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SIMULATION OF WORK OF COMBINED SUPPORT SYSTEM IN COMPLEX MINING-AND-GEOLOGICAL CONDITIONS

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Abstract. The purpose of the study was to find out the nature of the deformation for the frame support as part of the combined security system. In addition, our task was to study the destruction of the rock mass around the gateroad. The work was commissioned out by order of the PJSC "CG "Pokrovske"".

Previous researches showed that options of mathematical simulation for the combined support system are limited. It is related to by bulky performance of the model as well as nonlinear deformation of separated elements. For this particular study data set on the structure of rock mass around the gateroad has been collected. A rock mass is presented by the seams of coal, siltstone and sandstone. The combined support system comprises a yielding steel arches, an anchor and a filling body. The frame models with different shapes and sections were used. A physical model corresponded to reuse stage of a gob-side entry retaining. The equivalent materials method is used. The simulation scale was 1:50. A wooden shell is designed to contain transverse deformations. The model was loaded on a rigid testing machine in the constant deformation mode. The deformation speed was about 0.05 mm/s. 19 variations of the model were tested with different combinations of support parameters. For every model the ultimate compressive load value was determined. Dependences for gateroad of cross-section area change are obtained on the loading attached. Three particular areas of load-deformation support curve is recorded. These areas are as follows: increasing resistance area, falling resistance area and residual constant resistance area. It has been established that the form of the support is improved with an increase of the links number.

The results of the study have showed an increase for the resistance of the support while sprayed concrete is applied to the frame. The study also confirmed the efficiency of the reinforced filling body. For the most severe conditions, the use of a circular frame support is recommended. The results of the study could be applied for the design of direct-flow ventilation systems for the longwall panels of coal mines.

Keywords: coal mine, rock mass, frame support, combined support system, physical modeling.

Introduction. Direct-flow ventilation of longwall panels for coal mines provides the reuse of gateroads. The efficiency of frame support using after passing the first longwall is significantly reduced [1 - 4]. The pressure on the support is increased significantly, thus, it becomes asymmetric. The rock heaving also leads to a pressure decrease within the working section. For these difficult mining and geological conditions, it is necessary to search for new technical solutions. Their primary exploration is carried out by benchmark testing of the support [5, 6]. However, the enumeration of the options for the support and the conditions of its loading is time-consuming and expensive process. A faster and cheaper preliminary assessment of the support performance could be performed by means of simulation.

The most convenient one is numerical simulation [7-12]. However, the mathematical model roughly describes the dynamics of the support-massif system with the loss of the bearing capacity of the support. More opportunities are provided by means of physical modeling, specifically the equivalent materials method [13]. Physical modeling results are more illustrative ones. They allow studying the dynamics of the deformation process for large inelastic rock deformations. The use of modern technical means for the study of the process makes it possible to achieve comprehensive information of the process. For complicated geotechnical systems, the combined use of mathematical and physical modeling proves its efficiency [14, 15].

The results of physical modeling of frame-anchor systems as well as separate elements of the support in conditions of symmetric loading are well-known ones [16]. The study devoted to the modeling of asymmetrically loaded geotechnical system is well-known as well [17]. However, the studies mentioned do not take into account the whole complex of distinctions for the operation mode of the support after crossing the longwall. The research is devoted to modeling the operation of a combined support system. It is designed to support the gateroads when they are reused. In addition to frame support and anchors, the system contains a filling body. The main attention has been paid to the study of deformations of system elements at the stage of reducing load capacity.

The purpose of the study is to determine the parameters of the support system that operates in conditions of high asymmetric rock pressure.

Methods. To model the rock massif, its structure was adopted similar to the coal seam d_4 of PJSC "CG "Pokrovske"". The direct roof and floor of a working are represented by siltstone. The main roof consists of sandstone. The seams sequence and properties are the same for all the models. The rock layers dimensions and gateroads were selected according to the geometric similarity. The simulation scale was 1:50. Loads similarity is ensured by approximately equal ratio of strength parameters for rocks and related equivalent materials. Comparative parameters of rocks as well as equivalent materials are represented in Table 1.

Table 1 – Strength parameters of rocks and layers of the model

Rock (material)	Compressive strength $\sigma_{c.}$, MPa		Strength ratio
	rock (material)	equivalent material	
Sandstone	75	32	2.34
Siltstone	45	20	2.22
Coal	15	7	2.14
Filling body	35	15	2.33
Shotcrete	40	17	2.35
Broken rock	15	7	2.14

The combined support system is modeled by two frame supports, a set of anchors and a filling body. A few variations of every element of the system were made. The composition of the system is shown in Figure 1.

Element 1 models a sandstone layer. Plates 2 are equivalent to the layers of siltstone. The coal layer is modeled by the element number 3. Gateroad 4 is at the center of the model. It is fastened with a pair of frame fasteners 5. There is an anchor 6 located in between the frames. There are a few ways to strengthen the upper frame. Two double anchors 7 are used for fixing top of the frame.

For some variations of the model anchor 8 was used to fix the bases of racks on the floor of the seam. Shotcrete was used for further strengthening the support system. Reducing the pressure on the frame after the passage of longwall is provided by the construction of filling body 9. The filling body is placed in a wooden formwork 10. Between frame and filling body filler 11 is placed. Filler 12 models broken rock. The model is placed in a wooden frame 13 in order to block the transverse deformations.

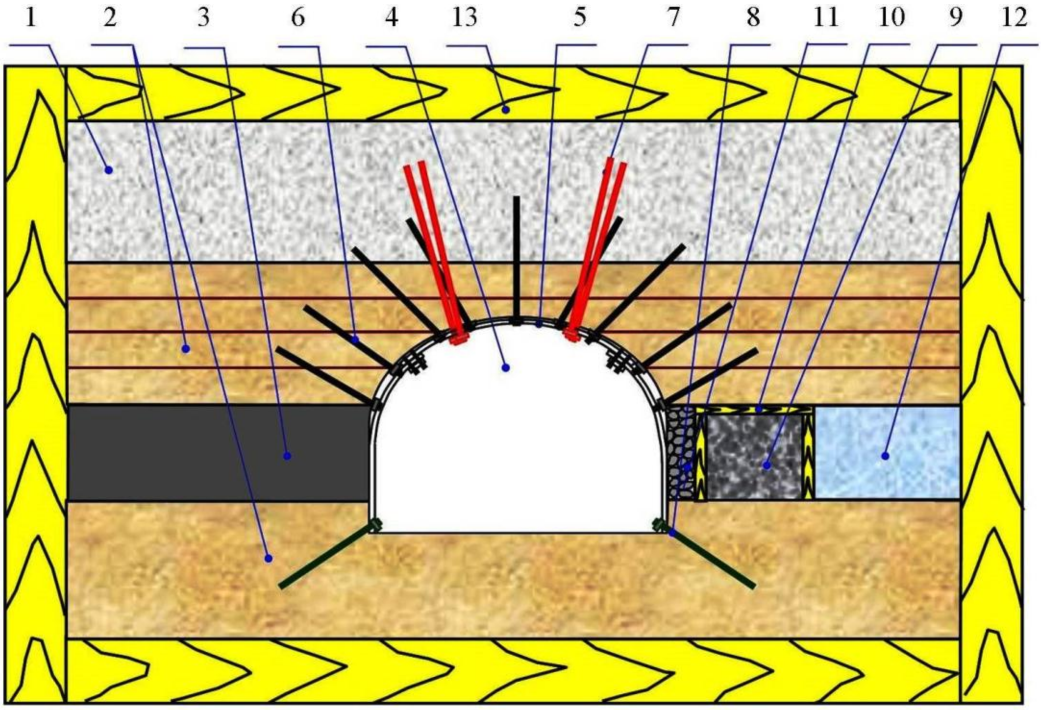

Figure 1 – The composition of the combined support system

Frame models differ by the number of elements, shape and cross-section area. The frame support elements are made of steel strip 14 x 60 mm in length and width respectively. The performance of a single option for the frame support is shown in Figure 2.

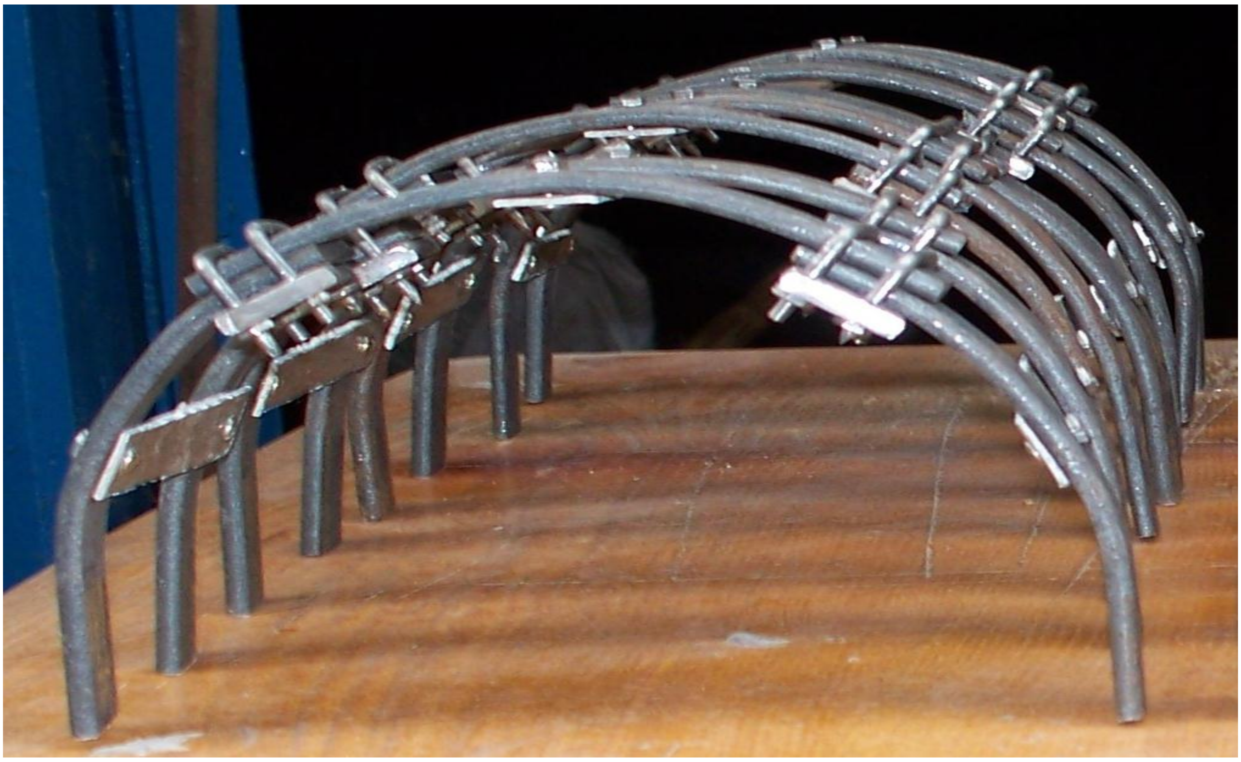

Figure 2 – Sets of models for three-element frame support

For some variations of the frames, additional elements are provided to strengthen the upper support. These elements are shown in Figure 3.

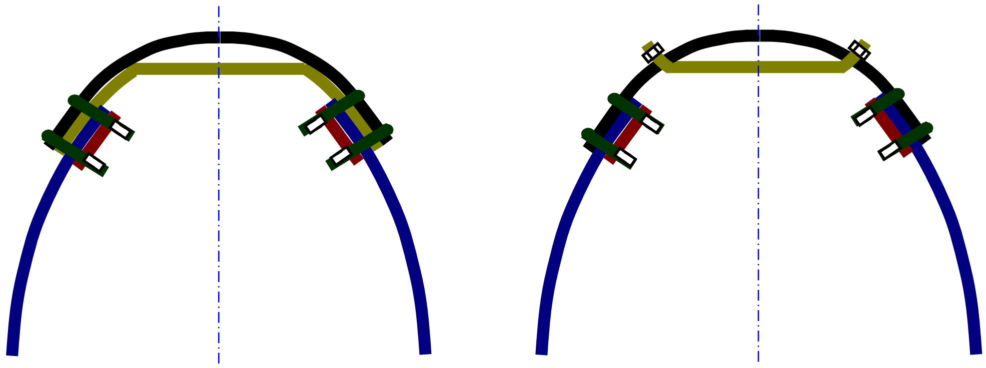

Figure 3 – The options for strengthening the upper component

A few variations of the filling body were applied to the models. These variations are shown in Figure 4.

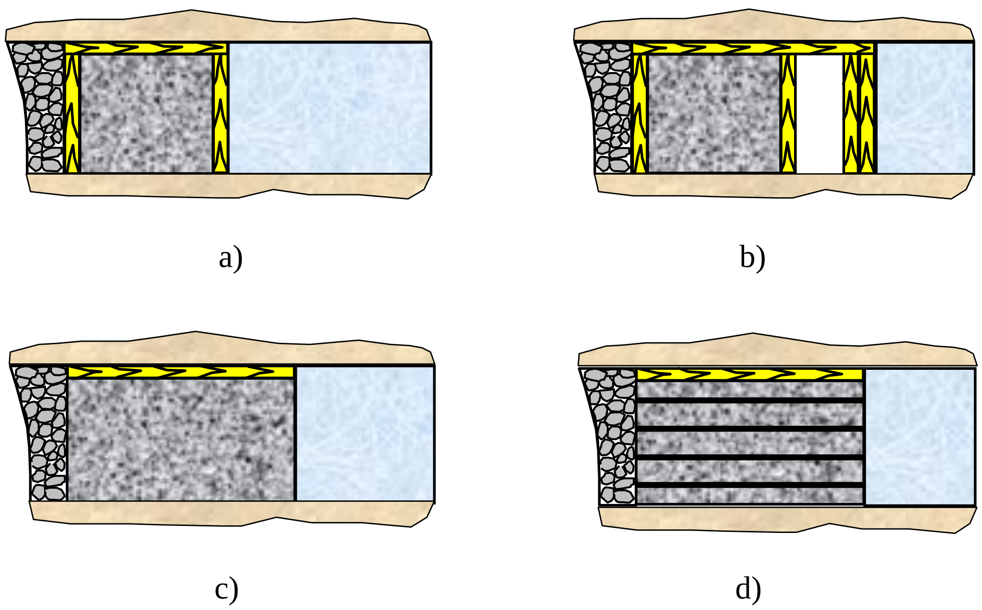

Figure 4 – The variations of the filling body

In option a) filling body prevails. However, in case of rapid movement of the working face, there is no time for filling body to gain the required strength. Its premature destruction leads to a rapid decrease of the cross-section for the roadway. Further, problems with a weak floor of a working have emerged. In this case, the use of a strengthened strip is recommended. Several options for its implementation are proposed. To unload the filling body, they are removed to the depth of the excavated space. The width of the gap between the rows of posts is 0.3 - 0.5 times the width of the filling body. In option b) the reinforcement is provided by additional rows of wooden props. This option requires a removable formwork. Option c) provides an increase of width for the filling body. At the same time, there are no vertical wooden props. This option requires a removable formwork while making up a filling body.

For option d) the wide filling body is additionally reinforced by means of reinforcing profile.

Combinations of several options for frame support during the change of other elements of the support system are implemented as 19 different physical models. The rock structure is the same for all the models. The distinguished features of the models are shown in Table. 2.

Table 2 – Basic parameters of physical models.

Model No.	Number of frame elements	Cross-section, m^2	Number of anchors*	Variation of the filling body	Features
1	3	15.5	9 + 4 x 2	a)	-
2	3	15.5	9 + 4 x 2	a)	without backfilling
3	3	15.5	9 + 4 x 2	a)	sprayed plaster base
4	3	18.0	9 + 4 x 2	a)	-
5	3	18.0	9 + 4 x 2	b)	sprayed plaster base
6	3	15.5	9 + 4 x 2	a)	sprayed plaster base
7	3	15.5	9 + 4 x 2 + 4	b)	-
8	3	18.0	9 + 4 x 2 + 4	a)	-
9	3	15.5	9 + 4 x 2 + 4	a)	without backfilling
10	3	18.0	9 + 4 x 2	b)	without backfilling
11	3	15.5	9 + 4 x 2	b)	strengthening of the upper component – a)
12	3	18.0	9 + 4 x 2	b)	strengthening of the upper component – a)
13	4	15.5	9 + 4 x 2 + 4	b)	circular support
14	4	18.0	9 + 4 x 2 + 4	a)	circular support
15	3	15.5	9 + 4 x 2	b)	-
16	3	18.0	9 + 4 x 2 + 4	c)	strengthening of the upper component – b)
17	5	17.1	9 + 4 x 2 + 4	c)	-
18	5	17.1	9 + 4 x 2 + 4	d)	-
19	3	18.0	9 + 4 x 2 + 4	d)	-

* anchors between frames + dual anchors + fixing of the arch's lower element

Original appearance of a single model is presented in Figure 5.

Experimental study process has been conducted on the test machine P500. The plates were in the shape of a square. Side length of a square equals 0.6 m. Maximum compressive load value equals 5MN. The fixed compressive load on the models did not exceed 0.2 MN. Such a correlation of sizes allowed to provide testing process in the constant deformation mode. Constant deformation velocity was nearly 0.05 mm/s.

Continuous video recording of the experimental study has been carried out. A scale measure unit was attached to the frame in order to control the change of the linear dimensions of the model.

Figure 5 – Model #8 set up prior to experimental study

A remote precision pressure gauge was also placed in the frame in order to record the load simultaneously with parameters mentioned. This pressure gauge has measured the oil pressure within the press hydraulic system. In this case, the correction for the force of friction of the press piston in the cylinder was taken into account.

Results and discussion. Based on the results of computer processing for video records, diagrams of deformation for the gateroad contour were obtained. An example of the diagram is shown in Figure 6.

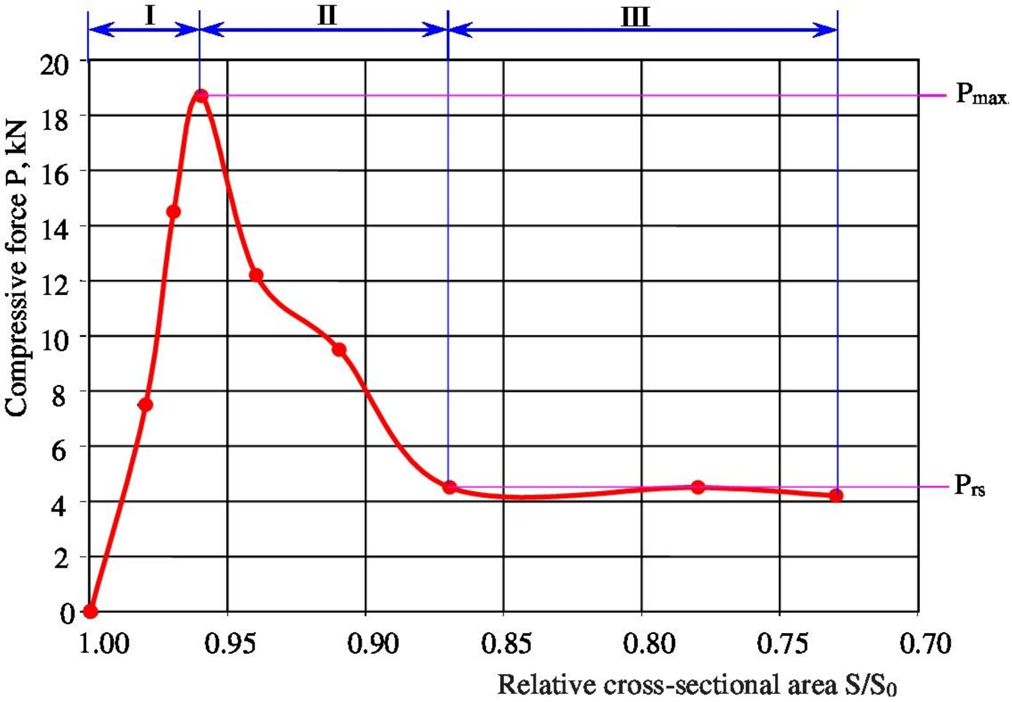

Figure 6 – Diagram of deformation for the gateroad contour of model #11

Three stages of deformation for the gateroad contour are clearly distinguished in the diagram. At stage I, the standard operation mode of the combined support system is implemented. Once the load is increased, the reduction in the area of workings is insignificant. It is mainly due to sealing the gaps between the frame and the contour of gateroad. Additional deformation occurs due to the movement of the upper part within the locks. Frame elements are barely deformed.

The load value of the support structure reaches out its maximum at the load value P_{max}. For an ideal support system, further deformation of the contour would occur at a constant value of the load reached out. However, at stage II, as a result of the large cracks formation within the rock around the gateroad, it significantly loses its bearing capacity. Destruction of the models also use several variations of the filling body that leads to an increase of the asymmetry for the support loads (Figure 7).

Figure 7 – Asymmetric deformation of the frame under loading for model #11

Analysis of the research results has shown an improvement of the support performance with an increased number of elements. Multi-element support is more suitable to for the frames subjected to the asymmetric pressure. In this case, the reduction of the frame cross section occurs mainly due to the slippage of the elements in the lower locks. Figure 8 shows the ultimate shape of the frame for the model #18 after experimental study being conducted.

At stage III, the support system turns into constant resistance mode. In this case, the large-block structure of the rock is fragmented into smaller parts. It is possible to smoothly indent the racks onto the floor of a working. This process is depicted in Figure 9.

Evaluation of the frame support efficiency along with additional elements of the support system is assessed by the values of several parameters. The main parameter is the maximum compressive load P_{max}, kN. The quality of the support is improved with an increase of the parameter’s value.

Figure 8 – The shape of the five-element frame after the test completion

Figure 9 – Racks pressed into the floor of a working for model #19

An important parameter is also the residual compressive load P_{res}, kN. Its high value contributes to an increase of the operating time of the colliery.

The results of processing for the gateroad deformation diagrams are given in Table 3.

Table 3 – Deformation-strength parameters of the models.

Model number	P_{max}, kN.	$P_{rest.}$, kN	Ratio $P_{rest.}$ / $P_{max.}$	Section		Ratio II/I
				I	II	
1	122	79	0.65	0.12	0.09	0.75
2	104	38	0.37	0.06	0.11	1.83
3	182	73	0.40	0.03	0.17	5.67
4	140	62	0.44	0.02	0.21	10.50
5	163	98	0.60	0.07	0.31	4.43
6	196	53	0.27	0.04	0.19	4.75
7	140	62	0.44	0.02	0.14	7.00
8	98	46	0.47	0.03	0.11	3.67
9	105	38	0.36	0.05	0.09	1.80
10	140	78	0.56	0.04	0.16	4.00
11	187	43	0.23	0.04	0.10	2.50
12	112	83	0.74	0.04	0.14	3.50
13	120	38	0.32	0.02	0.18	9.00
14	106	40	0.38	0.02	0.15	7.50
15	110	68	0.62	0.03	0.12	4.00
16	156	45	0.29	0.04	0.14	3.50
17	128	57	0.45	0.03	0.22	7.33
18	102	58	0.57	0.03	0.29	9.67
19	80	38	0.48	0.02	0.24	12.00

Yet another indirect parameter of the support efficiency is the ratio $P_{rest.}/P_{max.}$. The maximum value of this ratio equals 1. Lower values of the parameter contribute to the rapid loss of the gateroad cross-section.

The relative deformation of the cross-section of the gateroad is determined by the size of sections I - III. Section I corresponds to the regime of increasing support resistance. If support provides an effective performance, the deformation of the working in this section reaches out its minimum value.

Section II is a common one for the support performance after longwall passage. The optimal selection of the parameters for the support system leads to the slow decrease of the load capacity. An indirect parameter that describes the efficiency of the support for this mode of operation is the ratio of sections II and I. This ratio should be considered together with the value of the residual resistance of the security system $P_{rest.}$ (section III). Simultaneous increase of the ratios II / I and $P_{rest.}/P_{max.}$ proves the effective support performance.

A significant improvement of the support performance is obtained with the simultaneous application of the frame and a reinforced filling body. The models also use several variations of the filling body. Let's consider the model #5. The positive effect of shotcrete for increasing the maximum bearing capacity of the support is confirmed by the example of the model #3.

Effective performance of the support within the area of the bearing capacity loss is also achieved by strengthening the upper frame and simultaneous using a reinforced filling body. Model #12 has a low maximum value of the load capacity. However, along with model #5 it has a high residual resistance value.

Closed support is implemented for models #13 and #14. It is described by relatively low maximum values of the load capacity. Its advantage is a very smooth decrease of this indicator as extreme deformation is increased.

The best shape retention with a significant reduction of cross-section was obtained for five-element frames. They are implemented for models #17 and #18.

Conclusions. By means of physical modeling, the performance of several variations of combined support systems that use frame support has been investigated. The conditions for maintaining of reuse gateroad were modeled. The novelty of the experimental study consists of the simultaneous use of several support structures along with a variation of their parameters. Increasing of the parameters for the security system was established when sprayed concrete to the frames had been applied along with a reinforced filling body. The results obtained could be applied to the development of support as well as reinforcement of a coal mines gateroads with a direct-flow ventilation system.

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МОДЕЛЮВАННЯ РОБОТИ КОМБІНОВАНОЇ СИСТЕМИ КРІПЛЕННЯ В СКЛАДНИХ ГІРНИЧО-ГЕОЛОГІЧНИХ УМОВАХ

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Анотація. Метою досліджень було встановлення характеру деформації рамного кріплення в складі комбінованої охоронної системи. Окрім того, нашим завданням було вивчення руйнування породного масиву навколо гірничої виробки. Робота виконувалась на замовлення ПАТ «Шахтоуправління «Покровське».

Попередні дослідження показали, що можливості математичного моделювання комбінованої охоронної системи обмежені. Це пов’язано з об’ємним характером моделі та нелінійним деформуванням окремих елементів. Для цього дослідження були зібрані дані про будову породного масиву навколо гірничої виробки. Породний масив представлено шарами вугілля, алевроліту та пісковику. Комбінована охоронна система містила раму, анкери та литу смугу. Використано моделі рам різної форми та перерізу. Фізична модель відповідала ділянці підготовчої виробки повторного використання. Використано метод еквівалентних матеріалів. Масштаб моделювання складав 1 : 50. Для стримування поперечних деформацій призначена дерев’яна оболонка. Модель навантажувалась на жорсткій випробувальній машині в режимі постійної деформації. Швидкість деформування складала приблизно 0,05 мм за секунду. Досліджувалось 19 варіантів моделей з різними комбінаціями параметрів кріплення. Для кожної моделі визначено граничне стискаюче навантаження. Отримано залежності зміни площі поперечного перерізу виробки від прикладеного навантаження. Виділено три характерні ділянки роботи кріплення: зростаючого опору, спадаючого опору та залишкового постійного опору. Визначено умови вдавлювання стояків в підошву виробки. Встановлено, що збереження форми кріплення покращується зі зростанням кількості ланок.

Результати досліджень показали підвищення опору кріплення при нанесенні набризкбетону на раму. Дослідження підтвердило також ефективність застосування підсиленої литої смуги. Для найбільш важких умов рекомендовано використання замкнутого кріплення. Результати роботи можуть бути використані при проектуванні прямоточних схем провітрювання виїмкових дільниць вугільних шахт.

Ключові слова: вугільна шахта, породний масив, рамне кріплення, комбінована система кріплення, фізичне моделювання.

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