed in the haulage drifts of seams l_5 and l_6 at the experimental sites (Fig. 1) to observe the displacement of rocks along the contour. A mine surveying roulette (the error of measurements did not exceed ±2 mm) was used at the measurement stations to determine the value of side rock displacement on the contour of the workings. To this end, we determined a value of the convergence of benchmarks in the directions most typical of a steep fall. The arrangement of measuring stations is shown in Fig. 2.

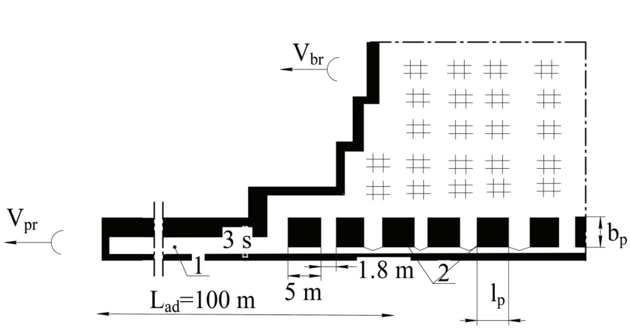

Fig. 1. Schematic of the experimental section to determine the displacements of lateral rocks on the contour of a haulage drift protected by coal pillars: 1 – haulage drift; 2 – coal pillars; 3 – measuring station; V_{br} – the speed of breakage operations, m/month; V_{pr} – the speed of preparatory operations, m/month; b_p – pillar height for the seam rise, m; l_p – pillar width for the seam front, m

During the operation of haulage drifts, the safety structures located above the working behind the working area are exposed to external force factors. When unloading a coal-bearing massif that hosts workings, the result of the convergence of lateral rocks is the compression of coal pillars. They exchange energy, which leads to the destruction of safety structures [8, 9].

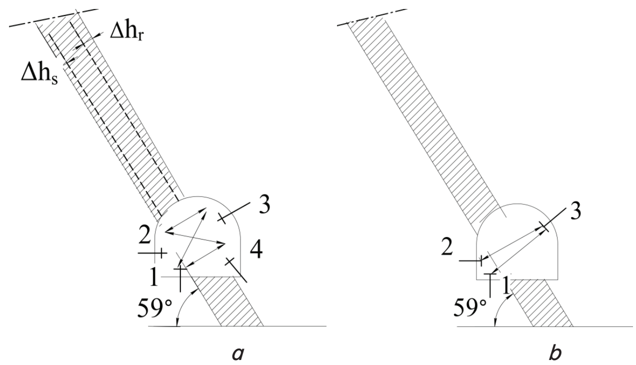

Fig. 2. Schematic of the measuring station to determine the displacements of lateral rocks on the contour of haulage drifts protected by coal pillars: a – seam l_5; b – seam l_6; 1, 2, 3, 4 – benchmarks; 1–3; 2–3; 2–4; 1–4 – convergence of benchmarks 1, 2 in the direction of benchmarks 3, 4; α – drop angle, degrees; $m=h$ – capacity of a coal seam, m; Δh_r, Δh_s – displacement of roof and soil, m; $\Delta h=\Delta h_r+\Delta h_s$ – compression value of a coal pillar, m

It is believed [8] that unloading a coal-bearing massif from compressive stresses contributes to the instantaneous transformation of the accumulated potential energy beyond the elasticity and strength of rocks to the work of destruction. This process includes the origin of microfractures in coal pillars, their development, and subsequent integration into macro-cracks [9]. It is obvious that under certain conditions there comes such a state of coal pillars that changes their properties to maintain, when exposed to external forces, the predefined form of equilibrium.

As the external load on the pillars increases, the density of the ruptures increases, and the main cracks are formed in them. The fragile body decomposes into parts. Meanwhile, under the uniaxial compression, during the last stage of destruction, the propagation of the main cracks in the pillars is hindered by the end cone zones [10]. The presence of such zones predetermines a model of the destruction of safety structures. The destruction of coal pillars depends on various factors, many of which are random and not studied in detail. These include the nature of loads, external conditions, internal defects, etc. As regards the task to be solved, we consider it the most simple and realistic to apply a model of coal pillars representing a linear-elastic body. The calculation scheme of such a model is based on the ratio between stresses and deformations [10, 11, 13]. This approach will make it possible, in the first approximation, to assess the performance of coal pillars at different stages of the operation of haulage drifts along the length of the working area.

It is known [11] that for a linear-elastic material in a state of equilibrium, the potential of stresses U_{st} (J/m^3) is numerically equal to the potential of deformations U_d (J/m^3), that is, the following ratio holds:

$$U_{st}=U_d \text{ and } \frac{\sigma^2}{2E}=\frac{E\varepsilon^2}{2}. \quad (1)$$

The specific potential energy of the above-drift coal pillars U_p (J/m^3) at compression can be divided into the energy of change in the volume U_{pv} (J/m^3) and the energy of change in the shape U_{ps} (J/m^3). And, for a uniaxial compression [11–13],

$$U_{pv} = \sigma_1^2 \cdot \left(\frac{1-2\nu}{6E} \right), \quad (2)$$

and

$$U_{ps} = \sigma_1^2 \left(\frac{1+\nu}{3E} \right), \quad (3)$$

where ν is the transverse deformation factor.

Under uniaxial compression, the transverse deformation factor ν is a kinetic parameter as it reflects the process of changing the size of the pillars in a cross-sectional direction. According to a study reported in [14, 15], the established value of the transverse deformation factor (ν) is the same for all solids and equals ν=0.25. Based on the results from the cited studies, we accept the value of the transverse deformation factor in the investigation of the deformation properties of coal pillars to equal ν=0.25.

Our analysis of research into the stability of haulage drifts of steep coal seams protected by pillars reveals that the issues of the performance of safety structures and the preservation of working areas have always been considered separately. Our paper proposes a comprehensive approach that includes a joint solution to the problem of pillars' stability and supported preparatory workings within a working area.

5. Results of studying the stability of haulage drifts protected by coal pillars

5. 1. Results of studying the manifestation of rock pressure in haulage drifts lengthwise a working area

Based on the results of field studies, we have built the displacement diagrams of the side rocks *u* (mm) on the contour of a haulage drift along seams l_5 and l_6 lengthwise a working area *l* (m) (Fig. 3, 4).

Fig. 3 shows the diagram of side rocks displacements *u* (mm) on the contour of a haulage drift of seam l_5 along the length of the working area *l* (m).

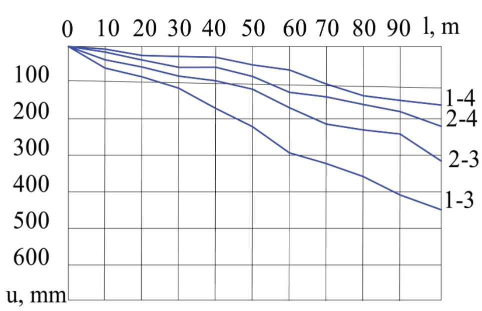

Fig. 3. Displacement diagrams of rocks *u* (mm) on the contour of a haulage drift of seam l_5 protected by coal pillars along the length of the working area *l* (m): 1–4, 2–4, 2–3, 1–3 – displacements of benchmarks

The derived dependences demonstrate that the largest displacements of lateral rocks on the working area contour are registered in the direction of benchmarks 1–3 and 2–3 (Fig. 3). In quantitative terms, the number of displacements *u* (mm) at the distance l=100 m behind the breakage face is, for benchmarks 1–3, u_{1-3}=450; for benchmarks 2–3, u_{2-3}=310 mm (Fig. 3). The displacements of lateral rocks in the direction of benchmarks 2–4 and 1–4 were, respectively, u_{2-4}=210 mm and u_{1-4}=160 mm (Fig. 3).

Fig. 4 shows the displacement diagrams of side rocks *u* (mm) on the contour of a haulage drift of seam l_6 along the length of the working area *l* (m).

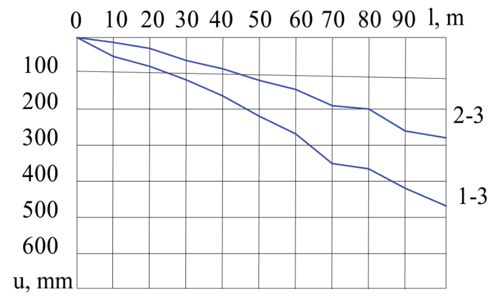

Fig. 4. Displacement diagrams of rocks *u* (mm) on the contour of a haulage drift of seam l_6 protected by coal pillars along the length of the working area *l* (m): 1–3, 2–3 – displacements of benchmarks

Based on the results of our field experimental studies, by measuring the convergence of benchmarks in the haulage drifts along the length of the working area section, we determined the maximum displacements of lateral rocks at the distance l=100 m behind the breakage face, in directions 1–3 and 2–3, at u_{1-3}=480 mm and u_{2-3}=380 mm (Fig. 4).

In all cases, we registered the deformation of the arch support of the haulage drifts and, at the distance $l>(20–30)$ m behind the breakage face, the deterioration in the stability of the workings. The displacements of roof rocks, exceeding the structural margin of the roof in the haulage drifts, were registered behind the face, at the distance $l \geq 40–60$ m (Fig. 3, 4). It was established visually that in the zone of exposure to breakage operations the lining in the haulage drifts was deformed specifically, from the side of the roof. From the soil of the coal seam, the rise of rocks was not significant and amounted to u_{1-4}=100–160 mm (Fig. 3).

To study the relationship between the length of the supported section *l* (m) of the haulage drift of seam l_5 and the convergence of lateral rocks *u* (mm) on the contour, which is accompanied by a compression of the pillar by the value Δh (m), we shall determine the correlation factor.

Calculate the correlation factor using a formula recommended in [16, 17, 22]:

$$r = \frac{\overline{xy} - \overline{x} \cdot \overline{y}}{S_x \cdot S_y}.$$

Experimental research data and the intermediate values required for calculation are given in Table 1.

After the transformations, we obtain the following values:

$$\overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i = 55, \quad \overline{y} = \frac{1}{n} \sum_{i=1}^{n} y_i = 0.245,$$

$$\overline{xy} = \frac{1}{n} \sum_{i=1}^{n} x_i \cdot y_i = 17.230,$$

$$S_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2 - (\overline{x})^2} = 28.723,$$

$$S_y = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2 - (\overline{y})^2} = 0.131.$$

Consequently, the correlation factor is equal to:

$r = 0.99.$

Since $r > 0.7$, there is a strong direct correlation between the experimental data [16, 17].

Table 1

Data to determine a correlation factor (seam l_5)

No. of entry	x_i	y_i	x_i^2	y_i^2	$x_i y_i$
1	10	0.05	100.0	0.0025	0.50
2	20	0.08	400.0	0.0064	1.60
3	30	0.12	900.0	0.0144	3.60
4	40	0.18	1,600.0	0.0324	7.20
5	50	0.21	2,500.0	0.0441	10.50
6	60	0.29	3,600.0	0.0841	17.40
7	70	0.31	4,900.0	0.0961	21.70
8	80	0.36	6,400.0	0.1296	28.80
9	90	0.4	8,100.0	0.1600	36.00
10	100	0.45	10,000.0	0.2025	45.00
Total	550.000	2.45	38,500.0	0.772	172.30

The correlation considered can be approximated by a direct regression line, which is easy to obtain using a least-square method [17, 23]. Its equation takes the following form:

$y = 0.0046x - 0.0053.$

A graphic representation of the correlation relationship between the length l (m) of the supported section of the haulage drift of seam l_5 when the pillar is compressed by Δh (m) is shown in Fig. 5, *a*.

By similar reasoning, we shall establish a link between the length of the supported section l (m) of the haulage drift of seam l_6 and the compression of the pillar by value Δh (m). In this case, the correlation factor is:

$r = 0.96.$

The direct regression line takes the following form:

$y = 0.0048x - 0.006.$

A graphic representation of the correlation relationship between the length l (m) and the amount of pillar compression Δh (m) is shown in Fig. 5, *b*.

The regression analysis has established a pattern in the convergence of lateral rocks in a working lengthwise the working area. This link indicates the possibility of using a linear-elastic body model to study the deformation properties of the above-drift coal pillars.

5. 2. Results of studying a mechanical model of the above-drift coal pillars

The study results are given in the form of analytical calculations of the model of coal pillars. This model is based on the experimental data from field observations, during which, as the working area advanced, we measured the movements of lateral rocks on the contour of the haulage drifts. The above-drift coal pillars were investigated as an example of the linear-elastic body whose equilibrium state is described by certain ratios between stresses and deformations. In this context, the effect of the end effects on the destruction of the pillar was taken into consideration.

Consider a coal pillar exposed to the compressing force F (N). According to Clapeyron's theorem [11, 18], work A (J) of the generalized external force F (N), applied statically to the above-drift coal pillar, is equal to:

$$A = \frac{1}{2} F \cdot \Delta h, \tag{4}$$

where Δh is the generalized displacement (the amount of compression of a coal pillar), m.

As regards the problem to be solved, Δh (m) is the value that quantifies the convergence of the roof and soil on the workings' contour, that is:

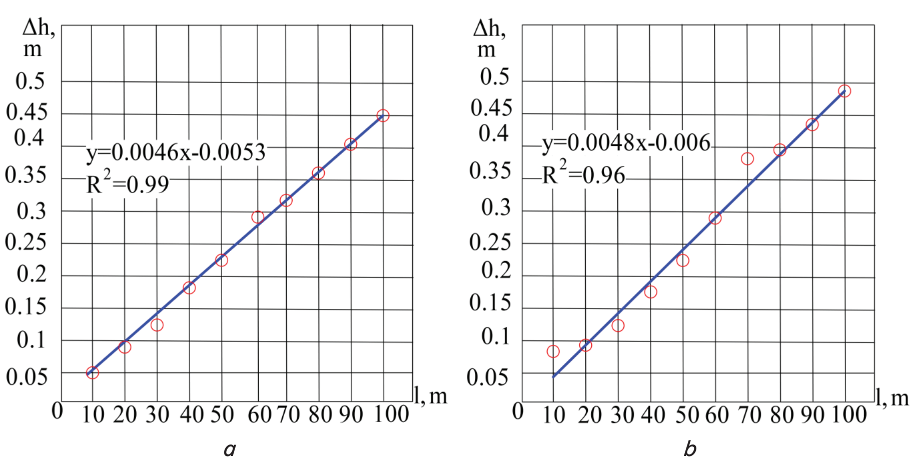

Fig. 5. Diagrams of changes in the amount of compression Δh (m) of the above-drift coal pillars along the length of the working area l (m): *a* — seam l_5; *b* — seam l_6

$$\Delta h = u_{1-3}. \tag{5}$$

We accept that work of the external forces is fully spent to transfer the kinetic energy of body movement T (J) and the accumulation of the fully reversible potential energy U (J), that is:

$$A = T + U. \tag{6}$$

Given that as a result of unloading a coal-bearing massif the external force is applied to the coal pillars slowly enough, the kinetic energy T (J) in expression (6) can be neglected [11, 18, 19]. It means:

$$A = U = \frac{E \cdot S}{h} \cdot \frac{\Delta h^2}{2}. \quad (7)$$

where $E{\cdot}S/h$ is the rigidity of the deformed body, N/m; E is the elasticity module, N/m^2; S is the area of the cross-section of a coal pillar, m^2; h is the thickness of a pillar, m;

$$\Delta h = \frac{\Delta h_p}{2} + \frac{\Delta h_s}{2}$$

– a change in the thickness of a pillar as a result of the convergence of lateral rocks, m.

Knowing the geometric dimensions of coal pillars as a deformable body, by multiplying and dividing expression (7) into E and h^2, we obtain a formula to determine work A (J) of the external forces:

$$A = \frac{EV}{2} \cdot \varepsilon^2 = \frac{\sigma^2 V}{2E}, \quad (8)$$

where V is the volume of a coal pillar, m^3; $\sigma=\Delta h/h{\cdot}E$ is the total stress experienced by a pillar, N/m^2; $\varepsilon=\Delta h/h$ is the relative deformation of a pillar.

Fig. 6 shows the diagrams of changes in the work of the external forces A (J) depending on the relative deformation ε of the above-drift coal pillars at compression.

It follows from the derived dependences that with an increase in the relative deformation of coal pillars ε the work of the external forces A (J) increases (Fig. 6, *a*, *b*).

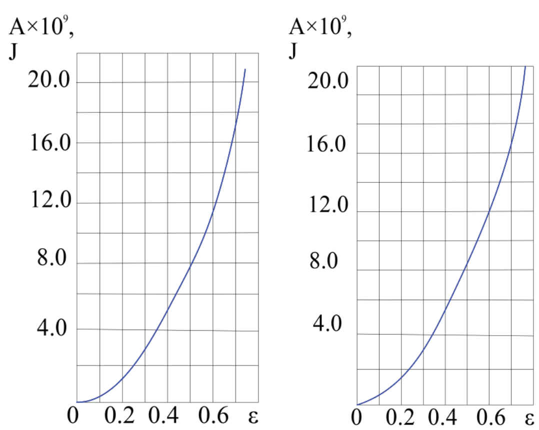

Fig. 6. Diagrams of changes in the work of the external forces A (J) depending on the relative deformations ε of the above-drift coal pillars at compression: *a* – seam l_5; *b* – seam l_6

The experiments on testing rocks for uniaxial compression demonstrated that the nature of the destruction of samples depends on the conditions of contacts between the compressed article and the plates of a testing machine [10]. When the end surfaces of compressed samples are in a state of full grip with the plates, the destruction occurs at the surface of the cone whose axis coincides with the axis of the compressed sample [10, 21].

In this study, we assume the shape of safety structures to be a parallelepiped (Fig. 7). The modeled sample is in a state of full grip with the roof and soil of the coal seam developed. We believe that the above-drift coal pillars are destroyed in line with a conical scheme (Fig. 7).

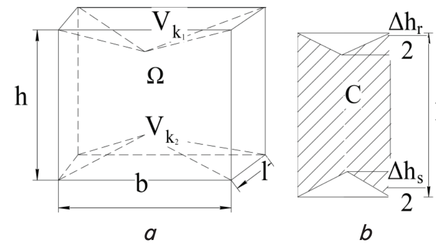

Fig. 7. Schematic of determining the geometric probability $P(C)$ of the occurrence of the main cracks of destruction in a coal pillar: *a* – in a three-dimensional region; *b* – in the plane: Ω is the region corresponding to the volume of the pillar; C is the region of destruction; V_{k1}, V_{k2} is the volume of conical regions in the total volume of the coal pillar, m^3; h is the thickness of the pillar, m; $S=b{\cdot}l$ is the area of the cross-section of the pillar, m^2; $\Delta h=\Delta h_r/2+\Delta h_s/2$ is the convergence of lateral rocks in a working, m

To quantify the process of damaging the above-drift pillars, we shall use the concept of a geometric probability, which makes it possible to determine the probability of the occurrence of the main cracks of destruction [10, 16, 20, 22]. Consider the above-drift protective coal pillar in the form of a parallelepiped with thickness h (m) and a cross-section S (m^2). Highlight in volume V (m^3) of this pillar the conical regions V_{k1} (m^3) and V_{k2} (m^3) (Fig. 7, *a*). Using the described geometric scheme (Fig. 7, *a*, *b*), we shall determine the geometric probability $P(C)$ of the occurrence of main cracks and, therefore, the destruction of the safety structure. In this case, we assume that it is equally possible that a random point can enter any place within the region Ω. The probability of entering the assigned set C will be equal to the ratio of volumes:

$$P(C) = \frac{V(C)}{V(\Omega)}. \quad (9)$$

The volume of the near-end conical zones V_k (m^3) in a total pillar volume can be determined from the following expression:

$$V_{k1} = V_{k2} = \frac{1}{3} S \frac{\Delta h}{2},$$

where Δh is the convergence of roof and soil in a working, m; S is the area of the cross-section of a coal pillar, m^2.

Fig. 7, *b* shows that $V_k = V_k^r + V_k^s$ (where V_k^r, V_k^s is the volume of the conical surface, respectively, from the side of the roof and soil). The volume of the assigned set C is determined as follows:

$$V(C) = V(\Omega) - V_k. \quad (10)$$

Then the probability of the occurrence of main cracks and the destruction of a coal pillar is equal to:

$$P(C) = 1 - \frac{1}{3} \cdot \frac{\Delta h}{h} = 1 - \frac{1}{3}\varepsilon, \quad (11)$$

where $\varepsilon = \Delta h/h$ is the relative deformation of a pillar at compression.

Table 2 gives values of the geometric probability $P(C)$ of the occurrence of the main cracks of destruction in a coal pillar along the length of the working area.

Table 2

Values of the geometric probability $P(C)$ of the occurrence of main cracks of destruction in a coal pillar at compression

l_5	l, (m)	10	20	30	40	50	60	70	80	90	100
	ε	0.08	0.15	0.2	0.32	0.35	0.48	0.52	0.58	0.66	0.73
	$P(C)$	0.98	0.95	0.93	0.9	0.88	0.83	0.82	0.8	0.77	0.75
l_6	l, (m)	10	20	30	40	50	60	70	80	90	100
	ε	0.13	0.14	0.17	0.24	0.35	0.45	0.61	0.63	0.66	0.79
	$P(C)$	0.96	0.95	0.94	0.92	0.88	0.85	0.8	0.79	0.78	0.72

Fig. 8 shows the diagram of changes in the value of relative deformation ε of the above-drift coal pillars at compression along the length of the working area l m.

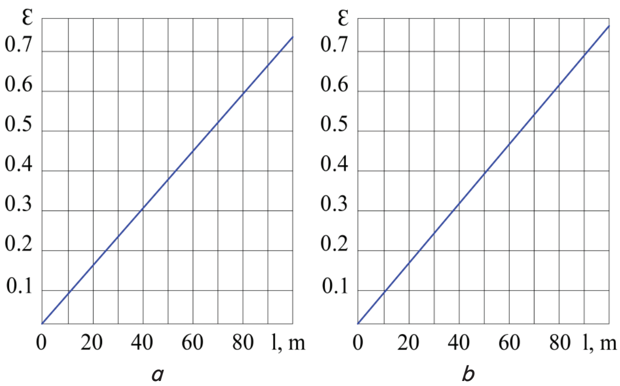

Fig. 8. Diagrams of changes in the value of relative deformation ε of the above-drift coal pillars at compression along the length of the working area l (m): *a* – seam l_5; *b* – seam l_6

Fig. 8 shows that the value of relative deformation ε lengthwise the drift l m changes in line with linear dependence. The maximum values of this value are registered at the distance l=100 m behind the breakage face and are equal, respectively, to ε=0.73 for seam l_5 and ε=0.79 for seam l_6 (Fig. 8, *a, b*).

Based on the above, the potential energy stored in the coal pillars as a result of the external force can be determined from an expression given in [11, 13]:

$$U_{st} = \frac{\sigma^2}{2E}. \tag{12}$$

It is believed [10] that elastic energy is directly proportional to the volume of the above-drift coal pillars. Because $P(C)$ shows how much of the energy is spent to destroy the pillars [10], the expression to determine the potential of deformations takes the following form:

$$U_d = \frac{E \cdot \varepsilon^2}{2} \cdot P(C). \tag{13}$$

Fig. 9 shows the diagrams of changes in the potential of stresses U_{st} (J/m^3) and deformations U_d (J/m^3) of coal pillars along the length of a haulage drift l (m). The magnitude of the deformation potential was determined from expression (13), taking into consideration the experimental data from Table 2.

The dependences received demonstrate that as the length of the working area l (m) increases, the values of U_{st} (J/m^3) and U_d (J/m^3) not only increase but also differ (Fig. 9). The maximum values of U_{st} (J/m^3) and U_d (J/m^3) were registered at l=100 m behind the breakage face, when, for the coal pillar of seam l_5, U_{st}=887·10^6 J/m^3 (Fig. 9, *a*, dependence 1), and, for the coal pillar of seam l_6, U_{st} =926·10^6 J/m^3 (Fig. 9, *b*, dependence 1).

A change in the deformation potential U_d (J/m^3) of the coal pillar follows the same dependence. However, for a coal pillar of seam l_5, the maximum values of U_d (J/m^3) at l=100 m correspond to U_d =667·10^6 J/m^3 (Fig. 9, *a*, dependence 2), and, for a coal pillar of seam l_6, U_d =670·10^6 J/m^3 (Fig. 9, *b*, dependence 2). The difference between the values of U_{st} (J/m^3) and U_d (J/m^3) indicates energy dissipation (Fig. 9).

Fig. 10 shows the diagram of changes in the specific potential energies of the above-drift coal pillar of seam l_5, when the volume U_{pv} (J/m^3) and the shape of a safety structure U_{ps} (J/m^3) change along the length of a haulage drift l, m.

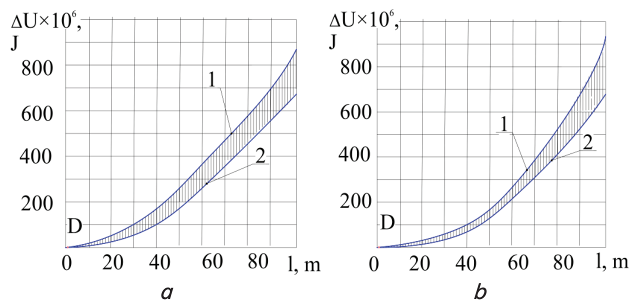

Fig. 9. Diagrams of changes in the stress potential U_{st} (J/m^3) and the deformation potential U_d (J/m^3) of the above-drift coal pillars along the length of a haulage drift l (m): *a* – seam l_5; *b* – seam l_6; 1 – U_{st} (J/m^3); 2 – U_d (J/m^3); shaded area is the zone of energy dissipation; point *D* is the point at which the boundary equilibrium state of a protective coal pillar is considered to have been achieved

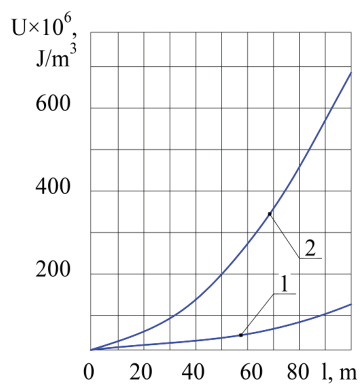

Fig. 10. Diagram of changes in the specific potential energies of the above-drift coal pillar of seam l_5 when the volume U_{pv} (J/m^3) and the shape of the safety structure U_{ps} (J/m^3) change along the length of a haulage drift l (m): 1 – U_{pv} (J/m^3); 2 – U_{ps} (J/m^3)

The specified dependences, established from expressions (2) and (3), indicate that the specific potential energy of coal pillars increases as the length of the supported section of a haulage drift is increased. In addition, the amount of the specific potential energy spent to change the volume of the pillars (Fig. 10, dependence 1) is much less than that to change their shape (Fig. 10, dependence 2). It has been established that of the total amount of the specific potential energy of a coal pillar, the result of its compression is that 16 % of the energy is spent on a change in volume (Fig. 10, dependence 1). At the same time, 84 % of energy is spent on changing the shape of a safety structure (Fig. 10, dependence 2).

It should be noted that the coal pillars used to protect the sections' preparatory workings, adjacent to the working area, represent specific technological structures. The physical characteristics of such structures depend on a large number of factors. However, the values of side rock displacements, established from the experimental study, characterize the deformation properties of coal pillars, and yield an actual assessment of the stability of haulage drifts with a margin of error of up to 15 %.

6. Discussion of results of studying the stability of haulage drifts

The operational experience of mines that develop steep coal seams shows that the practical mining operations mostly employ the technique to protect haulage drifts by coal pillars. The height of the pillars, preventing the influence of the worked-out space, is 8 m (Fig. 1). Under real conditions of the development of steep coal seams, coal pillars of this size are not capable of preventing the negative effects of rock pressure in haulage drifts.

The result of our experimental study has justified the conditions for the stability of haulage drifts protected by coal pillars. When conducting experiments to examine the manifestations of rock pressure in haulage drifts (Fig. 2), it was noted that the most difficult conditions for maintaining mining workings are formed in the zone of influence of breakage operations. In this zone, the largest displacements of side rocks on the contour of haulage drifts occur from the side of the roof of a coal seam (benchmarks 1–3, Fig. 3, 4). It has been registered that at the distance $l \geq (20–30)$ m behind the breakage face along the length of the working area, the stability of the haulage drifts is compromised. The lining in the haulage drifts deforms and demonstrates characteristic deflections on the side of the rocks of the hanging side. At the distance $l=100$ m, the displacements reach maximum values (u_{1-3}=440–490 mm, Fig. 3, 4).

The special feature of maintaining the sections' preparatory workings in the development of steep coal seams in the zone of influence of breakage operations is predetermined by the increased disruption of roof rocks (Fig. 3, 4). After processing experimental data, based on the displacement of rocks on the contour of the haulage drifts (Fig. 3, 4), we have established the linear dependence of the amount of the displacements of roof rocks with an increase in the length of the supported working area.

When unloading a coal-bearing massif that hosts the workings, the above-drift coal pillars are compressed and their linear sizes change. The change in the volume and shape of a coal pillar is the cause of the increase in the convergence of lateral rocks in the haulage drifts behind the working area (Fig. 3, 4).

Our study of the deformative properties of the above-drift safety structures employed a model of the linear-elastic body, in which the limit state of equilibrium of coal pillars is ensured at the equality of specific potentials of stresses U_{st} (J/m^3) and deformations U_d (J/m^3) (expressions 12, 13).

It was experimentally determined that at the site $0 \leq l \geq 10$ m the above-drift coal pillars demonstrate the main cracks of destruction. At the distance $l > 10$ m, ratio (1) holds no more. At point *D*, when the relative deformation of safety structures $\varepsilon > 0.1$ (Fig. 9, *a, b*; Table 2; Fig. 11, *a, b*), the limit equilibrium of coal pillars is considered to have been achieved. Expression (11) makes it possible to establish the probability of the occurrence of the main cracks of destruction in coal pillars during the operation of haulage drifts (Fig. 9, Table 2).

When a coal pillar is exposed to external forces, work *A* (J) is performed, which is a measure of the body's energy change (8) (Fig. 6). This work is spent on the deformation of safety structures and leads to the accumulation of potential energy in them *U* (J) (Fig. 10).

The potential energy of coal pillars is a function of their condition, which takes into consideration a change in the volume and shape when external forces act on safety structures – (2), (3). As a result of unloading a coal-bearing massif, when the action of external forces leads to the destruction of coal pillars (11), changes in their volume and shape (2), (3), we registered the growth of the displacement of lateral rocks on the contour of the haulage drifts (Fig. 3, 4). Moreover, with the increase in the length of the working area, the displacements increase and exceed the structural margin of the lining; the cross-section of preparatory workings decreases (Fig. 3, 4). The complete elimination of these shifts is possible by the installation, above the drift, of a safety structure, which has an initial rigidity equal to the rigidity of the removed part of the steep coal seam. This can be achieved only theoretically. Therefore, when resolving the issue of the stability of mining workings, it is necessary to predetermine the issues of the rigidity of safety structures. This could limit the movement of lateral rocks above a haulage drift to some acceptable value and ensure the unloading of a coal-bearing massif from stresses.

This study has considered the stability of haulage drifts and the performance of coal pillars used to protect the workings in a combination. This approach has allowed us to assess the stability of workings taking into consideration the deformation properties of safety structures. The results of our research could form a basis for building a mathematical model for predicting the stability of mining workings. The scope of this model's application is determined by the drop angles of a coal seam from $\alpha=45°$ to $\alpha=65°$, with the lateral rocks of any stability. The practical implementation of such a model would make it possible, at the working design stage, to determine the optimal parameters for safety structures, which could ensure the safe and accident-free maintenance of haulage drifts during their operation. However, additional theoretical and experimental studies are needed to fulfill this task.

Thus, based on our study, it can be concluded that in the development of steep coal seams, under conditions of great depths, the protection of haulage drifts by coal pillars of limited size is impractical. It is possible to ensure the operational condition of the sections' preparatory workings in the case where the above-drift safety facilities are stable and malleable when unloading a coal-bearing massif. Then the deformations of the roof, preceding the movement of lateral rocks, occur without violating the integrity of the overhanging rock mass. In order to ensure the stability of haulage drifts, non-pillar techniques should be used to protect the sections' preparatory workings. This area of research should be investigated in order to maintain the stability of mining workings. The presence, for example, of rubble strips from the crushed rock above a haulage drift limits the displacement of lateral rocks and makes it impossible for them to break down into a working. The use of non-pillar techniques to protect the sections' preparatory workings decreases the loss of coal in the working area, reduces the risk of endogenous fires, and sudden emissions of coal and gas.

7. Conclusions

1. The manifestation of rock pressure in the haulage drifts of steep coal seams protected by coal pillars follows the linear dependence of the displacements of roof rocks on the contour of supported workings along the length of the working area. This dependence is observed after the above-drift coal pillars used to protect the workings lose their stability and are destroyed. Under such conditions, the displacement of lateral rocks on the contour of the haulage drifts exceed the structural malleability of the lining. The workings' cross-section is reduced. In the absence of restriction of the displacement of roof and soil rocks in the worked-out space, it is impossible to maintain the operational condition of drifts.

2. The deformation properties of coal pillars indicate that the deterioration in the stability of haulage drifts protected by coal pillars is caused by the compression of the safety structures and the occurrence of the main cracks of destruction. At the distance $l>10$ m behind the breakage face, when the above-drift coal pillars enter an unstable state as a result of the action of external forces, there is a change in their volume and shape. This action causes a fracture of the pillars and contributes to the intensification of the process of shifting the lateral rocks on the contour of the haulage drifts along the length of the working area. In order to avoid accidents related to possible blockages of haulage drifts in the working areas of a coal mine, it is recommended to use the pillar-free protection techniques. These techniques include malleable structures erected above the sections' preparatory workings towards a seam rise, wide rubble strips, or blocking the worked-out space.

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REVEALING THE PATTERNS OF CHANGE IN THE TECHNICAL CONDITION OF REFRACTORY ELEMENTS IN THERMAL UNITS DURING OPERATION

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Operating conditions of thermal units for processing raw materials predetermine defects in refractory elements resulting in their gradual accumulation, which leads to a change in technical condition. A large number of defects, their development, and the achievement of critical values lead to difficulties in modeling the physical processes of changing the technical condition of refractory elements.

This study has investigated the mechanism of the occurrence, development, and accumulation of defects in refractory elements, as well as the processes of cumulative accumulation of damages; a probability model of their degradation has been constructed. The model was built using Markov chains; it describes the sequences of change in the states of refractory element damage and the probability of transitions between these states. Based on the statistical data about a change in the state of damage, the model makes it possible to assess the probability of a defect reaching the critical condition following the predefined number of load cycles. A special feature of the model is the possibility of its application to individual defects, as well as to refractory elements on which defects occur and develop, as well as to assemblies where such refractory elements are installed.

The main patterns of change in the technical condition of refractory elements of coke ovens have been established: the distribution of cracks of a certain length according to the number of coke oven output cycles; the probability of the occurrence of a crack of a critical length at a certain point during operation; the dependence of the probability of a refractory element failure on the predefined number of coke oven output cycles.

Based on the modeling results, it has been proposed, in order to prevent the degradation of refractory elements, to strengthen the structure of the surface layer of the refractory element by cold gas-dynamic spraying, to arrange laying elements that would stop the evolution of defects, and to make up schedules of hot repairs based on the time when the defects may reach critical values, determined during modeling

Keywords: refractory element, crack, change in technical condition, probability model, Markov chains

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1. Introduction

The service life of existing industrial thermal units spans quite a large period and may reach 25 years or longer. Over this time, they have significantly changed their technical condition and their resource is almost exhausted [1–5].

One of the main elements of such units, which most intensively change their technical condition, are refractory