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Modeling the influence of rolled profile strengtheners on the arch support load-bearing capacity

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Abstract

Purpose. Increasing the load-bearing capacity of metal arch supports used to maintain the mine workings due to strengthening in places with the highest bending moment.

Methods. The stress-strain state of the rock mass and support is analyzed using the ANSYS software package. The problem is studied in three variants: a support without strengtheners, a support with one strengthener in the area with the maximum bending moment, and a support with three strengtheners in the areas with the highest bending moments. To determine the bending moments and normal forces in a three-section metal arch support, the finite element method is used for specific and existing conditions, which is followed by the selection of the required standard size of the support.

Findings. The conducted research gives reasons to believe that the proposed variant for increasing the load-bearing capacity of the support, made from a special replaceable rolled profile (SCP), can significantly improve the state of mine workings. Obviously, the proposed solution can be applied not only to arch supports, but also to other structures of rolled metal support.

Originality. The pattern of changes in the values of internal forces arising in metal arch frame supports, depending on the deformation characteristics, the location of the strengtheners, as well as on the geometric characteristics of the mine working and the ratio of lateral and vertical loads on the support, has been determined.

Practical implications. The proposed variant for increasing the load-bearing capacity of the support can be used to sustainably maintain mine workings in difficult mining-geological conditions of the Karaganda Coal Basin mines.

Keywords: *mine working, rock pressure, arch support, deformation, resistance, bending moment, strengthener, special replaceable profile*

1. Introduction

Increasing the stability of mine workings is one of the most important tasks in the underground mining of mineral deposits [1]-[3]. Sufficiently reliable operation of metal support at shallow and medium depths is explained by the large safety margin in its structure. In this case, underestimation of some factors with small rock pressure manifestations does not significantly influence on the support operation [4]. At great depths, most metal fastening structures operate at the limit of their capabilities, and design errors immediately affect the stability of the fastening system [5]. Steel fastening structures are calculated, as a rule, for a predetermined load, the value of which is determined according to one of the rock pressure hypotheses or according to mine measurements. The side rock pressure in this case is presented in the form of vertical and lateral load. The vertical load is taken to be uniformly distributed, and the lateral load is taken to be uniformly distributed or according to the trapezoid law. In this case, it is assumed that between the fastening structure and the rock mass surrounding it, continuous contact is maintained along the entire perimeter [6]-[8].

With the deepening of mining operations in the Karaganda Coal Basin, the mining-geological and mining-technical conditions became more complicated. In addition, the size of the bearing pressure zones in the vicinity of stopes and the intensity of rock pressure manifestations in mine workings within the extraction fields have significantly increased [9]. More than 60% of the host rocks in the immediate roof of the coal seams of underground mine workings in the Karaganda Coal Basin mines are in an unstable state, and the immediate bottom rocks have a tendency to heaving [10]. Therefore, refastening of maintained mine workings reaches a two-threefold value during the production life, since more than 25% of them are annually repaired and a set of works is performed to increase their stability with significant material and labor costs.

Also, with an increase in the depth of mining, the labor intensity of maintaining mine workings has sharply increased (from 500 to 800 m – from 550 to 2000 people/shift per 1 km). This can be explained by the fact that the area of the bearing pressure manifestation, in addition to the stope face, also extends to the zones adjacent to the edge areas of the stope, where the extraction workings are located [11], [12].

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At present, one of the main goals of underground coal mining is the efficiency and sustainability of mining enterprises, including by maintaining mine workings in operating condition and reducing the cost of this, which, of course, affects the cost of coal produced [13], [14].

The area of the Karaganda Coal Basin is 3.6 thousand km^2. Its industrial centers are Karaganda, Saran, Shakhtinsk and Abay cities. According to 2018 data, the explored coal reserves, calculated to a depth of 600 m, in some areas – up to 800-900 m, amount to 9.3 billion tons, preliminary estimated – 5 billion tons (1984). The Karaganda Coal Basin is 120 km long and 30-60 km wide. In the south and west, the basin is bounded by fault zones, in the north and east by an erosional truncation of productive hard coal deposits [15]-[17].

In the Karaganda Coal Basin, 50% of all coal seam roofs are predominantly of medium strength; the share of low-strength ones is 25%; share of unstable is 20%; stable – 5%. Most of the mines developing coal seams at depths of 200-500 m are practically dry. Bottom rocks: 45% are of medium-strength of all coal seams; 20% are low-strength rocks; 20% are unstable; 15% are stable [18], [19].

General characteristic of the Karaganda Coal Mines Complex is presented in Table 1. The coal-bearing deposits of the Lower Carboniferous period form two closed troughs, separated by a complex anticlinal-type structure; low-angle bedding prevails, complicated by numerous disturbances in the form of overthrust faults and normal faults.

Table 1. Characteristics of the Karaganda Coal Mines Complex

Indicators	Values
Area, thousand km	3.6
Average thickness of mined-out seams, m	2.28
Seam dip angle – % flat-lying	90
Working seams/total	20/69
Geological reserves, billion tons	65
Balance reserves, billion tons	9.7
Average depth of mining, m	500-550
Gas-bearing capacity, m^3/t	55-40
Side rocks	medium stability and unstable
Production volume mln t/year	13

At present, only combine driving of mine workings is used in the Karaganda Coal Basin mines, and the dangerous, labor-intensive drilling and blasting method is excluded. The process of fastening the mine workings in the total cycle of driving takes from 25 to 50% of the time and labor costs. It is one of the main factors that reduce the pace of mining operations and the productivity of miners.

Supports made of heavy special rolled profiles (arch support), in conditions of a significant stress state of the rock mass, do not provide the necessary stability and non-repair maintenance of mine workings. The share of other supports used in the construction of horizontal and inclined mine workings is not so significant and amounts to 8.6% for monolithic concrete supports, 2.9% for tubing supports, 1.1% for roof-bolt supports, 1.1% for reinforced concrete prop stays with metal cap boards, and 0.7% for wooden supports.

Technical-and-economic indicators of fastening the mine workings with various types of support used in the mines of the Karaganda Coal Basin are presented in Figure 1. The main indicators on the support types used in the Karaganda Coal Basin mines are presented in Table 2 [12].

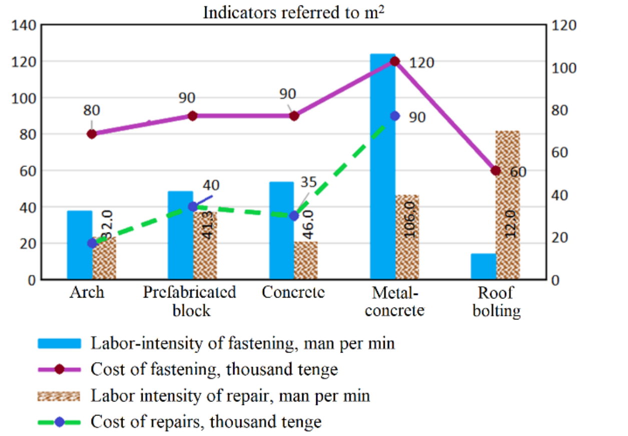

Figure 1. Technical-and-economic indicators of various types of fastening the mine working support

Table 2. Main indicators on the support types used in the Karaganda Coal Basin mines

Indicator	Years of operation					
	2014	2015	2016	2017	2018	2019
Driving of mine workings fastened with support, km	60	55	55	56	58	60
– arc	34	29.8	13	14	11	12
– combined	13.5	20	31	31	32	28
– roof-bolting	6.5	10.7	11	11	12	20
Production volume for longwall face, km/longwall face	4.5	5	5	5	5	5
Cost, thousand tenge/m						
– arch	78	85	100	100	100	100
– combined	60	66	80	80	80	80
– roof-bolting	55	60	65	65	65	65
Specific volume of driving, m/thousand tons	4.9	5.4	5.4	5.3	5.3	5.3

The complexity of the task of increasing the rock outcrop stability in the mine workings of the Karaganda Coal Basin mines is largely conditioned by the wide variety of mining-geological conditions in terms of thickness and dip angle of the seams, as well as in the structure and strength of host rocks, etc. The following mining-geological factors have the most significant influence on the rock outcrop stability [19]-[21]:

1. Stratification. With the strength of the seams for uniaxial compression of 50-60 MPa and their thickness of more than 0.8 m, the roof rock outcrops remain stable for more than 2 hours. With a seam thickness from 0.1 to 0.4 m and a compressive strength of rocks up to 40 MPa, the stable state time is maintained within an hour, and with a seam thickness of less than 0.1 m, which is typical for a friable roof, their stable state time is up to 0.6-0.3 hours. As a result of stratification, the stability of the roof rocks in the seams decreases by 1.5-4.0 times.

2. Fracturing. In highly fractured, disturbed rocks, occurring mainly over coal seams (mainly friable roof), with a distance between fractures of 0.01-0.2 m, their stability usually does not exceed 0.3 hours. Weak, highly fractured rocks with a distance between fractures of 0.3-0.5 m, with an ultimate compressive strength of 20-40 MPa, remain stable for 0.5-1.5 hours. Massive, fractured rocks, with a distance between fractures of 0.6-1.0 m, with σ_{compr} = 40-50 MPa,

remain stable for 2.0-3.5 hours. Due to fracturing, the stability of the roof rocks in the seams decreases by 3-15 times.

3. Moisture content. Sandstones based on carbonate cement with increasing moisture lose their strength characteristics by about 5%, siltstones based on siliceous and carbonate-siliceous cement – by 14%, siltstones with clayey cement – by 20-30%, argillites – by 40-60% and carbonaceous argillites – up to 80%. In the course of studying the influence of moisture content on the stability of roof rocks in the face space of the conducted in-seam workings, it has been revealed that sandstones and siltstones are not prone to softening, regardless of the time spent in the aqueous medium, and the softening coefficient is K_{soft} = 0.97-1.0. Argillites, siltstones, carbonaceous siltstones and argillites, weak and disturbed siltstones at high humidity for 3-9 hours soak and break into small pieces, as a result of which they almost completely lose their stability. The softening coefficient for carbonaceous and disturbed siltstones and argillites with σ_{compr} less than 40 MPa is K_{soft} = 0.5-0.7.

The following mining-technical factors have the most significant influence:

1. Mine working width. With an increase in the mine working width from 4 to 5 m, the rock displacements in the mine working increase by 23-28%.

2. Location depth. The main reason for worsening the state of development workings is the decrease in the ratio of rock strength to geostatic pressure with increasing depth of mining operations. An increase in the location depth from 450 to 600 m in seams 1.6-3.5 m thick leads to an increase in roof displacements in rocks with σ_{compr} < 45 MPa by 3.0-3.5 times, in rocks with σ_{compr} = 45-80 MPa, by 2.0-2.4 times, respectively.

3. Way of mine working protection. In the coal mass, the roof displacement, represented by strong rocks of σ_{compr} < 50-65 MPa, does not exceed 40-50 mm, rocks of medium strength of σ_{compr} < 30-40 MPa – 70-90 mm and weak rocks of σ_{compr} < 15-30 MPa – 110-150 mm. The bearing pressure influence on the extraction drifts at a depth of 300-400 m extends to 40-45 m ahead of the longwall face, and at a depth of more than 500 m – to 60-80 m. Before entering the zone of stope operations influence, the roof displacement of the extraction workings usually occurs uniformly. In the zone of stope operations influence, the roof displacement occurs 1.5-2.5 times faster from the side of the longwall face than from the side of the coal mass. Pillarless extraction workings in longwall faces experience the harmful mutual influence of stope and preparatory works in adjacent columns:

– not less than 50-75 m at a location depth of up to 450 m;
– 80-100 m at a location depth of more than 450 m;
– 100-120 m - at a location depth of more than 600 m.

In the mine workings, which were driven with undercutting in 10-12 months or more after mining-out of the adjacent longwall face, the displacement of roof rocks over the service life is 1.8-2.0 times less than in mine workings, which were driven before mining out of the adjacent column.

Thus, an increase in the depth of mine workings and a deterioration in the conditions for their maintenance leads to a steady increase in the use of heavy special profiles (SVP22, SVP27, SVP33) and a decrease in the use of light ones (SVP17, SVP19). The deterioration of conditions for maintaining mine workings leads to significant volumes of their repair.

To date, research on the improvement of metal support is carried out in three main directions:

– selecting the rational form;
– providing conditions for contact between the support and the border rock mass;
– improvement of the hinge part operation.

All these measures no longer have a significant influence on improving the performance of mine workings with metal frame support. In such a way, it can be considered proven that with an increase in the depth of mining, the use of traditional bearing-type support structures have a limited scope. The improvement of the support structure, as evidenced by world experience, should follow the path of using combined systems, the necessary structural element of which is the border rock mass itself, strengthened in one way or another. Such strengthening elements include roof-bolts of various designs, umbrella-type structures for especially difficult conditions and reinforcing mortars [15].

Thus, the multi-year research results in the mines of Germany have shown [22], [23] that at a depth of 1400 m, rock pressure can still be controlled by 80% of the length of drifts, provided that all known technical solutions are used, and, first of all: filling of the contact space, erection of cast strips around the drift, unloading the mass, strengthening it with binders or roof bolts, and a combination of these measures (Fig. 2). In addition, when planning the preparation of a stope zone, additional measures should be taken, such as location of mine workings in low-pressure zones and mining-out by methods that reduce the effect of increased pressure from side of the longwall faces, etc.

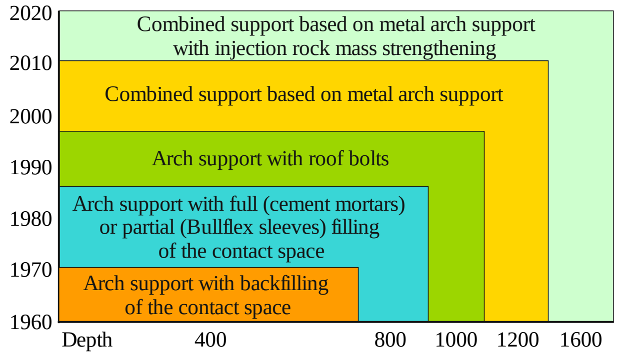

Figure 2. Development of support systems with increasing depth of mining operations [24], [25]

Given the current scale of using the steel support in coal mines (up to 90%), a significant impact on the cost of coal, an increase in the metal consumption of mine workings and the frequency of their refastening, the transition of mining operations to significant depths (700-1000 m), it is necessary to study the ways of improving the efficiency of support structures, reducing their cost and material consumption. An extensive approach has been adopted to increase the load-bearing capacity of the support, involving the use of heavier profiles and the transition to a higher density frame in accordance with the increase in the depth of mining and the sectional area of mine workings. However, this does not solve the problem of reliable operation of mine workings and does not meet the principles of economic feasibility.

This paper studies a way to solve the problem by using the strengtheners for SCP-type profiles made from rolled metal sections of the same standard size as the support itself, set in the areas of the arch support cap board, where the greatest bending moments are expected from the action of an external load. The length of the SCP segments is 200-300 mm.

In this regard, the purpose of this paper is to substantiate the increase in the load-bearing capacity of metal arch supports by strengthening in places with the largest bending moment by increasing the resistance moment in the most deformable areas of the frame support.

To achieve this purpose, the following tasks are set:

– determine the bending moments and normal forces in a three-section metal arch support based on calculations of the expected load on the support according to methodology of the Research Institute of Mining Geomechanics & Mine Surveying (VNIMI); to perform a calculation of bending moments and normal forces arising in the support, which can be implemented on a computer, for specific and existing conditions, followed by the selection of the required standard size of the support;

– analyze the stress-strain state of the rock mass and support using the ANSYS software package;

– study the main patterns of changes in the stress-strain state of arch supports when using strengthening elements of the supports; determine the locations of strengthening elements and perform the search for their optimal parameters.

2. Materials and methods

To substantiate the proposed solution, bending moments and normal forces in a three-section metal arch support are determined, which are implemented on a computer for specific and existing conditions, followed by the selection of the required standard size of the support. The stress-strain state of the rock mass and support is analyzed using the ANSYS software package [26], [27].

ANSYS provides a wide range of capabilities to perform project design, analysis, and optimization, as well as to solve complex structural strength, heat transfer, and acoustic problems. This project design verification program is a powerful tool for determining displacements, stresses, forces, temperatures and pressures, and other important parameters [28], [29].

In a number of cases, testing of samples is undesirable or impossible [30]. Designers using the ANSYS program can identify potential design faults or find out the best variant before the product is manufactured or put into operation. Finite element analysis using the ANSYS program can help to significantly reduce design and manufacturing costs, and add confidence to the developer in the correctness of his decisions. Therefore, the ANSYS software package has been chosen to solve this problem.

The problem is studied in three variants:

– support without strengtheners;

– support with one strengthener in the area with the maximum bending moment;

– support with three strengtheners in the areas with the maximum bending moments.

For mathematical modeling, a support from the special profile SCP-22 is used.

After creating a geometric model of the studied object, the initial parameters of the arch support material are set. Since the structural elements of the supports are made of hot-rolled steel, the corresponding deformation-strength characteristics of this material are taken during calculations:

– elasticity modulus is $2 \cdot 10^{11}$ N/m^2;

– Poison's ratio is $v = 0.3$;

– tensile strength is $4 \cdot 10^8$ N/m^2.

These characteristics are taken into account when mode-ling the full deformation diagram. The representation of the full deformation diagram makes possible to take into account the occurrence and development of plastic deformations in the frame, which are often observed in mine conditions [31], [32]. This approach helps to increase the adequacy of modeling to a real object. Further, for the calculation by the finite element method, a grid is created, where the object is fixed at the base and the mobility in all three directions is closed. The applied load is 20 kN from the outer surface of the object.

Before calculating the choice of fastening, let us study the physical and mechanical properties of rocks mined in three mines of the basin, under the conditions of which the use of the developed support structure is proposed.

Saranskaya Mine. The average values of the parameters of the physical and mechanical properties of coal-bearing deposits by lithological types, stratigraphic horizons and depth intervals are 500-600 m, for seams k_{12}-k_7, the ultimate compressive strength for sandstones is 72.0 MPa, for siltstones is 40.7 MPa, for argillites is 35.2 MPa; the ultimate tensile strength for sandstones is 4.4 MPa, for siltstones is 2.8 MPa, for argillites is 2.4 MPa; the adhesion factor only for sandstone is 13.4; the density is 2.7 g/cm³; the internal friction angle for sandstone is 22º.

Sandstones have the highest strength, and argillites have the lowest strength: interbedding of argillo-arenaceous rocks and siltstones has intermediate values. The strength of sandstones is in the range of 40.0-70.0 MPa. The maximum values of 100.0 MPa are typical for thick and persistent alluvial sandstones. These sandstones are fine-grained, homogeneous and monolithic. For siltstones, the strength varies over a wide range from 20.0 to 60.0 MPa. Sandy siltstones of partings are characterized by greater strength, while homogeneous siltstones, confined directly to the roof and bottom of coal seams, are characterized by lower strength. Argillites usually compose the immediate roof and bottom of coal seams and have low strength up to 30.0 MPa.

The argillites up to 1 m thick directly overlying the seams, as a rule, are unstable. They are broken by a dense pattern of endo/exo cleavage fractures, are saturated with prints of flora along bedding, easily stratified into thin plates, and their strength rarely exceeds 10.0 MPa. The remaining argillites in the roof and bottom are dense, less fractured, and are characterized by a strength from 10.0 to 30.0 MPa.

The ultimate tensile strength of rocks and their adhesion also decrease from sandstones to argillites. The density changes in the same order. Moisture and porosity of rocks increase from sandstones to argillites. The internal friction angle also changes in a similar way: from sandstones to argillites.

Tentekskaya Mine. Dolinskaya Formation is represented by gray and dark gray argillites, consertal sandstones. The fine horizontal stratification and widespread siderite concretions are clearly observed in the rocks. Dolinskaya Formation is characterized by a complex of phylloids distributed in three faunistical horizons between d_5-d_6, d_8-d_9 seams and above d_{11} seam. The low group combines the seams d_1, d_2, d_3, d_4 and d_6. The thickness of the rock stratum containing them is 60-80 m. The lithological stratum is equally represented by argillites, siltstones and sandstones.

The middle group combines the seams d_6, d_7, d_8. The thickness of this rock group is not consistent and is measured from 30 to 70 m, and the partings are composed mainly of sandstones and siltstones. The coal-free horizon between d_8 and d_9 is composed of 90-130 m interbedding of argillites, sandstones and siltstones.

The upper group consists of seams d_9, d_{10}, d_{11}. The thickness of the rock mass enclosed between seams d_9 and d_{11} decreases from south to north from 50-70 to 30-45 m. In the south-east, seams d_{10}-d_{11} merge into one seam. The total thickness of the Dolinskaya Formation is 510-530 m.

Seam d_6 – is the thickest seam in the mine field. The total seam thickness ranges from 5.21 to 6.12 m. It has a complex structure, namely, up to 8 interlayers from 0.01 to 0.10 m are identified in it. The interlayer in the upper part of the seam, 0.05-0.2 m thick, is most clearly distinguished, while the rest of interlayers do not have a definite position. The total thickness of the rock interlayers is on average 5% of the total seam thickness. In most of the field, the structure characteristic of the seam is homogeneous. The bottom and the roof of the seam are represented by argillites. The hardness coefficient ranges from 0.3 to 2.2. The thickness of argillites ranges from a few centimeters to 1-3 m. Regardless of the structure, fracturing is more strongly developed in the roof rocks. Their strength decreases as they approach the seam (the hardness coefficient is not more than 2.0). Bottom rocks are often prone to heaving.

The stability of bottom and roof rocks is much less than that of similar type of rocks from the interlayer stratum. In the roof of the seams, a friable roof often develops, which easily peels off from the main roof. The rock layers in the coal seams are mainly composed of thin-bedded, easily soaked, very weak argillites, which break up into small pieces during mining. Argillites, low carbonaceous and carbonaceous argillites usually have a sheet texture with catalyzed lapping planes and in the presence of water in coal seams they further reduce strength, turning into a clay mass in some cases.

Kuzembaev Mine. The rocks hosting coal seams are characterized by a rather variable composition. Along with argillites, siltstones and interbedding of argillo-arenaceous rocks are developed in the immediate roof of the seams. However, in general, the immediate roof of coal seams is represented by unstable argillites with a thickness of 0.4-2.0 m and strength of 8-15 MPa.

Table 3 presents the average physical and mechanical properties of rocks. The siltstones and the interbedding stratum of argillo-arenaceous rocks of the main roof occur above, the strength of which does not exceed 45 MPa. The presented bottom of the seams is variable in lithological composition and is represented by argillites, siltstones, and, less frequently, sandstones. Bottom argillites are very loose, weak, thickness up to 1.0-3.0 m and strength 8-12 MPa.

Table 3. Average physical and mechanical properties of the rock

Type of parameter	Rock type		
	Sandstone	Siltstone	Argillite
Ultimate compressive strength, MPa	63.5	38.5	20.4
Ultimate tensile strength, MPa	4.8	3.2	2.0
Specific density, kg/m^3	2770	2760	2710
Natural moisture content, %	3.65	6.50	6.70
Porosity, %	11.7	13.4	15.0

The above characteristics of the rocks in the immediate and main roofs lead to conclusion that the conditions for maintaining mine workings and ensuring their repair-free operation throughout the entire service life are very difficult. Moreover, the increase in the load-bearing capacity of the support cannot continue due to the increase in the SCP standard size, which leads to a high metal consumption of mine workings. The development of the adaptive properties of the fastening system involves the adaptation of its structural elements to the specifics of the load distribution and the nature of rock displacements. This requires optimizing the type of fastening, increasing the efficiency of yielding nodes, rational package of the load-bearing elements and the location of strengtheners on the frame.

This paper proposes to use a strengthener to increase the load-bearing capacity of special rolled profiles for the manufacture of supports in the mine workings, driven in the zone of active rock pressure. Figure 3 shows the SCP section strengthening.

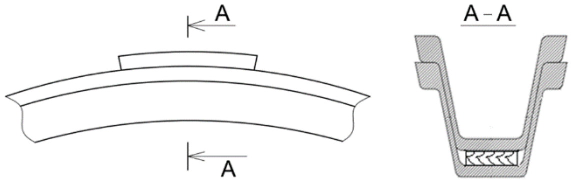

Figure 3. SCP section strengthener

Firstly, the stress-strain state of the arch support without strengtheners is calculated. Then, a strengthener 30 cm long is modeled, of the same standard size as the entire support in the middle of the support cap board, that is, in the area with the maximum bending moment. Then, the strengtheners are set in three places with the largest bending moments. Based on the calculation results, a static analysis is conducted, and post-processing shows the results of the stresses along the *x*, *y*, *z*, axes, as well as the maximum displacements.

3. Results and discussion

The task of assessing the stability of in-seam working is posed in a broader sense in comparison with traditionally accepted ideas. It is necessary to predict its state in terms of maintaining (or losing) operational characteristics according to a set of structural-and-technological standards for the reliable functioning of a mine working, taking into account the relevant requirements of safety rules. The implementation of safety rules should be assessed according to curves of predicted displacements of the mine working contour and comparison with permissible displacements in certain areas of its perimeter. If the requirements for reliable and safe functioning of the mine working are not met, then the issue of its stability as an artificial mining-technical structure becomes of paramount importance, since further exploitation of the mine working is unacceptable without performing certain repair and restoration work.

A graphical representation of the stress-strain state of the arch support based on the results of modeling is presented in Figures 4-6. Below, there is a line of stress correspondence to various color tones. The red stress field, which corresponds to a value of 20.76 MPa in Figure 4 in an arch, which is not strengthened, shows the zone of stress concentration. The computer model of the frame support is created according to the condition of the maximum possible representation of its structural peculiarities. The stress maxima in the frame are stably located in the rounded area, which is explained by the action of increased bending moments in this very area due to the intensive displacement of the border rocks in the roof and sides of the mine working, which is typical for weak rocks of the stratified mass.

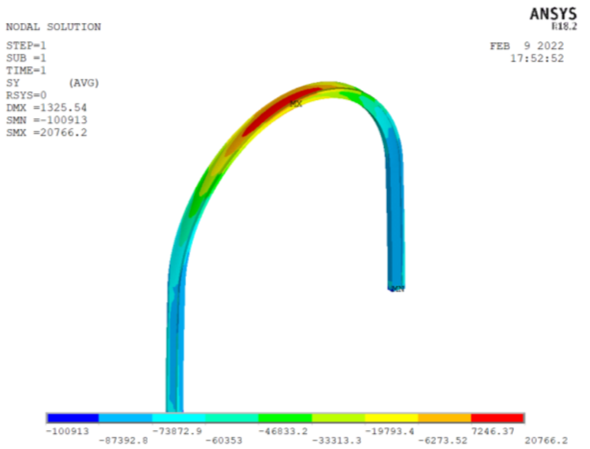

Figure 4. Stresses in the support arch without strengtheners

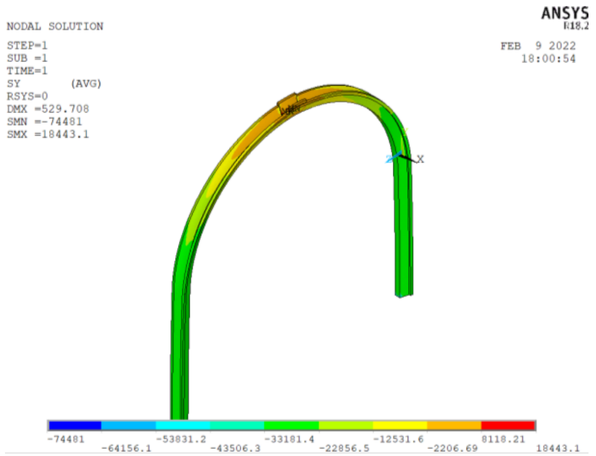

Figure 5. Stresses in the support arch when using one strengthener

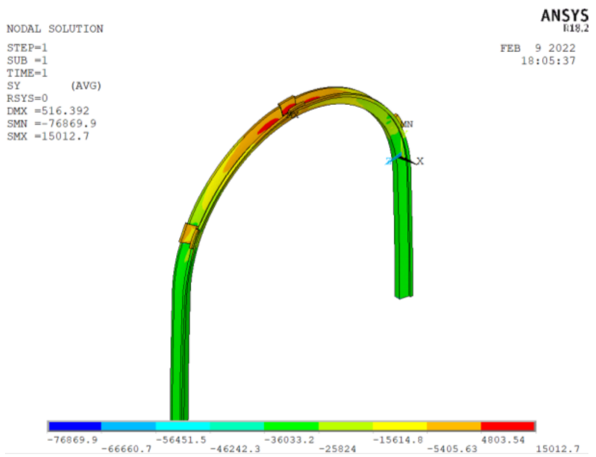

Figure 6. Stresses in the support arch when using three strengtheners

Thus, the frame support changes into the limiting state with the formation of a number of plastic hinges along its contour, which, on the one hand, give the frame increased yielding property in the most loaded sections, and, on the other hand, contribute to frame deformation, thereby excluding the possibility of exploiting the mine.

Figure 5 presents the stress-strain state of the arch support with 1 strengthener, where the maximum stress concentration along the y-axis is 18.44 MPa. The frame support stress-strain state (SSS), when using a single strengthener, is also significantly influenced by the deformation-strength characteristics of adjacent rock layers. Therefore, for a reasonable choice of the frame support of a mine working, it is necessary to take into account the relationship with the main influencing geomechanical parameters.

The frame support shown in Figure 5 experiences increased vertical compressive stresses and reduced horizontal stresses. Together, this generates concentrations of reduced stresses and the formation of extended areas of the plastic state in the curvilinear part of the prop stay and its bearing, which can lead to the loss of stability of the prop stays and frame support as a whole.

Figure 6 presents arch support with three strengtheners. As it can be seen from the stress scale, the maximum stress along the y-axis is 15.01 MPa.

The frame support, shown in Figure 6, is in a fairly stable stress state (according to the assessment criterion – the value of the stresses) regardless of the significant dependence on the deformation characteristics of the adjacent rock layers. Obviously, this is conditioned by the increased deformation capacity of the host rocks in the limiting state, which provides more uniform loading of the frame. In addition, this is conditioned by the presence of plastic hinges in the frame, which reduce the maxima of bending moment along its contour. A change in the deformation modulus of rock layers has an insignificant influence on the maximum both at decreased and increased strength characteristics.

The data obtained as a result of modeling are systematized and given in Table 4.

Table 4. SSS values in the support arch

Parameter	Support without strengtheners	Support with 1 strengthener	Support with 3 strengtheners
Maximum displacements, mm	132.554	120.34	51.64
Stresses along the x-axis, MPa	21.74	24.96	25.69
Stresses along the y-axis, MPa	20.76	18.44	15.01
Stresses along the z-axis, MPa	27.04	19.32	12.87
Equivalent stress (according to Mises), MPa	97.99	86.57	68.61

An analysis of the results of the performed numerical experiments leads to the conclusion that the proposed method for modeling metal support makes it possible to bring the model closer to real conditions. The results of this modeling (mine working with strengthened arch support) indicate a decrease in stresses in the sides and ahead of the mine working. This helps to reduce the possibility of sudden rock outbursts and deformation, increasing its load-bearing capacity.

The main advantage of applying the numerical method of research is the simplicity and speed of obtaining results. They make it possible to make an accentuated assessment of the stress-strain state of the modeled object. Thus, the ANSYS software product is suitable for modeling the geomechanical processes. It is thanks to this software that it is possible to conduct a high-quality mathematical modeling experiment and make the calculation with the finite element method as accurately as possible.

To design fastening elements as a system of the least weight and cost, it is necessary, in accordance with the law of load distribution, to distribute the structure material in such a way as to provide an approximately equal safety margin for all load-bearing elements. The modern capabilities of computer technology allow using the finite element method to model the operation of an arch support, as close as possible to the actual conditions of interaction with the rock mass. When leveling the acting stresses along the perimeter of the arch, the principle of using elements of the same strength must be abandoned. Under conditions of load concentration in the area of the arch vault, it is expedient to strengthen the cap board with an element from a special profile while creating pre-stressing of the frame.

4. Conclusions

The conducted research gives grounds to believe that the proposed variant for increasing the load-bearing capacity of the support made from the SCP rolled steel profile in combination with strengtheners from the same profile can significantly improve the state of mine workings due to a higher load-bearing capacity. The proposed solution can significantly reduce the metal consumption of mine workings, which is an obvious positive effect both for reducing the labor intensity of fastening the mine workings and for increasing the driving speed, and, consequently, for achieving a significant economic effect. The proposed method for increasing the load-bearing capacity of the support, obviously, can be applied not only to arch, but also to other structures of metal support and other rolled metal profiles.

It should be noted that when using strengtheners for support, it is necessary to accurately determine the areas on which the greatest bending forces act, especially with an asymmetric load on the support. This sets the task of more careful selection of methods for calculating the supports, taking into account all the essential parameters that determine the accuracy of calculating the loads and load-bearing capacity of the supports. Probably, for these purposes, it is necessary to use modeling of various variants for the support operation, changing such parameters as the depth of setting mine workings, their cross section, the hardness of the rocks in the immediate and main roof, fracturing, the angle of inclination of the driven mine working, etc.

On the basis of the conducted research, it is possible to compile a database of the most common variants, derive the functional dependences of various parameters from each other and thereby reduce the labor intensity of finding the required type and design of the support for non-repair maintenance of mine workings. In particular, this can be applied to the development in-seam workings located in the zone of increased influence of stope operations.

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References

[1] Abdiev, A., Mambetova, R., Abdiev, A., & Abdiev S. (2020). Development of methods for assessing the mine workings stability. *E3S Web of Conference*, (201), 01040. https://doi.org/10.1051/e3sconf/202020101040

[2] Glushikhin, F.P., Kuznetsov, G.N., Shklyarskii, M.F., Pavlov, V.N., & Zlotnikov, M.S. (2022). Forecasting influence of geological factors on stability of mine workings. *Modelling in Geomechanics*, 125-141. https://doi.org/10.1201/9780203746851-8

[3] Majcherczyk, T., Niedbalski, Z., Małkowski, P., & Bednarek, Ł. (2014). Analysis of yielding steel arch support with rock bolts in mine roadways stability aspect. *Archives of Mining Sciences*, *59*(3), 641-654. https://doi.org/10.2478/amsc-2014-0045

[4] Khomyakov, V.A., Iskakov, E.E., & Serdaliev, E.T. (2013). Investigation of gravelly soil during underground construction in Almaty. *Soil Mechanics and Foundation Engineering*, *50*(4), 171-177. https://doi.org/10.1007/s11204-013-9230-z

[5] Matayev, A., Abdiev, A., Kydrashov, A., Musin, A., Khvatina, N., & Kaumetova, D. (2021). Research into technology of fastening the mine workings in the conditions of unstable masses. *Mining of Mineral Deposits*, *15*(3), 78-86. https://doi.org/10.33271/mining15.03.078

[6] Sultanov, M.G., Mataev, A.K., Kaumetova, D.S., Abdrashev, R.M., Kuantay, A.S., & Orynbayev, B.M. (2020). Development of the choice of types of support parameters and technologies for their construction at the Voskhod field. *Ugol*, (10), 17-21. https://doi.org/10.18796/0041-5790-2020-10-17-21

[7] Sarybayev, O., Nurpeisova, M., Kyrgizbayeva, G., & Toleyov, B. (2015). Rock mass assessment for man-made disaster risk management. *New Developments in Mining Engineering. Theoretical and Practical Solutions of Mineral Resources Mining*, 403-409. https://doi.org/10.1201/b19901-70

[8] Arystan, I.D., Nemova, N.A., Baizbaev, M.B., Mataev, A.K. (2021). Efficiency of modified concrete in lining in underground structures. *IOP Conference Series: Earth and Environmental Science*, *773*(1), 012063. https://doi.org/10.1088/1755-1315/773/1/012063

[9] Akhunbaev, A. (2017). Sostoyanie i perspektivy ugol'noy promyshlennosti Kazakhstana. *Gorno-Metallurgicheskaya Promyshlennost'*, *8*(110), 1-11.

[10] Fedorov, E., Kassymkanova, K., Jangulova, G., & Miletenko, N. (2020). The influence of extensive caving zones on the state and behavior of the surface as a result of underground mining works. *E3S Web of Conferences*, (192), 03009. https://doi.org/10.1051/e3sconf/202019203009

[11] Korchak, A.V. (2001). *Metodologiya proektirovaniya stroitel'stva podzemnykh sooruzheniy*. Moskva, Rossiya: Nedra, 416 s.

[12] Steflyuk, Yu.Yu. (2017). *Razrabotka tekhnologii upravleniya ustoychivost'yu konturov gornykh vyrabotok v slozhnykh gornotekhnicheskikh usloviyakh ekspluatatsii*. Karaganda, Kazakhstan: KarGTU, 127 s.

[13] Kryshtanovych, M., Akimova, L., Akimov, O., Kubiniy, N., & Marhitich, V. (2021). Modeling the process of forming the safety potential of engineering enterprises. *International Journal of Safety and Security Engineering*, *11*(3), 223-230. https://doi.org/10.18280/ijsse.110302

[14] Petrov, N.I., Dimitrova, K.Y., & Baskanbayeva, D.D. (2021). On the reliability of technological innovation systems. *IOP Conference Series: Materials Science and Engineering*, (1031), 012044. https://doi.org/10.1088/1757-899X/1031/1/012044

[15] Smirnov, A.V. (2018). *Geomekhanicheskoe obosnovanie bezopasnoy tekhnologii podzemnoy dobychi uglya v neustoychivykh vmeshchayushchikh porodakh*. Dissertatsiya na soiskanie uchenoy stepeni doktora tekhnicheskikh nauk. Shakhty, Rossiya: Shakhtinskiy institute, 349 s.

[16] Kizryakov, A.D. (1983). Effects of overworking on the gas characteristics of coal beds in the Karaganda basin. *Soviet Mining Science*, *19*(1), 80-83. https://doi.org/10.1007/bf02497971

[17] Mozer, D.V., Levin, E.L., Gey, N.I., Karaneeva, A.D., Nagibin, A.A. (2015). Monitoring of ground deformation in the territory of the Karaganda coal basin. *Geodesy and Cartography*, *900*(6), 21-26. https://doi.org/10.22389/0016-7126-2015-900-6-21-26

[18] Kalyuzhnyy, A.S., & Zemtsovskiy, A.V. (2017). Issledovanie napryazhenno-deformirovannogo sostoyaniya massiva gornykh porod vblizi kar'yera na mestorozhdenii Oleniy Ruchey. *Trudy Gornogo Instituta Kol'skogo Nauchnogo Tsentra*, 278-282.

[19] Kenetayeva, A.A., Kenetayeva, Z.K., Tokusheva, Z.T., & Rabatuly, M. (2019). Methane content of coal seams of Karaganda basin. *IOP Conference Series: Materials Science and Engineering*, (516), 012020. https://doi.org/10.1088/1757-899x/516/1/012020

[20] Nurpeisova, M.B., Sarybaiev, O.A., & Kurmanbaiev, O.S. (2016). Study of regularity of geomechanical processes development while developing deposits by the combined way. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 30-36.

[21] Abakanov, T.D., Begalinov, A.B., & Abakanov, A.T. (2016). Seismic stability of tunnels at the Kapchagai hydropower plant. *Soil Mechanics and Foundation Engineering*, *53*(1), 60-65. https://doi.org/10.1007/s11204-016-9365-9

[22] Zeynullin, A.A., Abeuov, E.A., Demin, V.F., Aliev, S.B., Kaynazarova, A.S., & Kaynazarov, A.S. (2021). Estimation of ways to maintain mining works based on the application of anchor anchoring in the mines of the Karaganda coal basin. *Ugol'*, (2), 4-9. https://doi.org/10.18796/0041-5790-2021-2-4-9

[23] Kuanyshbekovna, M.M., Krupnik, L., Koptileuovich, Y.K., Mukhtar, E., & Roza, A. (2016). The system is "roof bolting-mountain". *International Journal of Applied Engineering Research*, *11*(21), 10454-10457.
[24] Grotovski, U. (1981). Pour analyser des pratiques langagières. *Glyukauf*, (17), 35-38. https://doi.org/10.3406/lsoc.1981.1360
[25] Aykkhoff, Yu. (2008). Tekhnika i tekhnologiya ankernogo krepleniya v sisteme shtrekovoy krepi. *Glyukauf*, *2*(3), 28-35.
[26] Grigoriev, O., Tereschuk, R., & Tokar, L. (2015). Assessment of economic efficiency AMS-A (anchor – meshwork – shotcreting) support structure in terms of coal mines. *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining*, 85-89. https://doi.org/10.1201/b19901-17
[27] Wu, X., & Tu, Z. (2017). Research of the shape of pressure arch in layered rock mass based on the Protodyakonov's theory. *Manufacturing Science and Engineering*, 250-255. https://doi.org/10.2991/icmse-17.2017.45
[28] Matayev, A.K., Lozynskyi, V.H., Musin, Abdrashev, R.M., Kuantay, A.S., & Kuandykova, A.N. (2021). Substantiating the optimal type of mine working fastening based on mathematical modeling of the stress condition of underground structures. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (3), 57-63. https://doi.org/10.33271/nvngu/2021-3/057
[29] Makshankin, D.N., Gogolin, V.A., Remezov, A.V., & Bedarev, A.V. (2010). Vozmozhnost' matematicheskogo modelirovaniya stendovykh ispytaniy arochnykh krepey. *Vestnik Kuzbasskogo Gosudarstvennogo Tekhnicheskogo Universiteta*, (2), 50-55.
[30] Glubokovskikh, Yu.S. (2018). *Issledovanie zakonomernostey izmeneniya nesushchey sposobnosti metallicheskikh arochnykh krepey s rasklinivayushchimi elementami*. Dissertatsiya na soiskanie uchenoy stepeni kandidata tekhnicheskikh nauk. Ekaterinburg, Rossiya: Uralskiy gosudarstvennyy gornyy universitet, 132 s.
[31] Begalinov, A., Almenov, T., Zhanakova, R., & Bektur, B. (2020). Analysis of the stress deformed state of rocks around the haulage roadway of the Beskempir field (Kazakhstan). *Mining of Mineral Deposits*, *14*(3), 28-36. https://doi.org/10.33271/mining14.03.028
[32] Shashenko, A., Gapieiev, S., & Solodyankin, A. (2009). Numerical simulation of the elastic-plastic state of rock mass around horizontal workings. *Archives of Mining Sciences*, *54*(2), 341-348.

Моделювання впливу підсилювачів профілів прокату на несучу здатність арочного кріплення

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Мета. Підвищення несучої здатності металевих аркових кріплень, що використовуються для підтримання гірничих виробок за допомогою посилення в місцях з найбільшим згинальним моментом.

Методика. Аналіз напружено-деформованого стану гірського масиву та кріплення здійснювався за допомогою програмного комплексу ANSYS. Завдання розглядалося в трьох варіантах: кріплення без підсилювачів, кріплення з одним підсилювачем на ділянці з максимальним згинальним моментом і кріплення з трьома підсилювачами – на ділянках з найбільшими згинальними моментами. Визначення згинальних моментів і нормальних сил у металевому арочному триланковому кріпленні здійснювалося методом скінченних елементів для конкретних, існуючих умов, з наступним вибором необхідного типорозміру кріплення.

Результати. Проведені дослідження дають підставу вважати, що запропонований варіант підвищення несучої здатності кріплення, що виготовляється із спеціального взаємозамінного профілю прокату (СВП), може істотно покращити стан гірничих виробок. Запропоноване рішення, очевидно, можна застосувати не лише до арочних, але і до інших конструкцій кріплення з металопрокату.

Наукова новизна. Встановлено закономірність зміни значень внутрішніх зусиль, що виникають у металевих аркових рамних кріпленнях, залежно від деформаційних характеристик, місць розташування підсилювачів, а також від геометричних характеристик виробки та співвідношення бічних і вертикальних навантажень на кріплення.

Практична значимість. Запропонований варіант підвищення несучої здатності кріплення може використовуватися для стійкого підтримання гірничих виробок у складних гірничо-геологічних умовах шахт Карагандинського вугільного басейну.

Ключові слова: *виробка, гірський тиск, арочне кріплення, деформація, опір, згинальний момент, підсилювач, спеціальний взаємозамінний профіль*