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Specifics of the influence of secondary support deformation characteristics on the gate roadways stability

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Abstract

Purpose. The research is aimed at determining the specifics of the influence of secondary support deformation characteristics on headgate stability in coal mines with steep-dipping seams.

Methods. The deformation characteristics of secondary supports are determined in mine conditions based on instrumental observations of the displacement of reference points on the contour of headgate along the extraction site length. Secondary supports studied are in the form of coal pillars and timber packs.

Findings. An assessment characteristic of the deformation properties of secondary supports is the ability to ensure the stability of side rocks and headgates in the mined-out space of the coal-rock mass. The determining factor in such an assessment is the load-bearing capacity of secondary supports. A distinctive peculiarity is a certain range of physical-mechanical characteristics and deformation processes, within which the resistance of supporting structures increases. At relative deformation $\varepsilon < 0.1$-0.2, the resistance of coal pillars increases, which ensures the continuity of side rocks around the haulage drift and limits their displacement on the contour. After losing load-bearing capacity ($\varepsilon > 0.2$), there is a periodic subsidence of the roof, which is accompanied by an increment in the displacement of side rocks on the headgate contour. In such conditions, the loss of cross-sectional area of the drifts exceeds 50%. For timber packs, after their compaction ($\varepsilon = 0.4$-0.5), resistance increases, effectively limiting the displacement of side rocks. The loss of cross-sectional area of the drifts does not exceed 30%.

Originality. The dependence between the change in cross-sectional area (S) of the haulage drift and relative change in the volume of secondary supports per unit of convergence of side rocks ($\Delta\bar{V}$) has been determined. The presence of such dependence makes it possible to assess the state of headgates supported behind the stoping face at the extraction site.

Practical implications. Coal pillars perform the functions of a supporting structure only within a certain range of deformation properties. Timber packs after their compaction allow limiting the displacement of side rocks on the headgate contour and ensuring its operational state.

Keywords: *headgate, secondary support, deformation characteristics, side rocks*

1. Introduction

To improve the efficiency of underground coal mining, it is necessary to improve the conditions aimed at ensuring the rational use of coal reserves. The solution to this problem is largely restrained by the unresolved issue of protecting and maintaining gate roadways. Increased mining depth and intensity of rock pressure manifestations in gateroads leads to deterioration of their operational state and is associated with deformation of arch support. Such mine roadways require repair.

In mines with steep-dipping coal seams, methods that allow the repair of gate roadways to be mechanized are practically not used. In real conditions of steep coal seam mining, the length of re-supported workings exceeds 50% of the length of the driven roadways. The labor intensity of repair work is increasing.

The stability of gateroads in conditions of steep-dipping coal seams can be ensured by using secondary supports that reduce the negative impact of rock pressure on the near-contour rock mass. This requires an assessment of the load-bearing capacity of secondary supports. Therefore, an effective solution to the problem of ensuring the stability of gateroads can be made based on studies of the deformation characteristics of supporting structures. The use of the results of such studies will make it possible to develop measures to preserve the operational state of gateroads, to prevent the caving of roofs and to improve occupational safety at the extraction sites of coal mines.

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In deep coal mines, the problem of ensuring the stability of gateroads is becoming more and more urgent. In conditions of steep-dipping coal seams, coal pillars and wooden secondary supports in the form of timber chocks, vertical timber sets, and breaker props are used for additional support of gateroads. Secondary supports are installed following the advance of the stoping face at the boundary with the mined-out space. They serve as supporting structures to create a backing for the displacing mass, and even when using combined support systems, they play a key role [1].

One of the peculiarities of maintaining mine roadways behind the stoping face in steep-dipping seams is that the displacement of caved rocks in the mined-out space towards the lower (haulage) drift creates a backing for the roof rocks, which slightly reduces the intensity of rock pressure manifestations. At the same time, in the absence of secondary supports or pillars from the side of the mined-out space, this creates conditions for the formation of long roof cantilevers from the side of the lower drift, the hanging of which without caving creates increased pressure on the mine roadway support [2]. As the length of the cantilever increases, both the deformation of the mine roadway and the deformation rate increase [3]. The spread of plastic deformation zones in coal-rock mass reaches its maximum in the range of bedding angles of 45-60° [4].

The analysis of the secondary supports used in mines where steep-dipping seams are mined shows that the largest volume is accounted for by pillars and timber chocks [5], [6]. The use of filling walls and their analogues for securing mine roadways in the mined-out space when mining steep-dipping seams is not widespread and mainly implemented in complex mechanized longwall faces [7], [8]. Typically, filling walls are used in combination with roof-bolt support in the zone of their location [4], which is not possible on thin seams. Stone or concrete block strips can be used at dip angles of up to 26° (with additional measures to stabilize the secondary support – up to 38°) [9].

A coal pillar is a fragile body and can be considered from the standpoint of linear fracture mechanics. Brittle failures are considered from the perspective of damage accumulation and propagation (spreading) of fractures [10]. In a real coal-rock mass, the pillar is in a limiting stress-strain state, and its load-bearing capacity is insufficient to support the stratified side rocks [11]. In such conditions, the pillars are prone to destruction and spalling, which negatively affects the stability of the gateroads. Under certain conditions, the pillars may also shift under the action of their own weight and the pressure of the rock in the mined-out space, leading to a significant deterioration in the conditions for maintaining the mine roadways [12].

Timber chocks made of round prop stays are unstable due to the small contact area between the secondary support elements and low initial thrust, and may be destroyed during small side rock displacements [13]. When using them, the displacement values in the mine roadways and the state of the primary support are approximately the same as when additionally supported by rubble strips [14]. Chocks made from wooden sleepers are more resistant to action of external forces, especially when the bottoms slip [15]. However, significantly more timber is used in the production of sleeper timber. When using timber packs, close contact with roof and bottom rocks is ensured, which positively affects the stability of gate roadways. However, significantly more timber is used in the construction of timber packs.

Timber chocks are yielding structures with increasing resistance: 4-point chocks made of sleeper timber achieve the highest resistance at shrinkage of about 35%, 6-point chocks – about 40%, 8-point chocks – 40-45%, timber packs – at shrinkage of 50%, and with further deformation, there is a gradual loss of load-bearing capacity [16]-[18]. Chocks made of sleeper timber are able to create resistance of several MN, but they acquire their working parameters at an initial convergence of 50-100 mm, which significantly contributes to the intensification of the convergence of side rocks at the initial stage of their deformation [16], [19].

Chocks filled with waste rock have significantly greater load-bearing capacity [18], but at steep slopes their use is problematic. It should be noted that the average convergence of side rocks is lower when using timber packs than when leaving coal pillars. Therefore, timber packs, having high load-bearing capacity after compaction, more effectively prevent the displacement of side rocks.

Practical application of non-pillar secondary supporting methods shows that when the deformation characteristics of secondary supports do not match the strength properties of side rocks, the stability of roadways deteriorates [20]. Therefore, it is expedient to conduct field studies of the deformation properties of secondary supports.

The assessment of the deformation properties of secondary supports for the analysis of the stability of gateroads is an urgent scientific task. It allows determining the nature of deformation processes in supporting structures, which should be taken into account when ensuring the operational state of haulage drifts (headgates) and improving occupational safety at extraction sites in coal mines with steep-dipping seams.

The research purpose is to identify the peculiarities of the influence of deformation characteristics of secondary supports on the stability of gate roadways in coal mines with steep-dipping seams. This approach makes it possible to assess the state of haulage drifts along the extraction site length and the loss of their cross-sectional area under various secondary support techniques to ensure coal mining in safe conditions.

To achieve this purpose, the following objectives are set:

– to assess the deformation characteristics of coal pillars in the zone of active rock pressure influence;

– to assess the deformation characteristics of timber packs in the zone of active rock pressure influence;

– perform a comparative analysis of the load-bearing capacity of secondary supports to prove the haulage drift stability at the extraction sites.

2. Methods

The research object is deformation processes and their effects in secondary supports to manage the state of side rocks in a coal-rock mass with gate roadways. The assessment of the load-bearing capacity of secondary supports is performed taking into account their relative deformation during the coal-rock mass de-stressing. The relative change in the volume of the secondary support per unit of convergence of the side rocks $\Delta\bar{V}$ (m^{-1}) is also taken into account. The deformation properties of secondary supports are studied in situ and assessed based on an analysis of their state in the mined-out space of extraction sites as the stoping face advances.

To study the periodic nature of rock pressure manifestations in headgates under various secondary support techniques, research was conducted at the Tsentralna Mine, DP Toretskvugillya (Toretsk, Ukraine). Experiments were conducted at a horizon of 1146 m at experimental sites of coal seams l_5 and l_6. Dip angle of coal seams is 59°.

The length of each experimental site is 100 m. The mining-geological conditions of experimental sites are given in Table 1. The scheme of experimental sites for determining side rock displacements along the contour and change in the cross-sectional area of headgates is shown in Figure 1.

Table 1. Mining-geological conditions of experimental sites

Seam index	Dip angle (α), degrees	Seam thickness (m), m	Side rocks			
			Roof		Bottom	
			Immediate	Main	Immediate	Main
l_5	59	0.60	Clay shale, thickness m = 1.6-2.2	Clay shale with a thickness of up to m = 8.5 m	Clay shale, sandy-clay shale with a thickness of up to m = 2.0 m	Sandstone, thickness m = 11.0 m
l_6	59	0.62	Clay shale, with a thickness of up to m = 1.4 m	Clay shale, with a thickness of up to m = 7.0-9.0 m	Clay shale, with a thickness of up to m = 1.5-2.5 m	Clay shale, with a thickness of up to m = 2.5-4.4 m

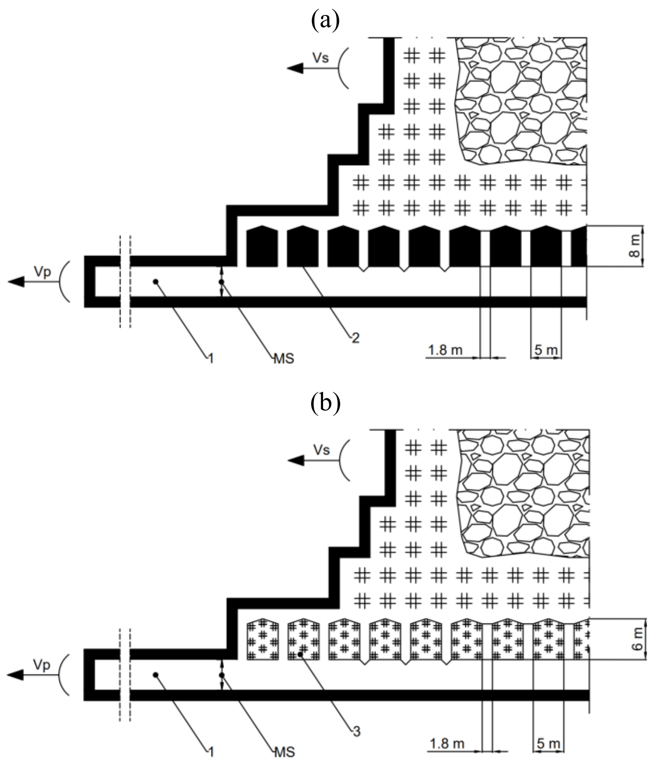

Figure 1. Schemes of experimental sites with various secondary support techniques: (a) chain pillars; (b) timber cages; 1 – haulage drift (headgate); 2 – pillar; 3 – block of timber chocks; MS – measuring station

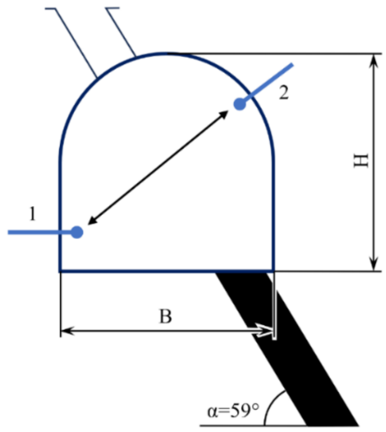

Figure 2. Schemes of measuring station: 1, 2 – reference points

During observations at experimental sites, reference points were placed along the mine roadway contour at specially equipped stations. The change in distance between reference points was recorded as the stoping face advanced. The scheme of measuring stations and location of reference points on the haulage drift contour are shown in Figure 2. To assess the change in cross-sectional area of the drifts, the width (B) and height (H) of the mine roadway were determined at the measuring station. Then, the change in cross-sectional area of the haulage drift was recorded. (S). Measurement error with a surveying tape measure is ±2 mm. The measurement scheme is shown in Figure 2.

At the extraction site of the l_5 seam, the haulage drift was additionally supported with coal pillars and after some time with timber packs.

The haulage drift driving speed is 14 m/month, and the speed of stoping operations is 11 m/month. At the extraction site of the l_6 seam, the haulage drift was additionally supported with coal pillars, and then by chocks made of timber sleepers. The haulage drift driving speed is 12 m/month, and the speed of stoping operations is 18 m/month. Cross-sectional area of haulage drifts is S = 8.5 m^2. The distance between the KMP-A3 arch support frames is 0.8 m.

Dimensions of secondary supports for headgates: coal pillars – 8 m in height, 5 m in width. Timber packs (7×7 sleepers) were used on the l_5 seam, and 16-point chocks made of timber sleepers (4×4 sleepers) were used on the l_6 seam. Chock block dimensions: height – 6 m, width – 5 m. Dimensions of a single chock in plan view: 1×1 m.

The relative deformation of secondary supports is determined by the Expression:

$$\varepsilon = \frac{\Delta h}{h_o}, \tag{1}$$

where:

Δh – convergence of side rocks according to measurements in the haulage drift, m;

h_o – height of the secondary support, m.

This research takes the convergence value as the change in distance between reference points 1 and 2 on the haulage drift contour, that is, $\Delta h = U_{1\text{-}2}$. The height of the secondary support is equal to the coal seam thickness.

The increment in side rock displacements (ΔU), as the distance from the stoping face increases, is determined by the Expression:

$$\Delta U = U_{(1-2)i} - U_{(1-2)i-1}, \tag{2}$$

where:

i – measurement interval number ($i = 1$ at a distance of 10 m from the face to the measuring station, $i = 2$ at a distance of 20 m, etc.).

To smooth out short-term fluctuations and identify characteristic trends in changes in the analyzed parameter, a 2-period variable average is used:

$$\Delta \bar{U} = \frac{\Delta U_i + \Delta U_{i-1}}{2}. \tag{3}$$

Specific change in the secondary support volume per unit of convergence of the side rocks ($\Delta \bar{V}$) during the coal-rock mass de-stressing is determined by the Expression:

$$\Delta \bar{V} = 1000 \cdot \frac{\delta V}{\Delta \bar{U}}, \tag{4}$$

where:

δV – relative change in the secondary support volume.

The parameter δV is determined by the Expression:

$$\delta V = (1 - 2\nu)\varepsilon, \tag{5}$$

where:

ν – Poisson's ratio.

It is assumed that when secondary supports are deformed, the external forces arising during the coal-rock mass de-stressing are spent on changing their shape and volume. The internal potential energy of deformation has levels, upon crossing which secondary supports change their stress-strain state, on which their further behavior depends [21].

3. Results and discussion

3.1. Deformation characteristics of coal pillars

When conducting research to determine the deformation characteristics of coal pillars, attention was paid to the displacement of side rocks (U) on the mine roadway contour and the change in its cross-sectional area (S) depending on the distance to the stoping face along the experimental site length. Experimental data on side rock displacements on the haulage drift contour and the change in cross-sectional area along the extraction site length are given in Table 2.

Table 2. Experimental data on side rock displacements (U) on the haulage drift contour, the change in cross-sectional area (S) along the extraction site length (l) with coal pillars as secondary support

l, m	Extraction site of the l_5 seam		Extraction site of the l_6 seam	
	U, mm	S, m^2	U, mm	S, m^2
10	40	8.3	30	8.1
20	70	8.2	50	8.1
30	110	8.0	100	7.6
40	120	7.4	180	7.6
50	250	6.7	270	6.7
60	340	6.7	360	6.6
70	380	5.8	420	5.7
80	420	4.7	500	4.8
90	450	3.95	570	4.6
100	460	3.95	570	4.1

Figure 3 shows graphs of side rock displacements on the haulage drift contour using the technique of secondary support with coal pillars along the experimental site length.

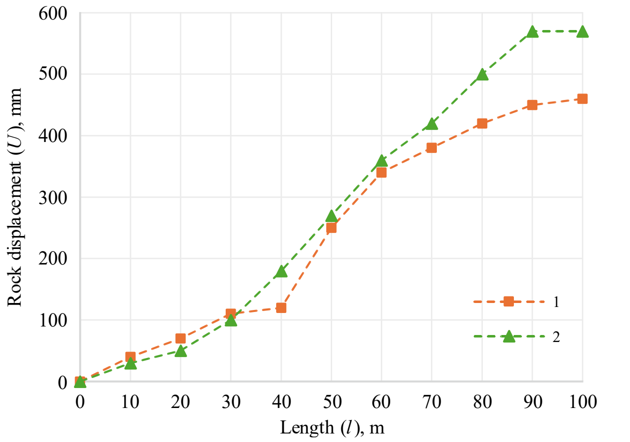

Figure 3. Graphs of side rock displacements (U) on the haulage drift contour using the technique of secondary support with coal pillars along the experimental site length (l): 1 – l_5 seam; 2 – l_6 seam

It was recorded that the largest side rock displacements on the haulage drift contour of 460 mm (Fig. 3, curve *1*) and of 570 mm (Fig. 3, curve *2*) occur at a distance of 90-100 m behind the stoping face. Intensive deformation of the yielding support occurs from the side of the roof. Characteristic peculiarities of the support deformation are the breaks in the lock joint clamps. The cause of bending and twisting of the frame links is the formation of a one-sided directed load.

Figure 4 shows graphs of the change in the haulage drift cross-sectional area when using the technique of secondary support with coal pillars along the experimental site length.

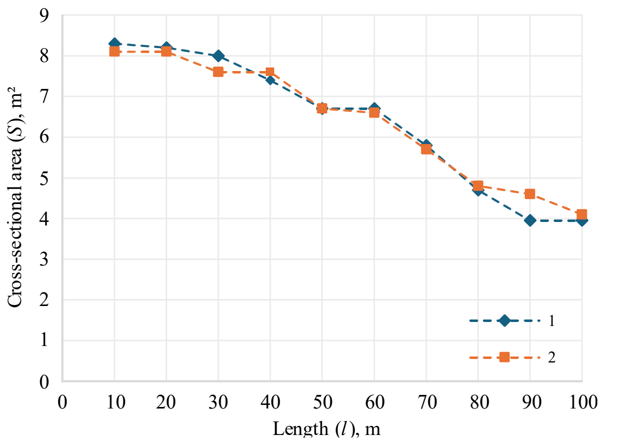

Figure 4. Graphs of the change in cross-sectional area (S) of the haulage drift using the technique of secondary support with coal pillars along the experimental site length (l); 1 – l_5 seam; 2 – l_6 seam

A change in the cross-sectional area of the haulage drift was recorded from 8.5 m^2 at the junction of the stoping face with the headgate to 3.95 m^2 at a distance of 100 m behind the stoping face for the experimental site of the l_5 seam (Fig. 4, curve *1*). And also up to 4.1 m^2 at a distance of 100 m behind the stoping face for the experimental site of the l_6 seam (Fig. 4, curve *2*). The loss of cross-sectional area of the haulage drift is 52% for the experimental site of the l_5 seam and 54% for the experimental site of the l_6 seam.

The load-bearing capacity of coal pillars was assessed based on an analysis of the average increment in displacements ($\Delta\bar{U}$) of side rocks on the haulage drift contour. The relative deformation of coal pillars and the relative change in their volume in the zone of active rock pressure influence behind the stoping face were also taken into account.

Table 3 shows the deformation characteristics of coal pillars at the extraction sites of the l_5 and l_6 seams, taking into account the increment in roof displacements on the haulage drift contour. Given data are calculated by Expressions (2)-(5).

Figure 5 shows graphs of the change in the increment of side rock displacements on the haulage drift contour along the extraction site length.

The graphs show that coal pillars above the drift in the zone of active rock pressure influence behind the stoping face are deformed when loaded by external forces. As a result of such interaction between the side rocks and secondary supports, the increment of side rocks displacements on the haulage drift contour along the experimental site length initially increases and then gradually decreases (Fig. 5, curves *1*, *2*).

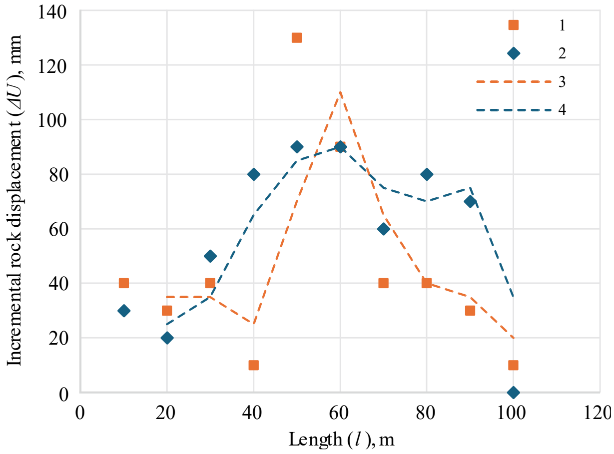

Figure 5. Graphs of the change in increment of side rock displacements (ΔU) on the haulage drift contour depending on relative deformation ε of coal pillars during the coal-rock mass de-stressing at the extraction site; 1 – l_5 seam; 2 – l_6 seam; 3, 4 – average displacement increment

Table 3. Deformation characteristics of coal pillars at the extraction sites

l, m	Extraction site of the l_5 seam					Extraction site of the l_6 seam				
	ε	δV	ΔU, mm	$\Delta\bar{U}$, mm	$\Delta\bar{V}$, m^{-1}	ε	δV	ΔU, mm	$\Delta\bar{U}$, mm	$\Delta\bar{V}$, m^{-1}
10	0.067	0.027	40	20	1.33	0.048	0.019	30	15	1.29
20	0.117	0.047	30	35	1.33	0.081	0.032	20	25	1.29
30	0.183	0.073	40	35	2.10	0.161	0.065	50	35	1.84
40	0.200	0.080	10	25	3.20	0.290	0.116	80	65	1.79
50	0.417	0.167	130	70	2.38	0.435	0.174	90	85	2.05
60	0.567	0.227	90	110	2.06	0.581	0.232	90	90	2.58
70	0.633	0.253	40	65	3.90	0.677	0.271	60	75	3.61
80	0.700	0.280	40	40	7.00	0.806	0.323	80	70	4.61
90	0.750	0.300	30	35	8.57	0.919	0.368	70	75	4.90
100	0.767	0.307	10	20	15.33	0.919	0.368	0	35	10.51

At the extraction site of the l_5 seam, at a distance of up to 40 m, the pillars retain their continuity, and the average increment of side rock displacements remains in the range of 25-35 mm (Fig. 5, curve *1*). A sharp drop in resistance of coal pillars is accompanied by an increase in increment of side rock displacements up to 130 mm and is recorded after the stoping face retreat by 50 m. Pillars begin to lose their load-bearing capacity (Fig. 5, curve *1*).

At the extraction site of the l_6 seam, an increase in increment of side rock displacements begins to be observed at a distance of more than 30 m and reaches a maximum of 90 mm, also after the stoping face retreat by 50 m. This process is associated with the beginning of gradual fracture formation in the pillars and a decrease in their load-bearing capacity (Fig. 5, curve *2*).

A decrease in load-bearing capacity of pillars and destruction of the roof over time leads to deformation of the support in the haulage drift and a reduction in its cross-sectional area.

3.2. Deformation characteristics of timber chocks made of sleepers

When conducting research that allowed determining the deformation characteristics of timber chocks made of sleepers, attention was paid to the displacements of side rocks (U) on the mine roadway contour depending on the distance to the stoping face along the experimental site length (l).

Experimental data on side rock displacements on the haulage drift contour and the change in cross-sectional area along the extraction site length are presented in Table 4.

Figure 6 shows graphs of side rock displacements on the haulage drift contour using the secondary support of with the haulage drift with timber chocks made of sleepers. The largest side rock displacements on the haulage drift contour, 405 mm (Fig. 6, curve *1*) and 510 mm (Fig. 6, curve *2*), are recorded at a distance of 70-80 m behind the stoping face.

Table 4. Experimental data on side rock displacements (U) on the haulage drift contour, the change in cross-sectional area (S) along the extraction site length (l) with timber chocks as secondary support

l, m	Extraction site of the l_5 seam		Extraction site of the l_6 seam	
	U, mm	S, m^2	U, mm	S, m^2
10	40	8.3	60	7.8
20	60	7.5	130	7.6
30	130	7.4	270	6.6
40	210	6.7	320	6.2
50	260	6.4	430	5.9
60	350	6.4	490	5.8
70	380	6.0	510	5.2
80	405	5.9	510	5.2
90	405	5.9	510	5.2
100	405	5.9	510	5.2

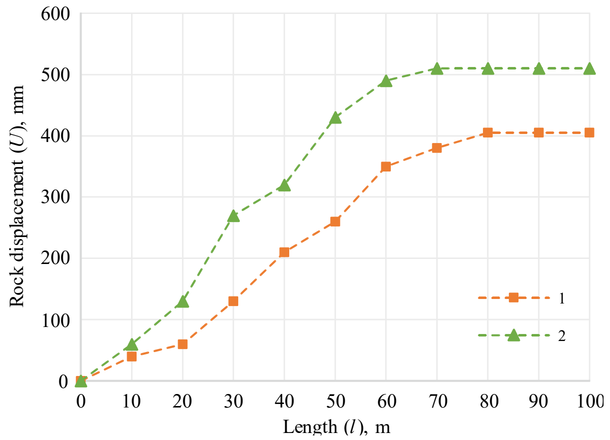

Figure 6. Graphs of side rock displacements (U) on the haulage drift contour using the technique of secondary support with timber chocks along the experimental site length (l); 1 – l_5 seam; 2 – l_6 seam

After that, the mine roadway state stabilizes. At a distance of up to 55 m behind the stoping face in l_5 seam conditions and up to 40 m in l_6 seam conditions, the mine roadway contour deformation is within the nominal yield strength of the arch support.

Figure 7 shows graphs of the change in cross-sectional area of the haulage drift when using the technique of secondary support with timber packs. The graphs show that at the extraction site of the l_5 seam, the mine roadway cross-section changes from 8.5 to 5.9 m^2 at a distance of 80 m behind the stoping face (Fig. 7, curve *1*).

The loss of cross-sectional area is 30%. At the extraction site of the l_6 seam, the cross-section of the mine roadway changes up to 5.2 m^2 at a distance of 70 m behind the stoping face. The loss of cross-sectional area is 40% (Fig. 7, curve *2*).

As a result of measurements to determine the side rock displacements, the height and width of the mine roadway along the length of the extraction sites, it has been found that the supports in the haulage drift have characteristic bendings and are deformed from the roof side. Displacements from the roof side at the experimental sites are accompanied by stratified bending. Clay shale in the zone of active rock pressure influence is broken by a series of fractures, which in some cases is accompanied by rock spillage into the drift.

Table 5 shows the deformation characteristics of timber chocks made of sleepers at the extraction sites of the l_5 and l_6 seams, taking into account the increment in side rock displacements on the haulage drift contour. The data presented are obtained using Expressions (2)-(5).

Figure 8 shows graphs of changes in the increment of side rock displacements on the haulage drift contour along the extraction site length. The graphs show the typical operating modes of timber chocks located in the mined-out space of the extraction site. At the extraction site of the l_5 seam, at a distance of up to 40 m behind the stoping face, in the zone of active roof subsi-dence, the average increment of side rock displacements gradually increases and reaches a maximum at a distance of 40-60 m (the maximum increment of side rock displacements of 90 mm is recorded at a mea-surement interval of 50-60 m).

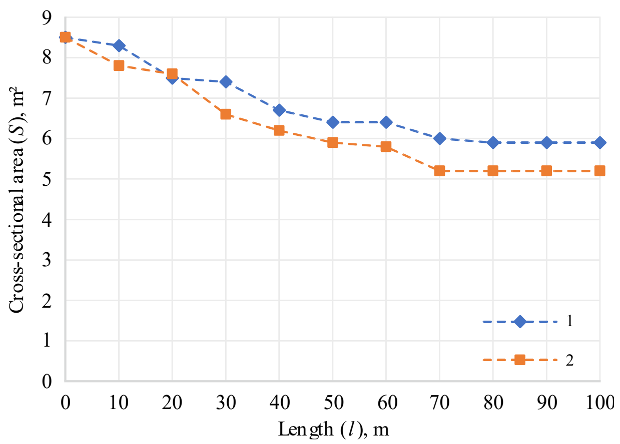

Figure 7. Graphs of the change in cross-sectional area (S) of the haulage drift when using the technique of secondary support with timber chocks along the extraction site length (l); 1 – l_5 seam; 2 – l_6 seam

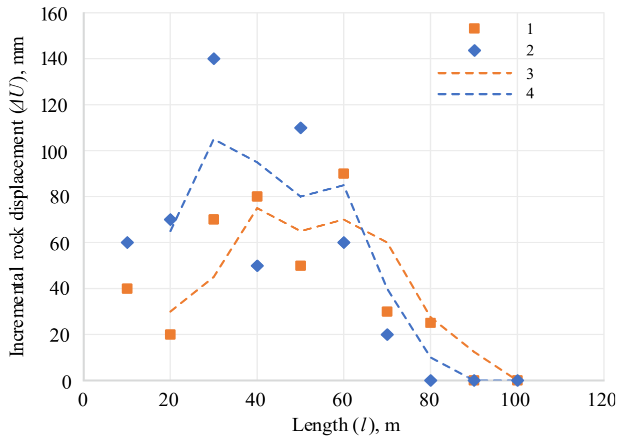

Figure 8. Graphs of changes in the increment of roof displacements (ΔU) on the haulage drift contour using the technique of secondary support with timber chocks along the experimental site length (l); 1 – l_5 seam, 2 – l_6 seam; 3, 4 – average displacement increment

Table 5. Deformation characteristics of timber chocks

l, m	Extraction site of the l_5 seam					Extraction site of the l_6 seam				
	ε	δV	ΔU, mm	$\Delta\bar{U}$, mm	$\Delta\bar{V}$, m^{-1}	ε	δV	ΔU, mm	$\Delta\bar{U}$, mm	$\Delta\bar{V}$, m^{-1}
10	0.067	0.064	40	20	3.20	0.097	0.093	60	30	3.10
20	0.100	0.096	20	30	3.20	0.210	0.201	70	65	3.10
30	0.217	0.208	70	45	4.62	0.435	0.418	140	105	3.98
40	0.350	0.336	80	75	4.48	0.516	0.495	50	95	5.22
50	0.433	0.416	50	65	6.40	0.694	0.666	110	80	8.32
60	0.583	0.560	90	70	8.00	0.790	0.759	60	85	8.93
70	0.633	0.608	30	60	10.13	0.823	0.790	20	40	19.74
80	0.675	0.648	25	27.5	23.56	0.823	0.790	0	10	78.97
90	0.675	0.648	0	12.5	51.84	0.823	0.790	0	0	–
100	0.675	0.648	0	–	–	0.823	0.790	0	0	–

In this case, there is a gradual compaction of secondary supports, which during this period actually operate in a yielding mode. After reaching a certain degree of compaction of the chocks, the increase in side rock displacements first decreases to 25 mm, and at a distance of 90-100 m it drops to zero (Fig. 8, curve *1*).

Similar processes are observed at the extraction site of the l_6 seam: as the secondary supports are loaded, they are gradually compacted, which is accompanied by an average increment of side rock displacements of 65-105 mm for every 10 m at a distance of 10-60 m. After that, the increment of displacements decreases to 20 mm, and at a distance of 80-90 m, it drops to zero (Fig. 8, curve *2*).

3.3. Comparative analysis of the load-bearing capacity of secondary supports based on their deformation properties

A comparative analysis of the load-bearing capacity of secondary supports is performed based on data on the average increment of side rock displacements on the contour of preparatory workings. Experimental data on relative deformation and relative change in volume of secondary supports in the zone of active rock pressure influence behind the stoping face are used. When supporting the haulage drift with coal pillars at the initial stage of deformation ($\varepsilon \leq 0.2$), their resistance increases. The average increment of side rock displacements is 25-35 mm (Fig. 9a, b, curves *1*, *2*).

With relative deformation of more than 0.2, there is a sharp drop in the resistance of coal pillars, accompanied by a gradual loss of their load-bearing capacity. As the fracturing process progresses, periodic subsidence of the roof occurs, causing the average increment value of side rock displacements to increase to 90-130 mm. After the pillars are deformed by 50-60%, the secondary supports lose their load-bearing capacity completely (Fig. 9a, b, curves *1*, *2*).

When supporting a haulage drift with timber chocks, at the initial deformation stage ($\varepsilon \leq 0.5$), the secondary supports are compacted. The maximum compression of timber packs is achieved at their relative deformation of 0.55-0.65, while 16-point chocks deform until the structure is completely destroyed (ε = 0.8-0.82) (Fig. 9a, b, curves *1*, *2*). After maximum compaction of secondary supports or actual closure of side rocks, further displacements of side rocks in the mine roadway practically do not occur.

Figure 10 shows graphs of the relative change in the volume of secondary supports per unit of convergence of side rocks depending on the relative deformation of coal pillars and timber chocks. Analysis of curves *1* and *2* shown in Figure 10 indicates an increase in the relative change in the volume of secondary supports per unit of convergence of side rocks with an increase in relative deformation of supporting structures. This process for coal pillars is accompanied by a loss of load-bearing capacity and destruction (Fig. 10a, b, curve *1*).

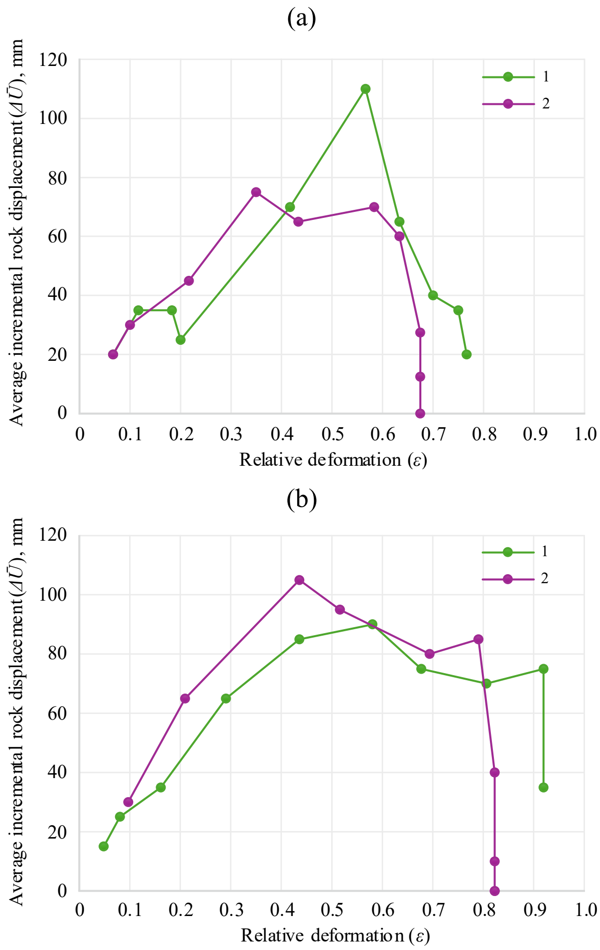

Figure 9. Graphs of the change in average increment value of side rock displacements ($\Delta\bar{U}$) on the haulage drift contour depending on relative deformation ε of secondary supports: (a) at the extraction site of the l_5 seam; (b) at the extraction site of the l_6 seam; 1 – coal pillars; 2 – timber chocks

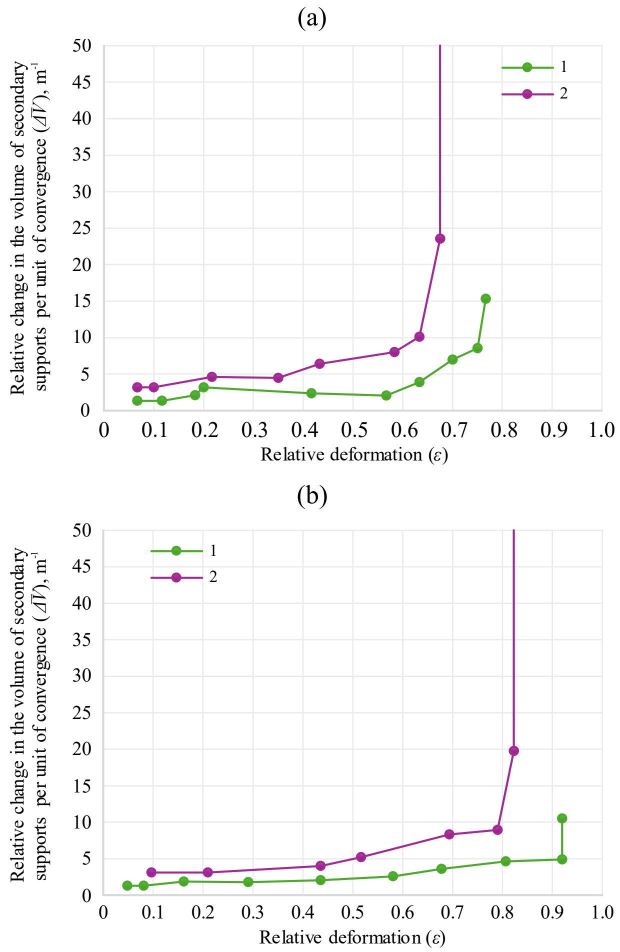

Figure 10. Graphs of relative change in the volume of secondary supports per unit of convergence ($\Delta\bar{V}$) of side rocks depending on relative deformation ε of supporting structures: (a) extraction site of the l_5 seam; (b) extraction site of the l_6 seam; 1 – coal pillars; 2 – timber chocks

For timber chocks, it is accompanied by compressing the supporting structures to their maximum compaction or final destruction (Fig. 10a, b, curve *2*).

Figure 11 shows graphs of the change in the cross-sectional area of the haulage drift depending on relative deformation of secondary supports. In conditions where coal pillars are used for additional support the gateroads, the change in cross-sectional area occurs after the loss of their stability ($\varepsilon > 0.2$) and gradual destruction ($\varepsilon > 0.6$) (Fig. 11a, b, curve *1*). When using timber chocks, the change in the cross-sectional area of mine roadways occurs more evenly as they are compacted (Fig. 11, curve *2*).

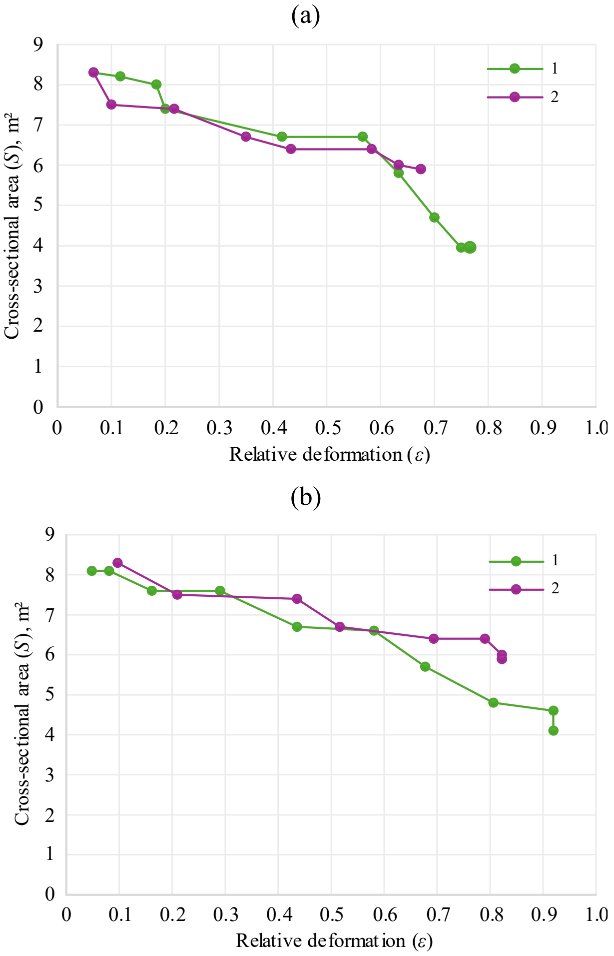

Figure 11. Graphs of the change in cross-sectional area (S) of the haulage drift depending on relative deformation ε of secondary support: (a) extraction site of the l_5 seam; (b) extraction site of the l_6 seam; 1 – coal pillars; 2 – timber chocks

Figure 12 shows graphs of the change in cross-sectional area depending on relative change in the volume of secondary supports per unit of convergence of side rocks.

There is a power relationship between the change in cross-sectional area of the haulage drift and relative change in the volume of secondary supports per unit of convergence of side rocks:

– when protected with coal pillars, the extraction site of the l_5 seam (Fig. 12a, curve *1*) $S = 9.3627 \cdot \Delta\overline{V}^{-0.342}$, determination coefficient is $R^2 = 0.877$, average approximation error is 7.2%;

– when supported with coal pillars, the extraction site of the l_6 seam (Fig. 12b, curve *1*) $S = 9.0478 \cdot \Delta\overline{V}^{-0.369}$, determination coefficient is $R^2 = 0.956$, average approximation error is 4.8%;

– when supported with timber chocks, the extraction site of the l_5 seam (Fig. 12a, curve *2*) $S = 7.8286 \cdot \Delta\overline{V}^{-0.085}$, determination coefficient is $R^2 = 0.6946$, average approximation error is 4.5%;

– when supported with timber chocks, the extraction site of the l_6 seam (Fig. 12b, curve *2*) $S = 7.7989 \cdot \Delta\overline{V}^{-0.075}$, determination coefficient is $R^2 = 0.78$, average approximation error is 4.0%.

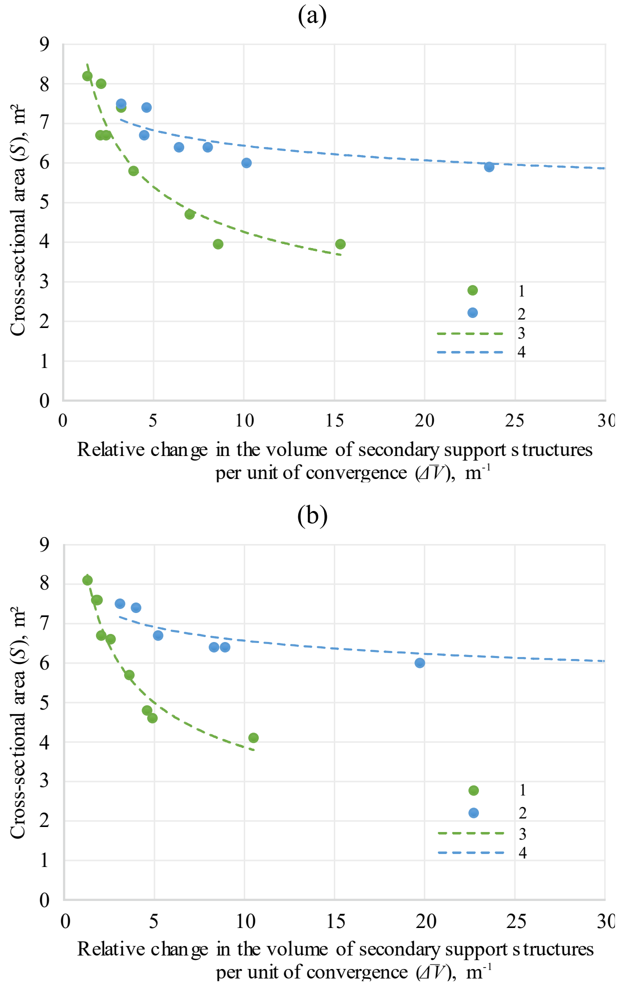

Figure 12. Graphs of the change in cross-sectional area (S) of the haulage drift depending on relative change in the volume of secondary supports per unit of convergence ($\Delta\overline{V}$) of side rocks in the zone of active rock pressure influence behind the stoping face: (a) at the extraction site of the l_5 seam; (b) at the extraction site of the l_6 seam; 1 – coal pillars; 2 – timber chocks; 3, 4 – power approximation

Based on the results of processing experimental data, the influence of the deformation properties of secondary supports on the stability of gate roadways has been identified based on the relative change in the volume of supporting structures, which manifests itself during the coal-rock mass de-stressing. The obtained result makes it possible to state that the stability of side rocks and haulage drifts in the mined-out space of the coal-rock mass is an evaluative characteristic of deformation processes in secondary supports.

The determining factor in the assessment is the load-bearing capacity and operating mode of secondary supports. Correlating the deformation characteristics of supporting structures with observations of rock contour displacements in mine roadways allows determining the parameters under which effective restriction of side rock displacements is achieved on the contour of gate roadways and in the mined-out space of the coal-rock mass.

For coal pillars, resistance increases at the initial stage of deformation, when the relative deformation of secondary supports does not exceed 0.1-0.2. After losing their load-bearing capacity, the roof gradually subsides. Under such conditions, there is a relative increase in the volume of coal pillars per unit of convergence of side rocks. The yielding support in the headgate is deformed, and the loss of cross-sectional area of the haulage drift is more than 50%. The risk of roof caving is almost at a critical level.

Discontinuity of coal pillars causes the loss of load-bearing capacity of the secondary support. This process changes the geometry of the secondary support and is accompanied by a transformation of its volume and shape. It also negatively affects the stability of the haulage drifts. In the zone of active rock pressure influence behind the stoping face, local loss of stability occurs due to discontinuity of coal pillars. This causes deformation of the mine roadway contour from the roof side. After exhausting the possibility of realizing the stability of local forms, the process of final destruction of pillars occurs. There is a spilling of coal into the headgate, an increase in the increment of side rock displacements on the contour and intense deformation of the arch-type yielding support. In such conditions, the threat of roof caving becomes critical, and the overall dimensions of haulage drift become dangerous.

For timber packs, the increase in resistance occurs after their compaction, when the relative deformation of secondary supports is 0.4-0.5. At the initial stage of deformation, with relative deformation up to 0.4, there is an increase in relative change in the volume of secondary supports per unit of convergence of side rocks, which indicates the compaction of supporting structures. With relative deformation more than 0.4-0.5, that is, after maximum compression, there is an increase in the resistance of the timber packs, the side rock displacement on the haulage drift contour is limited. Under such conditions, the loss of cross-sectional area of gateroads does not exceed 30%. On the other hand, chocks of non-solid structure (16-point) deform almost to the point of complete destruction (ε = 0.8-0.82), while maintaining resistance sufficient to stabilize the displacement increment at a certain constant level. The loss of cross-sectional area of the mine roadway reaches 40%.

Thus, the deformation characteristics of secondary supports determine their ability to respond to various external factors that manifest themselves during the coal-rock mass de-stressing. The stress-strain state of secondary supports depends on the mechanical characteristics of the material, design, and nature of deformation, which together determine the specific peculiarities of the operation of supporting structures. Coal pillars provide operational state of gateroads along the extraction site length only within a certain range of deformation properties (at the initial stage of deformation). In this range, the resistance of secondary supports increases. Timber packs after compaction (at the final stage of deformation) prevent the convergence of side rocks on the contour of gate roadways, allowing them to maintain their safe overall dimensions and avoid caving. Non-solid chocks operate as yielding structures over the entire deformation range, which leads to a slightly greater loss of cross-sectional area of the mine roadway compared to the case of using timber packs. Safe overall dimensions of gateroads are provided when the secondary supports involved operate in a mode of constant or increasing resistance. In such conditions, the roof caving becomes improbable. Safe working conditions created for miners in the workplace and increased coal production in coal mines with steep-dipping seams can be achieved by maintaining the operational state of gateroads and ensuring that secondary supports effectively perform their supporting functions.

4. Conclusions

Based on the results of the performed research, the deformation characteristics of secondary supports have been determined, which makes it possible to assess the impact of their shape and volume transformation on the stability of gateroads along the extraction site length. The problem of ensuring the stability of haulage drifts in mines with steep-dipping coal seams was being addressed to improve the safety of mining operations and ensure stable coal mining.

It has been experimentally proven that in the zone of active rock pressure influence along the extraction site length behind the stoping face, the stability of haulage drifts protected with coal pillars is ensured at the initial stage of deformation of the secondary supports. In conditions when the relative deformation of coal pillars is less than 0.1-0.2, the resistance of supporting structures increases and the displacements of side rocks on the haulage drift contour are limited. With relative deformation of more than 0.2, there is a gradual loss of load-bearing capacity of coal pillars, deformation of the support, which over time leads to the destruction of secondary supports and a loss of more than 50% of the cross-sectional area of the headgate.

It has been experimentally proven that when using timber packs at the initial stage of their deformation (ε < 0.4-0.5), compression and compaction of supporting structures occur. After deformation by 50-60%, an increase in resistance of timber chocks is observed, which allows limiting the displacement of side rocks on the haulage drift contour. Losses in the cross-sectional area of the headgate in such conditions amount to up to 30%. The use of more economical non-solid, albeit as dense as possible 16-point chocks, leads to an increase in the loss of cross-sectional area up to 40%.

Based on the results of a comparative analysis of the deformation properties of supporting structures, it has been found that at the mine roadway site supported behind the stoping face, there is a power relationship between the change in the cross-sectional area of the gate roadways and the relative change in the volume of the secondary support per unit of convergence of the side rocks. The determi-ning factor in the identified dependences is the change in the volume of secondary supports and the increase in their resistance, which occurs at different stages of deformation of secondary supports during the coal-rock mass de-stressing.

The research results can be used to substantiate the choice of a secondary support technique for haulage drifts in conditions of steep-dipping thin coal seams. However, a qualitative assessment of the load-bearing capacity of secondary supports for gateroads should take into account the change in the rigidity of supporting structures. Further research should take into account the influence of this parameter on the stability of gateroads. This will enable the development of measures aimed at preventing roof caving and ensuring the operational state of haulage drifts at extraction sites.

Author contributions

Conceptualization: SP, DC; Data curation: YP, YB, OV; Formal analysis: SP, LB, YB; Investigation: YP, YB, OD; Methodology: DC, SP, LB; Project administration: SP, OD; Resources: OD, YP; Supervision: DC, LB; Validation: DC, YB, OV; Visualization: YB, LB; Writing – original draft: DC, SP, YB, OD, YP, OV; Writing – review & editing: LB, SP. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Особливості впливу деформаційних характеристик охоронних споруд на стійкість підготовчих виробок

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Мета. Мета дослідження полягає у встановленні особливостей впливу деформаційних характеристик охоронних споруд на стійкість підготовчих виробок у вугільних шахтах з крутим заляганням пластів.

Методика. Деформаційні характеристики охоронних споруд встановлювались у шахтних умовах на основі інструментальних спостережень зміщення реперів на контурі підготовчих виробок по довжині виїмкової ділянки. Розглядались охоронні споруди у вигляді целіків вугілля та накатних кострів з дерев'яних шпал.

Результати. Оціночною характеристикою деформаційних властивостей охоронних споруд є здатність забезпечувати стійкість бічних порід і підготовчих виробок у виробленому просторі вуглепородного масиву. Визначальним фактором такої оцінки є тримкість охоронних споруд. Відмінною рисою є певний діапазон фізико-механічних характеристик та деформаційних процесів, в межах якого зростає опірність тримальних конструкцій. При відносній деформації $\varepsilon < 0.1$-0.2 опірність циликів вугілля зростає, що дозволяє забезпечити цілісність бічних порід навколо відкатного штреку та обмежити їх переміщення на контурі. Після втрати тримкості ($\varepsilon > 0.2$) відбувається періодичне просідання покрівлі, яке супроводжується зростанням приросту зміщення бічних порід на контурі підготовчої виробки. В таких умовах втрати площі поперечного перетину штреків складають понад 50%. Для накатних кострів з дерев'яних шпал після їх ущільнення ($\varepsilon = 0.4$-0.5) відбувається зростання опірності, за рахунок чого переміщення бічних порід ефективно обмежується. Втрати площі поперечного перетину штреків не перевищують 30%.

Наукова новизна. Встановлена залежність між зміною площі поперечного перетину S (м^2) відкатного штреку та відносною зміною об'єму охоронних споруд на одиницю конвергенції бічних порід ($\Delta\bar{V}$) (м$^{-1}$). Наявність такої залежності дає можливість оцінити стан підготовчих виробок, підтримуваних позаду очисного вибою на виїмковій ділянці.

Практична значимість. Цілики вугілля виконують функції тримальної конструкції лише в певному діапазоні деформаційних властивостей. Накатні костри з дерев'яних шпал після їх ущільнення дозволяють обмежити переміщення бічних порід на контурі підготовчої виробки і забезпечити її експлуатаційний стан.

Ключові слова: *підготовча виробка, охоронна споруда, деформаційні характеристики, бічні породи, експлуатаційний стан*

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