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Ensuring the excavation workings stability when developing excavation sites of flat-lying coal seams by three workings

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Abstract. On the basis of analysis of mining plans and field studies at mines of JSC SUEK-Kuzbass, it is shown that in conditions of increasing the size of excavation columns during the development of flat-lying coal seams the stress-strain state of the rock mass along the workings length changes significantly. The necessity of predicting the stress-strain state at the design stage of the workings timbering standards, as well as subsequent monitoring of the workings roof state and its changes in the mining operations using video endoscopes, is noted. The results of numerical studies of the stress-strain state of the rock mass during the development of excavation sites by three workings for various combinations of width of the pillars between the workings for mining-geological and mining-technical conditions of the "Taldinskaya-Zapadnaya-2" mine are provided. The stresses in the vicinity of the three workings are compared with the values obtained during the development of the excavation sites by double drift. A set of recommendations on the choice of the location of the workings, the width of pillars, timbering standards that ensure the stable condition of the workings throughout the entire service life at the minimal losses of coal in the pillars is presented.

***Keywords*:** coal seams; underground mining; excavation workings; stability; pillars; stress-strain state

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Introduction. The transition to the development of excavation sites of flat-lying coal seams with three workings on each side of the excavation column [1] to maintain a high level of productivity and maximize the use of the potential of modern stoping equipment [2] will ensure the competitiveness of underground coal mining [3]. There is a tendency to increase the size of excavation sites: lengths of longwalls up to 400 m and more, columns – up to 8 km [4]. In order to ensure consistently high coal production rates, timely reproduction of the stoping front and a stable state of workings and pillars are necessary [5]. The development of excavation sites by three drifts significantly expands the possibilities of using the potential of modern stoping equipment [6], but at the same time the volume of tunneling work increases. In such conditions, ensuring the stability of workings [7] during their entire service life, excluding additional downtime of stoping equipment and the cost of repairing workings, becomes particularly relevant [8].

In the coal mines of Russia, the system of long-pillar mining is mainly widespread [9] with the development of excavation sites by double drifts separated by remnant chain pillars. The workings are carried out in a rectangular cross-section, roof bolting is used as the main type of support [10]. The use of three workings with two rows of chain pillars between them allows to use different options for the width of the pillars and their location in the rock mass [11]. At the same time, the parameters of the pillars should ensure the operational condition of the workings during the entire service life, but not lead to a significant increase in coal losses in the pillars compared to the development by double drifts. Thus, the geomechanical justification of the parameters of the pillars and workings during the development of excavation sites by three drifts is an urgent scientific and practical task.

Methodology. To determine the parameters of the pillars [12] and the timbering standards of the workings during the transition to the development of excavation sites by three drifts, a review of the world experience of working out flat-lying coal seams with long faces with such a development scheme was carried out [13]; full-scale studies of the state of workings and inter-column pillars at the mines of JSC SUEK-Kuzbass from 2016 to 2019 were carried out during the development by double drifts and numerical studies by the finite element method implemented in the Ansys software package.

Development of excavation sites by double drifts is the main one in the mines of Russia. The analysis of the mining plans of the mines of JSC SUEK-Kuzbass ("Komsomolets", "Polysaevskaya", "Taldinskaya-Zapadnaya-1", "Taldinskaya-Zapadnaya-2", "Named after A.D.Ruban", "Named after V.D.Yalevskyi", "Named after S.M.Kirov") showed a general trend of increasing the size of excavation sites [14]. Thus, the length of the excavation pillars along the seam 52 of the mine "Named after V.D.Yalevskyi" over the past 14 years has increased from 2300 (2005) to 4700 m (2019); the length of the longwall during this period has increased from 140 to 400 m [15].

Previous studies have shown [16, 17] that the realization of the potential of modern high-performance stoping equipment requires a change in the scheme traditionally used in Russia for the development of excavation columns with double drifts [18], and a transition to the development of excavation sites with three workings is also necessary (Fig.1). This makes it possible to use the potential of modern equipment more fully when working out large-sized excavation columns [19], increases the ability to control gas emission and the rock mass state at the excavation sites. At the same time, the issues of ensuring the stability of excavation workings and pillars during the service life require additional study.

The efficiency of maintaining the excavation workings adjacent to the stoping faces is influenced by mining-geological and mining-technical factors [20]: the presence of areas of high rock pressure zones, tectonically stressed and unloaded zones, etc. [21]. In such zones, the structure of the roof rocks changes, fracturing increases [22], which can lead to a violation of the workings stability. According to the analysis, at six of the seven operating mines of JSC SUEK-Kuzbass, the maintenance of excavation workings is complicated by the presence of increased rock pressure zones formed as a result of the mining of contiguous seams. With large sizes of excavation sites, the stress-strain state (SSS) of the rock mass varies significantly along the length of the excavation column [23], therefore, the forecast of the SSS of the rock mass and its changes in the course of mining operations is necessary for the correct choice of the timbering standards parameters of the workings.

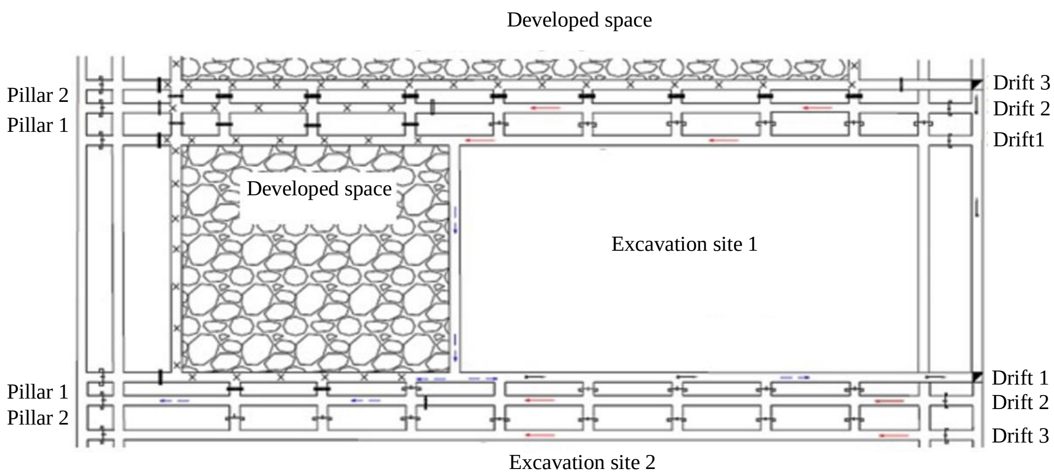


Fig.1. Development of excavation sites by three workings

Field studies. The stability of the workings [24], fixed by roof bolting [25], largely depends on the fracturing [26] and interlayers of roof rocks, which can be assessed using video endoscopic studies [27], which were carried out in the workings of the mines “Named after S.M.Kirov”, “Taldinskaya-Zapadnaya-1”, “Named after V.D.Yalevsky”, “Named after A.D.Ruban”, “Kotinskaya”, “Komsomolets”, “Taldinskaya-Zapadnaya-2”, adjacent to stoping faces, when preparing excavation sites by double drifts [28]. In total, from 2016 to 2019, more than 50 boreholes with a diameter of 30 mm and a length of 7-8 m were studied using video recording. The drilling site of the boreholes was located in the center of the cross-section of the workings so that the mouth of the borehole was at the level of the roof (Fig.2).

According to research, on average fractured rocks [29] extend to a depth of no more than 1.5 m from the mouth of the borehole, which is approximately 20 % of its length. In the presence of a false roof, a zone of intensely fractured rocks up to 0.5 m in size is observed. The main part along the length of the borehole (60-70 % of the total length) are monolithic rocks, including those with a helical orientation of furrows on its walls. A small part falls on fractured, overflowing and interlayer rocks (10-20 %).

As the stoping face moves, the SSS of the rock mass around the working can change significantly [30]. Depending on the position of the stoping face relative to the measuring boreholes, it is necessary to conduct video filming in the zones: before/after the approach and at the time of the influence of the bearing pressure of the longwall [31]; residual stresses after the approach of the second longwall [32]. The data obtained as a result of a periodic survey of the workings condition and a numerical assessment of the SSS of the rock mass in the periods under consideration will allow to develop criteria for ensuring the stability of workings for specific conditions, which can later be used in real-time monitoring systems of the state of workings.

Numerical studies. To assess the stability of workings during three-drift development of excavation sites, numerical studies of the SSS of the rock mass and its changes were carried out [33] with the development of mining operations using the finite element method implemented on the basis of the Ansys software package [34]. The research was carried out for a volumetric problem using an elastic-plastic model. The impact of loads on the rock mass was taken into account using the Coulomb – Mohr model. The conditions of the problem allow to obtain the values of SSS parameters as close as possible to the results of field studies of geomechanical processes, taking into account the

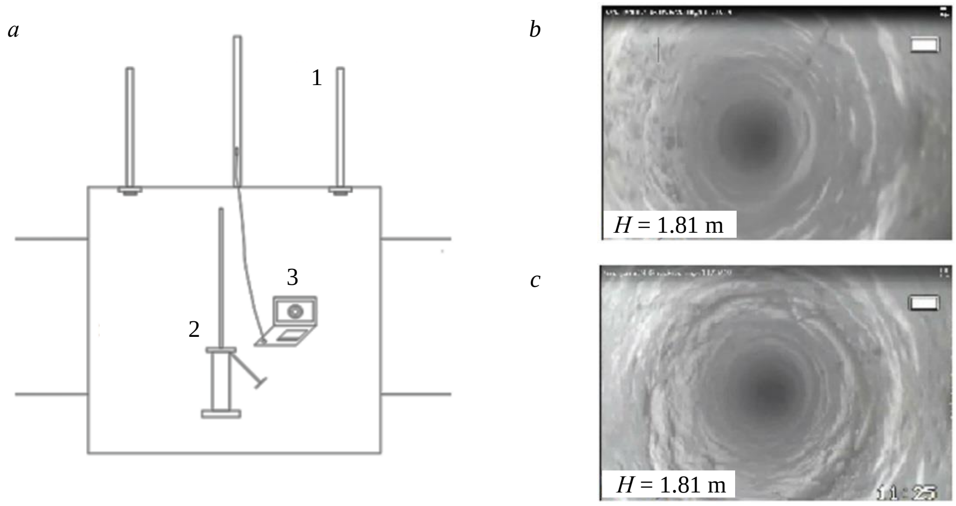


Fig.2. The scheme of the video endoscopic study (*a*) and a fragment of the results of the roof studies workings using a video endoscope: images of the borehole before the bearing pressure influence of the longwall (*b*) and in the zone of bearing pressure influence (*c*)

1 – roof bolting; 2 – manual drilling rig; 3 – video endoscope

mining and geological conditions of the host rock mass and the parameters of the development of the excavation site [35]. The boundary conditions of the problem are accepted in accordance with the gravitational type of geomechanical development conditions and are presented as restrictions of normal displacements at the boundaries of the computational domain: the upper boundary of the model corresponds to the day surface, is free from external loads and satisfies the condition $\sigma_y(0, x, z) = \gamma qH = 0$ at the lower and lateral boundaries, respectively, the vertical and horizontal components of the displacement vector and tangential components of the stress tensor were assumed to be zero. The volumetric force γq reflects the weight parameter with which the rock mass acts on the horizontal lower boundary of the model. The contacts of rocks with different characteristics are in rigid coupling relative to each other, and the contours of open outcrops (workings) are free from external loads ($\sigma_n = \tau_n = 0$).

When preparing excavation sites by three drifts (Fig.1) in the considered mining and geological conditions ("Taldinskaya-Zapadnaya-2" mine), different variations of the system "excavation site 1 (ES1) – drift 1 (D1) – pillar 1 (P1) – drift 2 (D2) – pillar 2 (P2) – drift 3 (D3) – excavation site 2 (ES2)" are possible, the qualitative description of which is presented in Table 1.

Table 1

Options for the location of workings in the ES – D3 system

The ratio of the pillars size	Pillar 1 < Pillar 2	Pillar 1 = Pillar 2	Pillar 1> Pillar 2
The width of the pillar, m	8.28 и 16.52	12.4	16.52 и 8.28
Total width of the pillars, m	30	30	30
Working width, m	5.2	5.2	5.2

The model of the rock mass includes: the coal seam 69, the host rocks, the developed space and the workings outlining the excavation site (Fig.3). The main physical and mechanical properties of the seam and the host rocks correspond to the properties of the real rock mass in the conditions of the "Taldinskaya-Zapadnaya-2" mine.

For numerical studies, three variants of the model were built with a different number of excavation workings and their location in the rock mass. The model with two excavation drifts (Fig.4, *a*) reflects the SSS of the rock mass (the main acting vertical stresses) during the development of flat-lying coal seams using the most common scheme for the development of excavation sites in the mines of Russia. The variant of development by three drifts (Fig.4, *b*) is implemented by placing an additional working while preserving the size of the pillar [36] used in the development of double drifts. Three cases of drift placement in a pillar having a total width of 30 m are considered (Table 2). Each model allows to consider three stages of maintaining drifts in the rock mass over time and evaluate the SSS of the rock mass around the excavation workings. The research was carried out for the depth of mining operations 550 m.

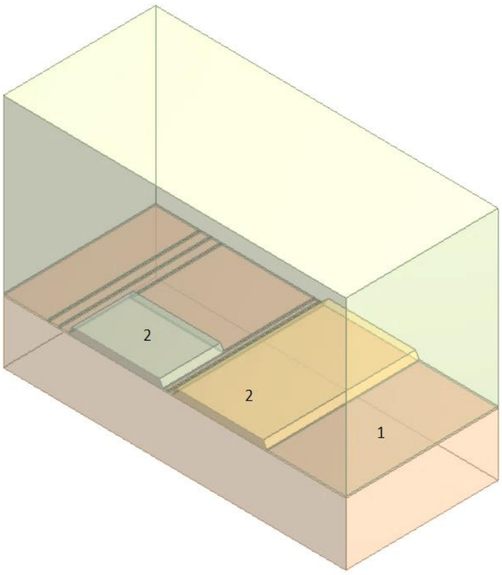


Fig.3. Rock mass model
1 – coal seam 69; 2 – developed space

In the Table 2 shows the plots of vertical stresses obtained in three main cross-sections: outside the zone of influence of the longwall bearing pressure (A-A), in the zones of the longwall bearing pressure (B-B) and the residual bearing pressure behind the longwall (C-C).

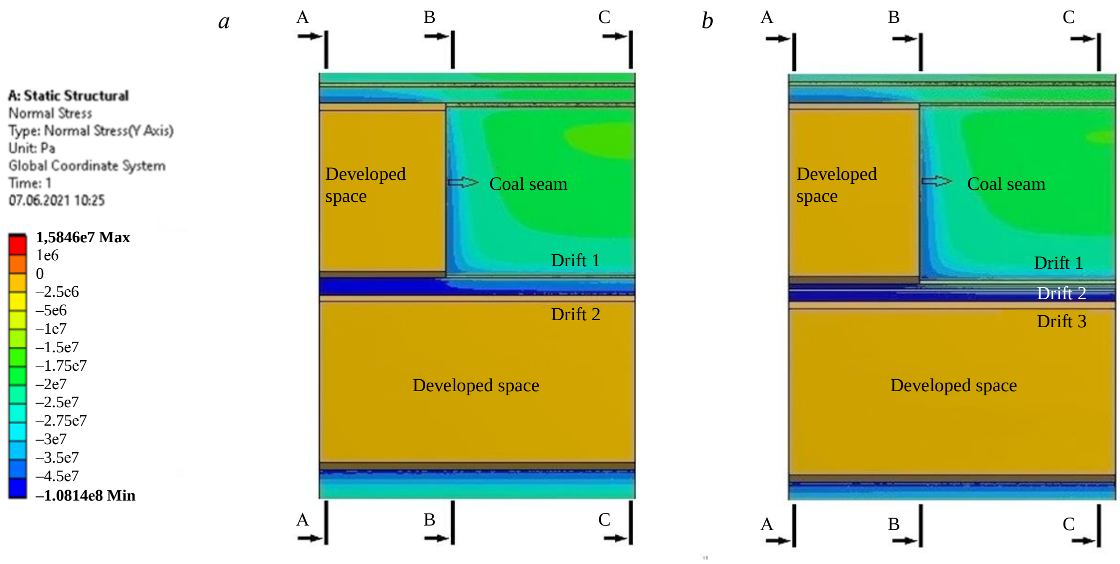
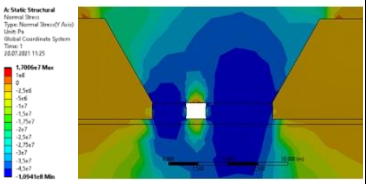
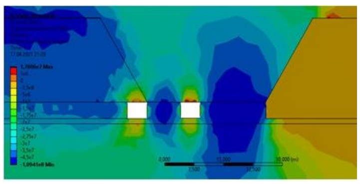
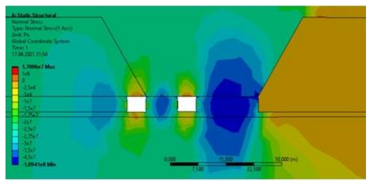
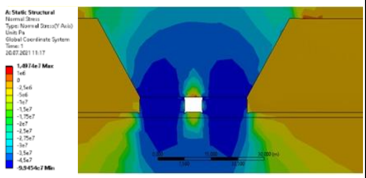
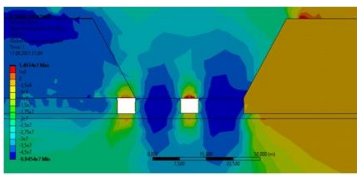
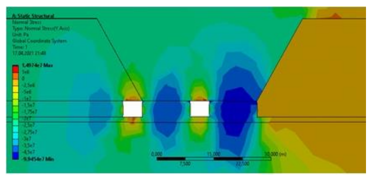
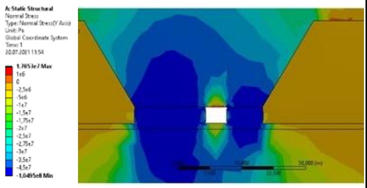
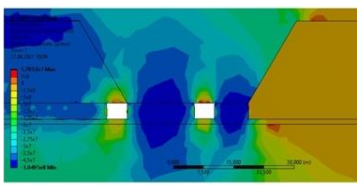
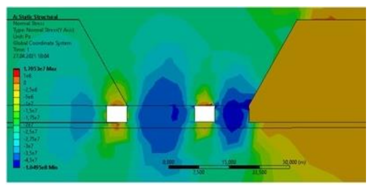
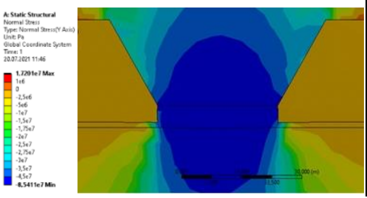
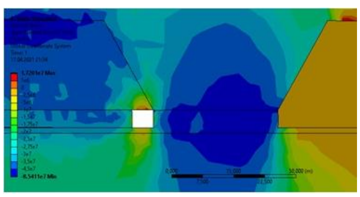
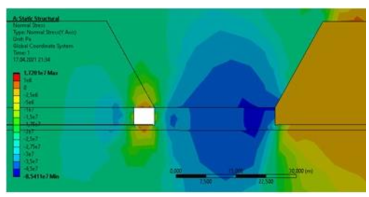


Fig.4. Results of studies of the stress state of the rock mass in the cross-sections under consideration along the 69 seam during the development of excavation sites: *a* – by double drifts; *b* – by three workings

Table 2

Vertical stress fields in three main cross-sections

Development scheme	Cross-sections		
	A-A	B-B	C-C
Three-drift. The width of the pillars is 8.28 and 16.52 m			
Three-drift. The width of the pillars is 12.4 m			
Three-drift. The width of the pillars is 16.52 and 8.28 m			
Double-drift. The width of the pillar is 30 m			

As can be seen from Table 2, the stresses in the rock mass around the workings increase from 7 to 12-14 MPa as the excavation area is worked out. The values of the main vertical acting stresses in the roof, relative longitudinal deformations and displacements occurring around the workings are presented in Tables 3, 4.

Table 3

SSS of the rock mass along the contour of the workings on the 69 seam during the development by three workings

Parameter	The width of the pillars								
	8.28 and 16.52 m			12.4 m			16.52 and 8.28 m		
Cross-section	A-A	B-B	C-C	A-A	B-B	C-C	A-A	B-B	C-C
Stresses in the roof, MPa	11.54	8.66	7.012	10.43	10.73	7.05	11.29	9.22	8.10
Stresses in the floor, MPa	10.76	8.77	5.91	7.23	7.65	5.14	8.84	8.9	5.42
Relative longitudinal deformations ε_x	0.0018	0.0011	0.0009	0.0011	0.0010	0.0006	0.0017	0.0009	0.0008
Relative longitudinal deformations ε_y	0.0179	0.0128	0.0093	0.0091	0.0070	0.0059	0.01975	0.01490	0.0126
Relative longitudinal deformations ε_z	0.0012	0.0007	0.0005	0.0008	0.0006	0.0003	0.0011	0.0007	0.0004
Total displacements, m	0.162	0.161	0.154	0.177	0.174	0.167	0.168	0.163	0.156
The ratio of the acting vertical stresses to the ultimate strength of the roof rock	0.34	0.25	0.20	0.30	0.31	0.21	0.33	0.27	0.23

Table 4

SSS of the rock mass along the contour of the workings on the 69 seam during the development by two workings

Parameter	The width of the pillar is 30 m	
Cross-section	B-B	C-C
Maximum stresses in the roof, MPa	8.63	5.36
Relative longitudinal deformations ε_x	0.0007	0.0005
Relative longitudinal deformations ε_y	0.0122	0.0098
Relative longitudinal deformations ε_z	0.00004	0.00002
Displacements, m	0.161	0.154
The ratio of the acting vertical stresses to the ultimate strength of the roof rock	0.25	0.16

According to the presented models, the condition of rocks in the roof and floor at a distance of 2.5 m from the contour of the workings was assessed. During the development by three drifts, the stresses formed around the additional working were studied. The obtained values allow to determine the stresses formed around the additional working and to assess the condition of the roof and floor rocks throughout the entire service life of the working (Fig.5).

The displacement of the middle working towards the stoping face ensures a reduction in the influence of the bearing pressure on the third working on average by 10-20 %. At the same time, reducing the size of the pillar between the drift adjacent to the longwall and the drift being extinguished behind the stoping face slightly increases the operating stresses. When comparing the stresses in the vicinity of the three workings with the values obtained during the development of the excavation sites by double drifts, an increase in the maximum stress level in the presented cross-sections by 10-13 % is observed.

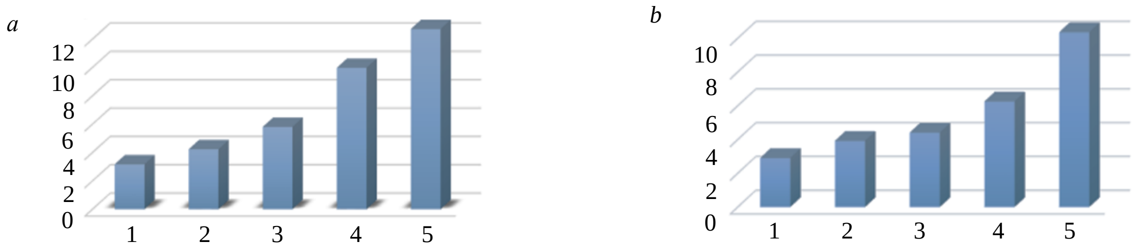


Fig.5. Vertical stresses in the roof (*a*) and floor (*b*) of additional working

1 – before the beginning of the bearing pressure influence of the longwall; 2 – in the zone of the bearing pressure influence of the first longwall; 3 – in the zone of the residual bearing pressure of the first longwall; 4 – in the zone of the bearing pressure of the second longwall; 5 – in the zone of the residual bearing pressure of the second longwall

Conclusion. The increase in the size of excavation sites at the mines of JSC SUEK-Kuzbass leads to a significant change in the conditions for maintaining workings along the length of the excavation column. For the conditions of 69 seam of the "Taldinskaya-Zapadnaya-2" mine at depths up to 550 m with a length of excavation columns up to 4700 m, up to 3-5 sections along the length of the column can be identified, the conditions for maintaining workings in which vary from favorable to extremely difficult.

When shifting to the development of excavation sites by three workings, the most preferable option from the point of ensuring their stability is the option with the use of pillars of different widths with a smaller pillar working in a flexible mode located at the developed space of the worked out column.

Development of excavation sites by three workings is possible without increasing coal losses in comparison with development by double drifts, i.e. with the use of pillars between workings, the total width of which does not exceed the width of the inter-drift pillar when preparing double drifts. From the point of maintaining the workings, the changes in the SSS of the rock mass are insignificant (the increase in the stress level does not exceed 13 %).

When switching to the development of excavation sites by three workings, it is necessary to strengthen the barring of the workings walls with roof bolting, since the destruction of the workings walls from the side of the pillar is possible, followed by a violation of the roof stability.

To prepare recommendations for making additions to the instructions for roof bolting workings at coal mines, mine studies of the stability of workings and pillars at excavation sites are required, prepared using three workings on each side of the column, including endoscopic studies of the roof condition at the different stages of excavation site operation.

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