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DETERMINING THE STABILITY OF ROLL-BACK STRETCHES IN STEEP LAYERS WHEN UNLOADING A COAL ROCK MASSIF

Daria Chepiga
Corresponding author
PhD, Associate Professor*
E-mail: daria.chepiha@donntu.edu.ua
Serhii Podkopaiev
Doctor of Technical Sciences, Professor*
Oleksandr Shashenko
Doctor of Technical Sciences, Professor**
Oleksandr Skobenko
PhD, Associate Professor**
Oleksandr Demchenko
General Director
SE "Ukrshachthidrozakhyst"
Pryladnyi lane, 2a, Kyiv, Ukraine, 02000
Yevgen Podkopayev
Doctor of Philosophy (PhD)
Limited Liability Company Manufacturing Company ELTEKO
O. Tyhoho str., 2, Kostyantynivka, Ukraine, 85105
Valentyna Fedorchuk-Moroz
PhD, Associate Professor
Department of Civil Security***
Zakhar Matsuk
PhD, Associate Professor
Department of Labor Protection, Civil and Technogenic Safety
SEI "Prydniprovska State Academy of Civil Engineering and Architecture" (PSACEA)
Ukrainian State University of Science and Technology
Lazaryan str., 2, Dnipro, Ukraine, 49010
Oleksandr Shymchuk
PhD, Associate Professor
Department of Building and Civil Engineering***
*Department of Mining Management and Labour Protection
Donetsk National Technical University
Potebni str., 56, Lutsk, Ukraine, 43003
**Department of Construction, Geotechnics and Geomechanics
Dnipro University of Technology
Dmytra Yavornytskoho ave., 19, Dnipro, Ukraine, 49005
***Lutsk National Technical University
Lvivska str., 75, Lutsk, Ukraine, 43018

The object of this study is the condition of side rocks in a coal rock massif with preparatory workings. The task solved was to ensure the stability of preparatory workings to improve the safety of miners' activities.

The bearing capacity of protective structures in the preparatory mining workings along the length of the excavation section in a coal mine was comparatively assessed.

The operational condition of the roll-back stretch, when using a protective technique that involves coal pillars, is provided for at their relative deformation $\varepsilon<0.25$ and relative volume change $\delta V<0.1$. At a distance of $l>50$ m behind the cleaning pit, at $\varepsilon\geq0.6-0.8$, there is a decrease in the load-bearing capacity of coal pillars and the destruction of the roof. The loss of cross-sectional area of the roll-back stretch is 50 %. Under such conditions, the level of a roof collapse threat is approaching a critical state. When using rolling bundles made of wooden sleepers at $\varepsilon>0.21$ and $\delta V>0.16$, conditions are created around the preparatory workings at which the integrity of the roof is ensured through the gradual sealing of protective structures. At a distance $l>60$ m, the increase in lateral rock displacements reaches the minimum values $\Delta U=10$ mm, and the loss of the cross-sectional area of the roll-back stretch is 30 %.

The kind of functional dependence between the length l (m) of the roll-back stretch with different protection techniques and the relative change in the volume dV of protective structures was experimentally determined. Such a dependence makes it possible to assess the bearing capacity of protective structures along the length of the excavation area in the zone of active influence of mountain pressure behind the cleaning pit.

The operational condition of roll-back stretches when using coal pillars is ensured within the limits of their deformation resource, which limits the use of this protection technique. To ensure the stability of preparatory workings, it is advisable to use rolled bundles made of wooden sleepers. After their compaction, the movement of side rocks is limited in the worked-out space of the excavation site

Keywords: roll-back stretch, protective structures, bearing capacity, displacement of lateral rocks, excavation site

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1. Introduction

The world experience of coal mines indicates that the effectiveness of working out coal seams under safe conditions depends to a large extent on the stability of the preparatory mine workings. To ensure their operational condition, various protection techniques are offered, the use of which makes it possible to preserve the integrity of side rocks around the workings. But the practiced protection techniques (coal pillars, bundles made of wooden risers, wooden bundles) do not always ensure the integrity of the roof and the stability of preparatory workings along the length of the excavation site.

Under conditions of steep coal seams, the specificity of maintaining preparatory mine workings in excavation sections of coal mines is determined by the angle of inclination of the seams, the fracture nature of the coal rock massif, and the disturbance of the roof. Under such conditions, the stability of workings behind the cleaning hole deteriorates, the fastening is deformed, which contributes to the accident from the collapse of stratified rocks.

The operational condition of preparatory workings is ensured by the performance of repair operations. The length of the workings being repaired or re-fastened is about 50 % in relation to the completed workings. The labor intensity of repair work is constantly increasing, which is determined not only by difficult mining and geological conditions but also by the types of operation during the renewal of workings. To a large extent, this is due to the lack of reliable and effective ways to ensure the stability of roll-back stretches, taking into account the bearing capacity of protective structures. Therefore, the task to ensure the stability of roll-back stretches of steep formations is urgent. It can be solved by improving protection techniques for preparatory workings when considering operational issues related to protective structures. In general, when solving this task, it is necessary to compare the bearing capacity of protective structures, their mechanical characteristics, and the physical-mechanical characteristics of side rocks in a coal rock massif. Scientific research into this area is important. After all, using the results will allow us to devise measures aimed at preventing the collapse of side rocks, limiting their movements in the produced space of a coal rock massif, as well as preserving the stability of roll-back stretches.

In the coal pillar-free preparation of excavation sites under conditions of a steep fall, wooden bundles are used to protect the roll-back stretches [5]. It is believed [6] that wooden bundles reach their greatest resistance at a shrinkage of 50 %.

The disadvantages of such protective structures are the imperfection of their mechanical characteristics and the slow growth of resistance during displacements of lateral rocks in the worked-out space. However, taking into account the number and layout of the components of a wooden bundle, it is possible to increase their rigidity [7].

In the case of intensive displacements of lateral rocks in the zone of active influence of rock pressure, deformation of the flexible arch support and its individual elements is observed. To improve the stability of the preparatory mine workings, it is proposed to increase the density of installation of arch fasteners along the length of the excavation site [8]. Such a technical solution does not radically affect the reduction of displacements of side rocks on the working contour. Fasteners passively affect the near-contour array.

All this allows us to state that in order to ensure the operational condition of the preparatory workings along the length of the excavation site, the issue of their stability should be considered together with the assessment of the bearing capacity of protective structures. This approach will make it possible to estimate the change in the cross-sectional area of the roll-back stretches, which is necessary when justifying the choice of the protection technique for workings. The study of the deformation properties of protective structures, as well as the assessment of their bearing capacity, is an important component in the analysis of stability of preparatory mine workings, which is carried out to solve the issues of improving the safety of miners and the efficiency of coal mining. Therefore, it is a relevant task to investigate the deformation properties of protective structures and assess their bearing capacity in mines.

2. Literature review and problem statement

In order to ensure the stability of preparatory mining workings in the excavation area of a coal mine, it is necessary to correctly choose the shape and dimensions of the cross-section, the parameters of the arch fastening and protective structures, which are erected on the border with the worked-out space.

On layers of a steep fall, the protection of preparatory mining workings is carried out by coal pillars or various wooden structures [1, 2]. It is shown that a protective coal pillar of limited dimensions is a classic object in the linear mechanics of destruction. When the coal rock massif is unloaded, the coal pillar enters the ultimate stress-strain state. The presence of defects in it reduces the bearing capacity of the protective structure [3]. It is important to note that under such conditions, coal pillars are prone to destruction and shedding. This situation leads to the appearance of cavities above the preparatory workings and deterioration of stability. The reason for this may be the lack of assessment of the bearing capacity of the protective structure when operating the workings.

As the depth of mining operations increases, the size of coal pillars also increases. At the same time, it becomes difficult to work out the coal reserves in the neighboring layers. The reason is the concentration of loads in coal pillars and side rocks [4]. All this has a negative impact on the stability of side rocks and protective structures. Over time, their destruction occurs, as well as collapse into the workings.

3. The aim and objectives of the study

The purpose of our study is to determine the influence of the deformation properties of coal pillars and rolled bundles made of wooden sleepers on the stability of roll-back stretches at steep formations. This approach makes it possible to assess the bearing capacity of protective structures along the length of the mining area to ensure safe working conditions for miners and increase coal production.

To achieve the goal, the following tasks were set:

– to investigate the stability of a roll-back stretch for the case of protection technique involving coal pillars, taking into account the increase in the displacements of side rocks on the contour of the preparatory workings;

– to investigate the stability of a roll-back stretch for the case of protection technique involving rolled bundles made of wooden sleepers, taking into account the increase in lateral rock displacements on the contour of the preparatory workings;

– to carry out a comparative assessment of the bearing capacity of protective structures to substantiate the stability of a roll-back stretch with different protection techniques at the excavation site of a coal mine.

4. The study materials and methods

The object of our study is the condition of side rocks in a coal rock massif with preparatory workings. It is believed [3] that the internal potential energy of objects of the mechanics of a deformed body under static loading has critical values, on which the stress-strain state depends. Beyond them, there is a decrease in the strength of protective structures and a change in their relative volume, which significantly affects the stability of preparatory workings. When unloading a coal rock massif, the behavior and stress-strain state of protective structures is considered by the change in their relative volume. This parameter was determined based on data from the measurements of convergence of the lateral rocks on the contour of a roll-back stretch, based on the relative deformation λ, which simplifies calculations.

In order to study the stability of a roll-back line at the excavation site and to assess the bearing capacity of protective structures, field experiments were conducted at the "Centralna" mine, DP "Toretskvugilya". In the excavation area of the layer l_5, the roll-back stretch was protected by coal pillars. Dimensions of the protective structure: height, 8 m; width, 5 m. In the extraction area of layer l_6, the roll-back stretch was protected by rolled bundles made of wooden sleepers. Dimensions of the protective structure: height, 6 m; width, 5 m. The length of each experimental site $l=100$ m. The depth of mining operations is 1146 m. The scheme of the experimental sites is shown in Fig. 1. The mining and geological conditions of the experimental sites are given in Table 1.

The scheme of the measuring station and the location of reference points on the contour of a roll-back stretch are shown in Fig. 2.

Changes in the cross-sectional area of a roll-back stretch with different protection techniques were established at the measuring station as the cleaning pit moved forward. The width B (m) and height H (m) of the workings were determined. After their registration, the area of the cross-section of the roll-back stretch was determined.

All measurements (distance between reference points, the height and width of workings) were carried out using a surveyor's tape measure. The measurement error was ±2 mm.

The cross-sectional area of the roll-back stretch $S=8.5$ m^2. The distance between the frames of the arch flexible fastening (AP-3) is 0.8 m. Stretching along the layer l_5 and l_6 was carried out with the help of blasting operations. The speed of roll-back stretch execution in the layer l_5 is 10 m/month, in the layer l_6 is 12 m/month. The speed of cleaning works on layer l_5 and on layer l_5 is 8 m/month. The method for managing the roof in the clearing of a pothole is the complete collapse of the roof.

The relative deformation of the protective structure was determined from the following expression [9]:

$$\lambda = \frac{\Delta h}{h_0}, \qquad (1)$$

where Δh is the convergence of side rocks according to the measurements in the roll-back stretch, m; h is the height of the protective structure, m.

The value Δh (m) was taken to be a change in the distance between reference points 1 and 3 on the contour of a roll-back stretch, i.e.:

$$\Delta h = U_{1-3}.$$

The height of the protective structure h (m) corresponded to the thickness of the coal seam:

$$h = m.$$

As an indicative indicator for the stability analysis of roll-back stretches, taking into account the displacements of side rocks, the value of increase in the roof displacements ΔU (mm) on the contour of a roll-back stretch with different protection techniques was used [5].

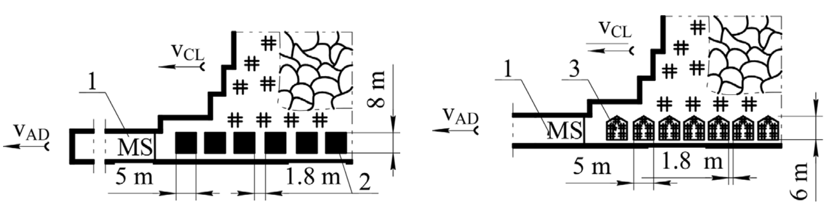
The increase in displacements of the roof on the working contour as it moves away from the cleaning face along the length of the excavation site was determined similar to [5, 10, 11]:

$$\Delta U = U_{(1-3)i} - U_{(1-3)i-1}. \qquad (2)$$

Table 1

Mining and geological conditions of experimental sites

Layer index	Angle of incidence α, degree	Thickness m, m	Side rocks			
			Roof		Sole	
			Direct	Dominant	Direct	Dominant
l_5	59	0.6	Clay shale with a thickness of up to $m=1.7$–2.5 m	Clay shale with a thickness of up to $m=10$ m	Clay shale, sandy-clay shale with a thickness of up to $m=2.0$ m	Sandstone with a thickness of up to $m=10$ m
l_6	59	0.62	Clay shale with a thickness of up to $m=1.1$ m	Clay shale with a thickness of up to $m=8$–10 m	Clay shale with a thickness of up to $m=0.8$–2.5 m	Clay shale with a thickness of up to $m=2.5$–4.4 m



a *b*

Fig. 1. Schematic of experimental sites: *a* — along the layer l_5 when coal pillars are used; *b* — along the layer l_6 when using rolled bundles made of wooden sleepers to protect the roll-back stretch; 1 — roll-back stretch; 2 — coal pillars; 3 — rolled bundles made of wooden sleepers; the height of a coal pillar is 8 m, the width is 5 m; the height of the rolled bundle is 6 m, the width is 5 m; V_{CL}, V_{AD} — speed of cleaning and preparatory operations; *MS* is a measuring station

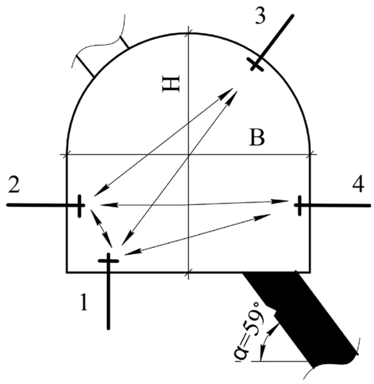


Fig. 2. Schematic of the measuring station for determining the displacements of side rocks on the contour of a roll-back stretch and the change in the cross-sectional area of preparatory workings along the length of the excavation section: 1, 2, 3, 4 – reference points; 1–2, 1–3, 1–4, 2–3 – displacement of reference points 1, 2 in the direction of 3, 4; *H* – height of workings, m; *B* – height of workings, m; α is the incidence angle of the formation, degrees

Application of the simple moving (sliding) average method [10, 11] with an averaging period of 2 is necessary for smoothing short-term fluctuations, i.e.:

$$\overline{\Delta U} = \frac{\Delta U_i - \Delta U_{i-1}}{2}. \qquad (3)$$

The relative change in the volume of protective structures δV during unloading of the coal rock massif was determined from the following expression [12]:

$$\delta V = (1-2\nu)\lambda, \qquad (4)$$

where ν is Poisson's ratio.

It should be noted that when considering the results of the research, the combination of experimental data on plots was meant to visualize the change in lateral rock displacements U (mm), the increase in displacements ΔU (mm), the cross-sectional area S (m^2) of a roll-back stretch along the length l (m) of the experimental site. Also, to visualize the change in the cross-sectional area S (m^2) depending on the relative deformation e and the relative change in the volume of protective structures δV when unloading the coal rock massif.

5. Results of investigating the stability of roll-back stretches taking into account the deformation properties of protective structures and their bearing capacity

5. 1. Results of investigating the stability of a roll-back stretch when protecting with coal pillars

Our studies on the stability of a roll-back stretch with the protection technique using coal pillars were carried out on the experimental section of the layer l_5 with length l=100 m behind the cleaning pit in the zone of active influence of mountain pressure.

Fig. 3 shows the plots of displacements of side rocks on the contour of a roll-back stretch with the protection technique using coal pillars along the length of the experimental section.

It was recorded that the displacement of the roof on the contour of a roll-back stretch (movement of reference points 1 and 2 in the direction of reference point 3) increases from U_{1-3}=80 mm and U_{2-3}=40 mm at distance l=10 m to the values U_{1-3}=520 mm and U_{2-3}=440 mm at distance l=100 m behind the cleaning pit (Fig. 3, curves 1, 2).

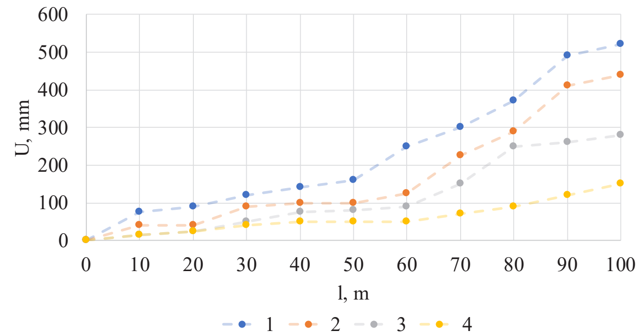


Fig. 3. Plots of displacements of side rocks *U* (mm) on the contour of a roll-back stretch of the layer l_5 for the case of protection technique using coal pillars along the length *l* (m) of the experimental section: 1 – displacement of reference points 1–3; 2 – displacement of rappers 2–3; 3 – displacement of reference points 2–4; 4 – displacement of reference points 1–4

The displacement of the sides of the working (movement of reference point 2 in the direction of reference point 4) reaches the values U_{2-4}=280 mm at distance l=100 m behind the cleaning pit (Fig. 3, curve 3). The rise of the rocks of the sole in a roll-back stretch (movement of reference point 1 in the direction of reference point 4) is U_{1-4}=150 mm at l=100 m behind the cleaning pit (Fig. 3, curve 4).

Fig. 4 shows the plots of change in the cross-sectional area and increase in the displacements of lateral rocks on the contour of a roll-back stretch along the length of the experimental site.

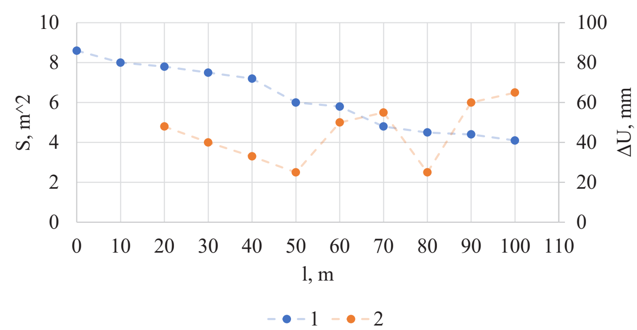


Fig. 4. Plots of change in the cross-sectional area *S* (m^2) and increase in the displacements ΔU (mm) of side rocks on the contour of a roll-back stretch when using a protection technique with coal pillars along the length *l* (m) of the experimental section: 1 – *S* (m^2); 2 – ΔU (mm)

Our plots (Fig. 4) demonstrate that the cross-sectional area of a roll-back stretch changes along the length of the experimental site. Such a change was recorded from S=8.5 m^2 at the junction of the mine with the preparatory workings (l=0) to S=4.2 m^2 at distance l=100 m behind the cleaning pit (Fig. 4, curve 1). At the same time, the increase in displacements of the roof in the area of $20<l<50$ m decreases from ΔU=44 mm to ΔU=22 mm, which indicates a static load on the coal pillar and an increase in its resistance as a result of unloading the coal rock massif (Fig. 4, curve 2).

In the area of $50<l<70$ m, the increase in displacement of the roof increases to the value $\Delta U=46$ mm (Fig. 4, curve 2). The coal pillar loses stability, the bearing capacity decreases. At distance $l\geq75$ m behind the cleaning hole, the increase in roof displacements increases from $\Delta U=25$ mm to $\Delta U=65$ mm at distance $l=98$ m (Fig. 4, curve 2). The complete destruction of the protective structure, the spilling of coal and stratified side rocks into the mine is noted. At the same time, the fastening of the preparatory workings is strongly deformed. The loss of the cross-sectional area of a roll-back stretch is 50 %.

5. 2. Results of investigating the stability of a roll-back stretch when protected by rolled bundles made of wooden sleepers

Our studies on the stability of roll-back stretches with the protection technique involving rolled bundles made of wooden sleepers were carried out on the experimental section of the layer l_6 with length $l=100$ m behind the cleaning hole in the zone of active influence of mountain pressure.

Fig. 5 shows the plots of displacements of lateral rocks on the contour of a roll-back stretch along the length of the experimental site.

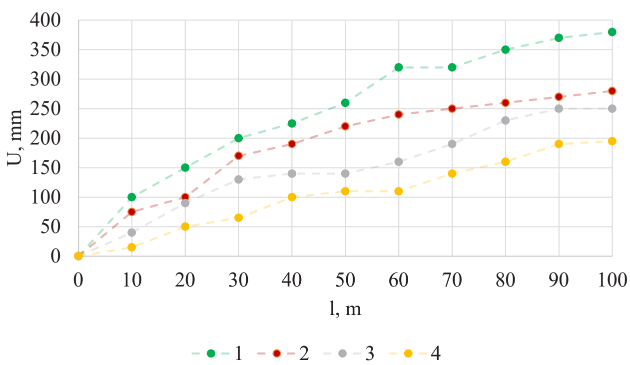


Fig. 5. Plots of displacements of lateral rocks ΔU (mm) on the contour of a roll-back stretch of the layer l_6 with the protection technique using rolled bundles made of wooden sleepers along the length l (m) of the experimental section: 1 – displacement of reference points 1–3; 2 – displacement of reference points 2–3; 3 – displacement of reference points 2–4; 4 – displacement of reference points 1–4

The maximum displacements of lateral rocks on the contour of the preparatory workings are recorded from the side of the roof. The magnitudes of movement of reference points 1 and 2 in the direction of reference point 3 at distance $l=100$ m behind the cleaning pit is $U_{1-3}=380$ mm and $U_{2-3}=280$ mm (Fig. 5, curves 1, 2). The minimum values of the movement of reference points at $l=100$ m were recorded when reference point 1 was moved in the direction of reference point 4 and is $U_{1-4}=190$ mm (Fig. 5, curve 4). The displacements of the sides of the workings were recorded in the direction of reference points 2–4 and, at $l=100$ m, equaled $U_{2-4}=230$ mm (Fig. 5, curve 3).

Fig. 6 shows the plots of change in the cross-sectional area and increase in the displacements of lateral rocks along the length of the experimental site.

It was recorded that the cross-sectional area of a roll-back stretch changes from $S=8.5$ m^2 (at $\lambda=0$) to $S=5.95$ m^2 at distance $l=100$ m behind the clearing pit (Fig. 6, curve 1). At the same time, on the $20\leq l\leq60$ m section, the increase in roof displacements decreases from $\Delta U=68$ mm to $\Delta U=37$ mm. On the $50\leq l\leq60$ m section, the increase in roof displacements increases to the value $\Delta U=52$ mm and then decreases to the value $\Delta U=10$ mm (Fig. 6, curve 2). This can be explained by the compaction of protective structures in the sections at $l=20$–50 m and $l=60$–80 m. After compaction of the rolled bundles from sleepers, on the section $l\geq70$ m, the cross-sectional area of a roll-back stretch practically does not change. Area losses are 30 %.

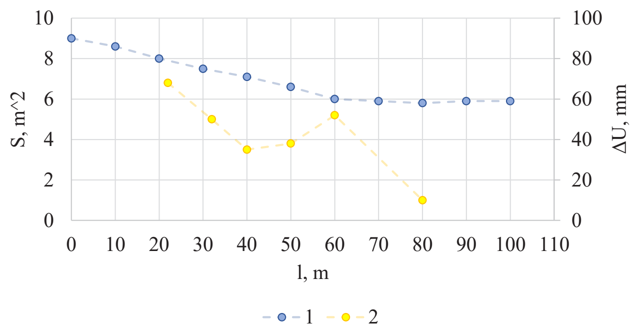


Fig. 6. Plots of change in the cross-sectional area S (m^2) and increase in the displacements ΔU (mm) of side rocks on the contour of a roll-back stretch with the protection technique using rolled bundles made of wooden sleepers along the length l (m) of the experimental site: 1 – S (m^2); 2 – ΔU (mm)

5. 3. Comparative assessment of the bearing capacity of protective structures to substantiate the stability of a roll-back stretch with different protection techniques

A comparative assessment of the bearing capacity of protective structures was performed on the basis of experimental data on the increase in displacements ΔU (mm) of side rocks on the contour of a roll-back stretch. The relative deformation of coal pillars and rolled bundles and the relative change in their volume δV when the coal rock massif was unloaded were also taken into account.

Fig. 7 shows the plots of change in the increase in displacements of lateral rocks on the contour of a roll-back stretch due to the relative deformation of protective structures.

When protecting a roll-back stretch by coal pillars and their deformation up to 25 %, the protective structures work under the mode of resistance growth. With an increase in the relative deformation $\varepsilon>0.25$, there is an increase in the displacement of the roof, which indicates the loss of stability of the protective structure. As the process of crack formation in coal pillars develops and their deformation exceeds 60 %, the increase in roof displacements increases until the complete destruction of the protective structure (Fig. 7, curve 1).

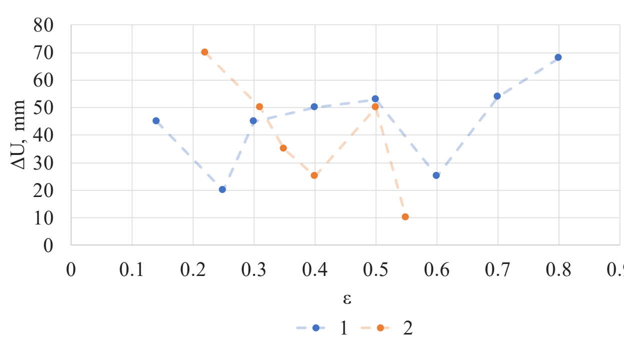


Fig. 7. Plots of change in the increase in displacements ΔU (mm) of side rocks on the contour of a roll-back stretch due to the relative deformation ε of the protective structure: 1 – coal pillars; 2 – rolled bundles from wooden sleepers

With the step-by-step deformation of rolled bundles made of wooden sleepers from 22 % to 40 % and from 50 % to 55 %, the increase in displacements of the roof constantly decreases. Such an interaction of side rocks with rolled bundles under their static load indicates the operation of protective structures under the mode of increasing resistance. The maximum compression of rolled bundles occurs at their relative deformation ε=0.55, after which the further movement of side rocks is limited (Fig. 7, curve 2).

Table 2 gives experimental data on changes in the deformation properties of protective structures along the length of the excavation site. Taking these data into account, the plots shown in Fig. 8–12 were constructed.

Table 2

Deformation properties of protective structures in preparatory mine workings, established on an experimental site with length *l* (m)

l, m	Protective structure			
	Coal pillars		Rolled bundles from sleepers	
	ε	δ*V*	ε	δ*V*
0	0	0	0	0
10	0.1	0.04	0.16	0.15
200	0.14	0.05	0.24	0.23
30	0.2	0.08	0.32	0.3
40	0.23	0.09	0.35	0.33
50	0.25	0.1	0.4	0.41
60	0.43	0.17	0.5	0.48
70	0.5	0.2	0.53	0.5
80	0.63	0.25	0.56	0.53
90	0.83	0.33	0.59	0.56
100	0.86	0.34	0.61	0.58

Fig. 8 shows the plots of changes in the cross-sectional area of a roll-back stretch with different protection techniques depending on the relative deformation of protective structures.

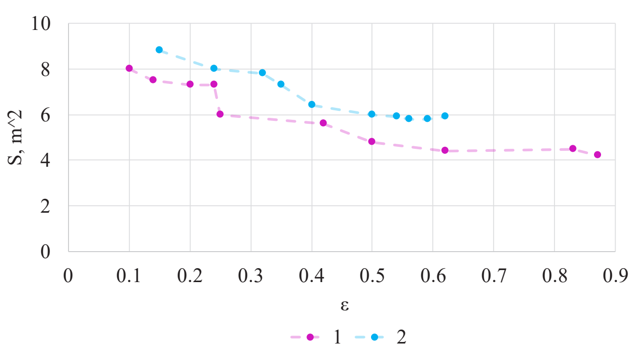


Fig. 8. Plots of change in the cross-sectional area S (m^2) of a roll-back stretch due to the relative deformation ε of the protective structure: 1 – coal pillars; 2 – rolled bundles from wooden sleepers

The plots (Fig. 8) demonstrate that when using the technique of protecting a roll-back stretch with coal pillars, the cross-sectional area changes from S=8.0 m^2 to S=7.5 m^2 when the protective structure is deformed to the value ε=0.23. When the deformation of a coal pillar is greater than ε>0.25, the section of the stretch decreases and, at ε=0.86, it is equal to S=4.2 m^2 (Fig. 8, curve 1). This condition of the preparatory workings is associated with the loss of stability of the protective structure and, over time, a decrease in the load-bearing capacity.

When protecting a roll-back stretch with rolled bundles made of wooden sleepers, the section of a roll-back stretch decreases from S=8.4 m^2 at ε=0.15 to S=5.95 m^2 at ε=0.6, i.e., as the protection structures are compacted (Fig. 8, curve 2).

A similar situation occurs when determining the influence of the relative change in the volume of protective structures dV on the change in the cross-sectional area of the mine S (m^2) as a result of unloading the coal rock massif. When protecting a roll-back stretch with coal pillars, the cross-sectional area of a roll-back stretch decreases after the loss of stability of the protective structure. The relative volume change from δV=0.1 to δV=0.34 is recorded in the process of loss of stability and destruction of the protective structure (Fig. 9, curve 1). Under such conditions, the condition of the roof deteriorates, and its stability is not ensured.

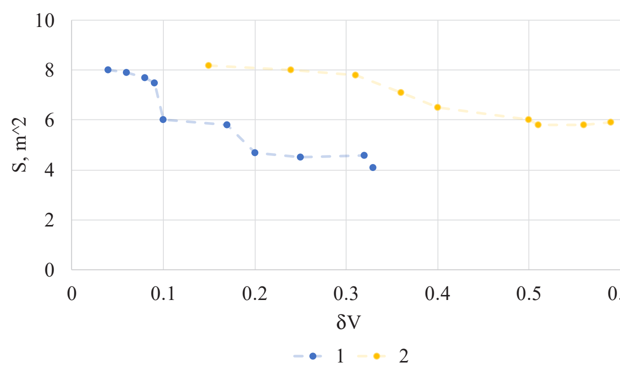


Fig. 9. Plots of change in the cross-sectional area S (m^2) of a roll-back stretch as a result of the relative change in the volume of protective structures δV: 1 – coal pillars; 2 – rolled bundles from wooden sleepers

When using rolled bundles made of wooden sleepers, the cross-sectional area decreases with a relative change in volume from δV=0.16 to δV=0.5 (Fig. 9, curve 2).

Fig. 10 shows the plots of relative change in the volume of protective structures due to their longitudinal deformation.

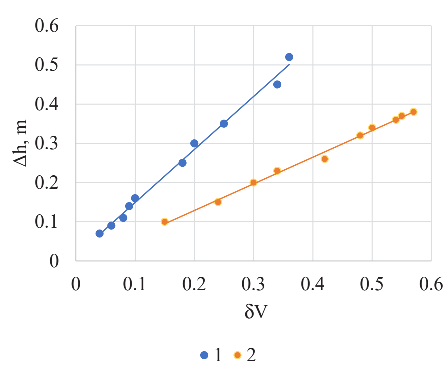


Fig. 10. Plots of relative change in the volume of protective structures δV due to their longitudinal deformation Δh (m) when the coal rock massif is unloaded: 1 – coal pillars; 2 – rolled bundles from wooden sleepers

For coal pillars, with an increase in longitudinal deformation from Δh=0.08 m to Δh=0.52 m, the relative change in the volume of protective structures is from $\delta V=0.04$ to $\delta V=0.34$ (Fig. 10, curve 1).

For rolled bundles made of wooden sleepers, when the longitudinal deformation changes from $\Delta h=0.1$ m to $\Delta h=0.37$ m, the relative volume change is from $\delta V=0.15$ to $\delta V=0.58$ (Fig. 10, curve 2).

Fig. 11 shows the plots of relative change in the volume of protective structures δV against their relative deformation.

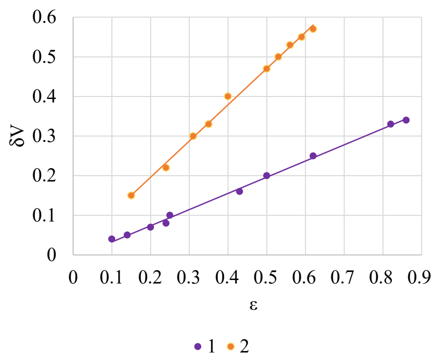


Fig. 11. Plots of relative change in the volume of protective structures δV against their relative deformation ε: 1 — coal pillars; 2 — rolled bundles from wooden sleepers

For coal pillars, the change in parameter δV is recorded from 0.04 to 0.34 with an increase in relative deformation from $\varepsilon=0.1$ to $\varepsilon=0.86$ according to a linear relationship (Fig. 11, curve 1). When using rolled bundles made of wooden sleepers, when the relative deformation changes from $\varepsilon=0.16$ to $\varepsilon=0.61$, the relative volume change is from $\delta V=0.15$ to $\delta V=0.58$ (Fig. 10, curve 2).

Fig. 12 shows the plots of relative change in the volume of protective structures in preparatory workings along the length of the excavation site.

It was established that when protecting workings with coal pillars, with an increase in the length of the excavation area from $l=10$ m to $l=100$ m behind the cleaning pit, the relative change in the volume of protective structures increases from $\delta V=0.04$ to $\delta V=0.34$ (Fig. 12, curve 1). There is an exponential dependence of the following type between the studied parameters:

$$\delta V=0.0344e^{0.0245l}, \tag{5}$$

with the coefficient of determination $R^2=0.96$ [13, 14].

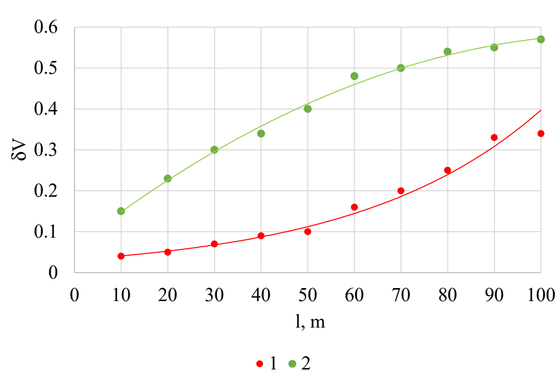


Fig. 12. Plots of relative change in the volume of protective structures δV along the length of the excavation site l (m): 1 — coal pillars; 2 — rolled bundles from wooden sleepers

When rolled bundles made of wooden sleepers are used for protecting the roll-back stretch, with an increase in the parameter l from 10 m to 100 m, the relative change in the volume of protective structures increases from $\delta V=0.15$ to $\delta V=0.58$ (Fig. 12, curve 2). There is a logarithmic relationship between the parameters l (m) and δV:

$$\delta V=0.1985\ln(l)-0.3499, \tag{6}$$

with the coefficient of determination $R^2=0.96$ [13, 14].

The established dependences characterize the deformation properties of protective structures associated with the process of their destruction or compaction, which makes it possible to estimate the load-bearing capacity of the structures.

6. Discussion of results of investigating the roll-back stretches taking into account the deformation properties of structures and their bearing capacity

Based on the results of mine research on the stability of a roll-back stretch under different protection techniques, a comparative assessment of the bearing capacity of protective structures was performed. To assess the bearing capacity of protective structures, experimental data on the displacements of lateral rocks and their growth on the contour of a roll-back stretch along the length of the excavation site were used. At the same time, the change in the cross-sectional area of a roll-back stretch was determined. This makes it possible to comparatively assess the bearing capacity of protective structures and the effectiveness of protection techniques in preparatory workings.

In order to assess the deformation properties of protective structures in the area affected by the cleaning works behind the cleaning pit and to determine their influence on the stability of preparatory workings, the value of their relative deformation and the relative change in volume were determined.

Analysis of the displacement plots of side rocks on the contour of the preparatory workings with different protection techniques (Fig. 3, 5) allows us to state that the deformation of the arch flexible fastening occurs most intensively on the side of the roof. This is confirmed by experimental data, which recorded the maximum movements of reference points 1 and 2 in the direction of reference point 3 (Fig. 3, 5, curves 1, 2). The loss of the cross-sectional area of a roll-back stretch along the length of the experimental site with the protection technique using coal pillars is 50 % (Fig. 4, curve 1) and 30 % when applying rolled bundles made of wooden sleepers (Fig. 5, curve 1).

When the resistance of a coal pillar increases (section $l=20$–50 m), at the relative deformation of $\varepsilon<0.25$, the increase in roof displacements from $\Delta U=44$ mm to $\Delta U=23$ mm occurs. The loss of the cross-sectional area is 30 % and is within the limits of the flexibility of the arch fastener installed in a roll-back stretch (Fig. 4, curves 1, 2). However, after the loss of stability by the protective structure ($l=50$ m, $\varepsilon=0.25$), its bearing capacity decreases. An increase in the displacement of the roof is also recorded, which continues until the complete destruction of coal pillars ($\Delta U=55$–68 mm, $l=98$ m, $\varepsilon=0.8$) (Fig. 4, curve 2; Fig. 7, curve 1). Under such conditions, the loss of stability by a roll-back stretch is 50 % (Fig. 4, curve 1), and the level of the threat of roof collapse after delamination is approaching a critical state.

When using rolled bundles made of wooden sleepers and increasing the relative deformation of protective structures from $\varepsilon=0.22$ to $\varepsilon=0.4$ (section $l=20$–50 m), the increase in roof displacements decreases from ΔU=70 mm to ΔU=25 mm. After the second stage of compaction (section l=50–60 m), when the relative deformation of the protective structure changes from ε=0.4 to ε=0.5, the increase in roof displacements increases to the value ΔU=50 mm. At distance $l \geq 60$ m, there is an increase in the resistance of rolled bundles, due to which the increase in roof displacements decreases to the value ΔU=10 mm (l=80 m) (Fig. 6, 7, curve 2). Under such conditions, the movement of side rocks on the contour of a roll-back stretch is limited, and their collapse into the working becomes impossible.

Analysis of the plots of change in the cross-sectional area S (m^2) of a roll-back stretch due to the relative deformation e and change in the volume of protective structures δV indicates a significant loss (50 %) of the cross-sectional area after the loss of the load-bearing capacity of coal pillars (ε=0.25–0.86) (Fig. 8, curve 1). When using rolled bundles made of wooden sleepers, the deformation of the arch attachment along the length of the notch section occurs gradually. After the protective structure is sealed, at $\varepsilon>0.55$, the deformation of the fastening stops. The loss of cross-sectional area is 30 % (Fig. 8, curve 2). This situation is explained by the relative change in the volume of protective structures along the length of the excavation site (Fig. 9, curves 1, 2).

For coal pillars, after loss of stability (Fig. 7, curve 1), with an increase in longitudinal deformation Δh (m), relative change in volume δV (Fig. 11, curve 1), their destruction and reduction in bearing capacity occur. As a result of such processes in the coal-bearing massif, an increase in the displacements of roof increases (Fig. 7, curve 1), and the cross-sectional area decreases (Fig. 8, 9, curve 1).

For rolled bundles made of wooden sleepers, the increase in longitudinal deformation Δh (m) contributes to the compaction of protective structures due to a relative change in their volume (Fig. 11, curve 1). After that, the increase in displacements of the roof decreases (Fig. 7, curve 2), and the loss of the cross-sectional area of a roll-back stretch stops (Fig. 8, 9, curve 2).

It was experimentally established that in the excavation area of a coal mine at the interval $0<l<100$ m behind the cleaning pit, there is a functional dependence between the length l (m) of a roll-back stretch and the relative change in the volume of protective structures ((5), (6)). With the protection technique involving coal pillars, an exponential dependence is recorded between the studied parameters (expression 5), and with the protection technique with rolled bundles made of wooden sleepers – a logarithmic dependence (expression 6). The determining factors of the established dependences are the increase in lateral rock displacements ΔU (mm) on the contour of a roll-back stretch and the relative deformation of protective structures e during their compression under conditions of unloading the coal rock massif. The presence of such dependences makes it possible to estimate the bearing capacity of protective structures in preparatory workings in the zone of active influence of mountain pressure.

The comparative characteristic of the bearing capacity of protective structures for roll-back stretches is based on a comprehensive study on the stability of preparatory workings, in contrast to [1, 2, 4]. At the same time, the convergence of side rocks on the contour of the preparatory workings and the relative change in the volume of protective structures during unloading of the coal rock massif were taken into account. This result makes it possible to estimate the change in the cross-sectional area of the workings, its overall dimensions along the length of the excavation site.

Thus, having certain physical-mechanical and deformation properties, rigid (coal pillars) and flexible (rolled bundles made of wooden sleepers) protective structures play the role of load-bearing structures. Such structures in the worked-out space of the coal rock massif along the length of the excavation site ensure the stability of preparatory workings. Coal pillars under conditions of unloading the coal rock massif temporarily limit the convergence of side rocks around the workings. When using this protection technique, preparatory workings at a considerable distance from the cleaning hole require repair.

Rolled bundles made of wooden sleepers, when the maximum compaction values are reached, as evidenced by the relative change in their volume and the decrease in the increase in the displacements of side rocks on the contour of the workings, ensure a smooth gradual deflection of the roof. Under such conditions, the collapse of side rocks becomes impossible, and the loss of the cross-sectional area is reduced to minimal values.

The results of our research could be used in coal mines with steep beds to prevent side rock collapses. A comparative assessment of the bearing capacity of protective structures is necessary to justify the choice of the protection technique for preparatory mining workings.

The established dependences (Fig. 12) make it possible to estimate the bearing capacity of protective structures in the zone of active influence of mountain pressure and a distance of up to 100 m behind the cleaning face in the excavation area of the coal mine. Such a limitation must be taken into account in the practical application of the results.

In further research, it is expedient to take into account the influence of changes in the bearing capacity of protective structures on the frequency of failures of arched flexible fasteners along the length of the extraction section. A better qualitative assessment of the load-bearing capacity of protective structures should take into account the change in their stiffness and its effect on the stability of roll-back stretches. This will make it possible to devise measures to preserve the operational condition of preparatory workings and improve the safety of miners in coal mines.

7. Conclusions

1. When applying the protection technique for a roll-back stretch using coal pillars under conditions where their relative deformation is $\varepsilon>0.25$, and the relative change in volume is $\delta V>0.1$, there is a loss of stability of protective structures. After the reduction of the load-bearing capacity of protective structures, there is an uncontrolled increase in the displacements of lateral rocks on the contour of the preparatory workings. Such a process over time leads to their collapse. At distance $l>50$ m behind the cleaning pit along the length of the excavation section, the increase in displacements reaches values of $U \geq 45$–50 mm, due to which the arch fastening in the preparatory workings is deformed. When the relative deformation of the coal pillars is $\varepsilon \geq 0.6$–0.8, the loss of the cross-sectional area of a roll-back stretch reaches 50 %, and the level of threat of roof collapse in the mine is approaching a critical state.

2. When applying the protection technique for a roll-back stretch using rolled bundles made of wooden sleepers, when their relative deformation is $\varepsilon>0.21$, and the relative change in volume is $\delta V>0.16$, conditions are created at which the protective structures are gradually compacted. The use of such

protective structures makes it possible to limit the movement of side rocks on the contour of the preparatory workings. At distance $l \geq 60$ m behind the cleaning cut along the length of the excavation section, the increase in lateral rock displacements reaches minimum values of $\Delta U \leq 10$ mm, and the loss of the cross-sectional area of a roll-back stretch is 30 %. Under such conditions, the operational condition of the roll-back line along the length of the excavation section is ensured.

3. On the basis of the established deformation properties of coal pillars and rolled bundles made of wooden sleepers, a comparative assessment of their bearing capacity was performed. The determining factors of this dependence are the relative deformation of protective structures ε and the relative change in volume δV, which are recorded when the coal rock massif is unloaded. The operational condition of roll-back lines using the method of protecting by coal pillars is ensured within the limits of their deformation resource, when the relative deformation of the protective structures is in the range of values $0 < \varepsilon < 0.25$, and the relative change in volume $\delta V < 0.1$. The transition of these levels is associated with the destruction of protective structures, the creation of conditions for the collapse of lateral rocks in workings and the loss of its stability. Preservation of the operational state of the roll-back lines with the protection technique using rolled bundles made of wooden sleepers is ensured after the gradual compaction of protective structures, when their relative deformation is within $0.21 < \varepsilon < 0.55$, and the relative change in volume is $0.15 < \delta V < 0.58$. Under such conditions, the resistance of protective structures increases, and the movement of side rocks is limited, which makes it possible to create safe working conditions for miners in the preparatory workings of the excavation area.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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