DETERMINING THE EFFICIENCY AND PARAMETERS OF RUBBLE STRIP REINFORCEMENT

The necessity of development and improvement of methods and means for the protection of preparatory roadways, in particular, protective structures, was proved on the basis of ordinary rock with binding surfaces. Analysis of the results of the study on the use of protective structures of ordinary rock and bounding surfaces was performed. It has shown the feasibility of reinforcing rock structures to ensure operational conditions for the protected roadways. Such structures include rubble strips reinforced with partitions made of metal mesh. To determine their efficiency and reinforcement parameters, studies were performed using provisions of structural mechanics, soil mechanics, and bulk media, as well as physical modeling using natural materials.

According to the results obtained in the performed studies, the efficiency of reinforcement of rubble strips with a metal grid was proved and a procedure for calculation of reinforcement parameters that need to be considered in designing the above structures was developed. Such parameters include width and height of the strip, class of reinforcement, its diameter and tensile strength, size of the grid cells, angle of internal friction of rocks, and diameter of maximum rock pieces in the strip.

It was established that reinforcement of the rubble strip by partitions made of metal meshes can reduce the width of the strip and volume of the rock fill by 1.33...2.66 times without losing the structure rigidity. To do this, the condition of reinforcement strength in grids must be met. It consists of comparing its tensile strength with maximum stresses in the partition. These stresses are determined by the magnitude of the load on the rubble strip from the roof rocks, the diameter of the reinforcement, and the maximum rock pieces, as well as relative extensional strain in reinforcement

Keywords: rubble strip, bounding surface, metal mesh, physical modeling, strength condition, reinforcement parameters

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1. Introduction

With an increase in depth of mining operations in conditions of coal mines, the problem of ensuring the operational condition of preparatory roadways is becoming increasingly difficult. This condition depends on a large number of geological and mining factors. In order to reduce the cost of roadways and ensure high loads on walls, special attention is paid to excavation systems with the reuse of roadways and efficient ventilation of excavation sites. This solves several complex problems related to the development and implementation of shoring and protection systems [1], providing direct-flow ventilation [2], roof management [3–5], monitoring the condition of mine roadways [6]. Particular attention is paid to the development and improvement of methods and means for the protection of preparatory roadways behind the breakage face.

All over the world, preparatory roadways behind walls are mostly protected in a massif and coal pillars [7]. Pillars are destroyed at high external loads and are unable to ensure the operational condition of roadways [8, 9] and safe excavation conditions for miners [10, 11]. There are also cases when leaving pillars to protect roadways is unacceptable because of significant losses of minerals [12–14] or the tendency of coal to self-ignite [15, 16]. In such cases, technologies are used when artificial structures made of wood [13, 17], concrete [18], ordinary rock [19, 20], etc. are used instead of coal pillars.

It is obvious that these structures must be practically feasible, low-cost, and provide effective protection of roadways. The cheapest in terms of material costs are protection means involving the use of ordinary rock. But because of their significant pliability, they cannot be considered effective. Therefore, it is necessary to improve them in order to reduce their pliability and improve bearing capacity.

Rubble strips are conventional protection means based on the use of ordinary rock. The possibility of leaving the rock in mines has influenced the popularity of this technology. It was proved that rubble strips are cheaper than other means, practically feasible in the mechanization of their erection and the initial costs are compensated by reducing the cost of maintenance of roadways and cost of rock disposal [21]. However, these structures have their own disadvantages including large amounts of rock, a high proportion of manual labor in its movement and laying, low load-bearing capacity, and significant pliability. These shortcomings prompt us to find new engineering solutions to raise the bearing capacity of the strips while reducing the required volume of rock. Therefore, studies on the efficiency and parameters of reinforcement for rubble strips are relevant.

2. Literature review and problem statement

To reduce the pliability of the rubble strip and increase its bearing capacity, engineering solutions are increasingly being introduced into its construction. These solutions are mostly related to the use of various bounding surfaces which use wooden racks, fabric, rubber, or paper covering, metal sheets or rods, and the like. New materials for bounding surfaces have also appeared: high-strength steel, fiber-reinforced polymer, and geogrid [19].

A method of increasing the bearing capacity of rubble strips by creating pre-spacer anchors that are tightened between racks is proposed in a patent [22]. Fences and support struts in the structure are made flexible in horizontal and vertical directions with the possibility of drawing together the fences when tightening anchors between fences and moving the filling rock. This makes it [possible to increase the strip density and load-bearing capacity. This technology is known as an invention that does not specify what and how is to be used to tighten anchors between fences after filling the area between them with rock. That is, the issues of strip spacing technology remain unresolved.

To increase the rigidity of the rock structure, it was proposed to use rigid separating gaskets between rock layers in the line of the height of the structure. In [23], rock supports with gaskets made of dense cardboard, wood, or plastic were tested until the gaskets were destroyed. It was established that division of the support into layers by rigid gaskets significantly increases its bearing capacity. Division of the support by gaskets made of weak materials was not considered but it was suggested that such a solution is implementable as well. The process of regulating the compression characteristics of a separately standing rock support with rigid gaskets was described in [24] with reference to the results of laboratory studies. Only the width and height of the support were taken into account as well as the number of rigid gaskets along the height of the structure. The possibility of a loss of bearing capacity of such support at the destruction of partitions was supposed. It was established that division of the support into layers by collapsible rigid gaskets leads to

a decrease in its rigidity and when the width of the support is more than 6 times the height, such gaskets are inefficient. That is, gaskets between layers should not break. Then a bearing core is formed in each layer between the gaskets. Its width depends on the height of the corresponding layer because the size of the edge zone of the layer is equal to its height. It is with decreasing the layer height that size of the core zone increases. The more layers in the rock strip, the larger the load-bearing core, the stiffer the structure, and the higher the load-bearing capacity of the whole structure. Thus, the use of rigid gaskets can increase the bearing capacity of the rubble strip and reduce the volume of embedded material (rock). However, the creation of such a structure is too hard because there will be a problem with transportation and movement of metal sheets to the place of their laying.

There are technologies that do not involve direct reinforcement of the rock volume but the filling of special shells. For example, in British mines, protective structures were lined with paper bags reinforced with wire. The bags were filled with ordinary rock directly in the face [25]. A technology similar to this method has been proposed, however, reinforced strong fabric was used as a shell which was to outline the rock pedestals [26]. This method involved pneumatic delivery of crushed rock in this shell via a pipeline. The need for crushing embedded material and additional devices has limited application of this technology.

Another approach was implemented in the technology when a solid wall of bags filled with coal waste mixed with rock was built in layers along the roadway. The bag shells can be plastic or fabric. A technology when a wall erected of bags filled with rock was both a means of protection and formwork for closing the excavated space is described in [27]. The main disadvantages of the technology include high complexity and the long duration of the work. However, the use of bags with rock enables isolation of preparatory roadway from the goaf, reduction of displacement in protected roadways, and creation of safe working conditions [28]. The pliability from 17 to 34 % was provided. However, this method showed the following disadvantages in its tests: the need for a large quantity of bags, inability to control the density of bag filling which causes an up to 34 % increase in the pliability of the strip built of bags. It was noted in [19] that the costs of implementing this method are acceptable for coal mines due to the use of coal waste. But it was indicated that the load-bearing capacity of the walls was about 3 MPa. It was not enough to cut layers of the immediate roof and there was a need for additional strengthening measures. That is, there is also a need for improving this method to ensure its widespread use.

Separately located rock supports with flat and writhing gaskets made of fabric and metal mesh laid between the rock layers were tested. It was established that the proposed structures have a high load-bearing capacity. With three gaskets made of metal mesh, the shrinkage of supports was 12–14 % [29]. Supports with four fabric gaskets had a lower bearing capacity and allowed a 25 % shrinkage [30]. These results only qualitatively indicate the effectiveness of the technology because granite rubble was used in the models instead of mine rock. The influence of grid parameters on the stability of supports was also not considered.

The technology of reinforcing the rubble strip with metal mesh was tested in a coal mine (Fig. 1) [31]. Recommendations for its use were based on the results of physical and numerical simulations, were purely experimental in nature

without careful selection of mesh parameters in partitions. In particular, the influence of stability of reinforced rubble strips, their width, and fractional composition of the laid rock was not considered.
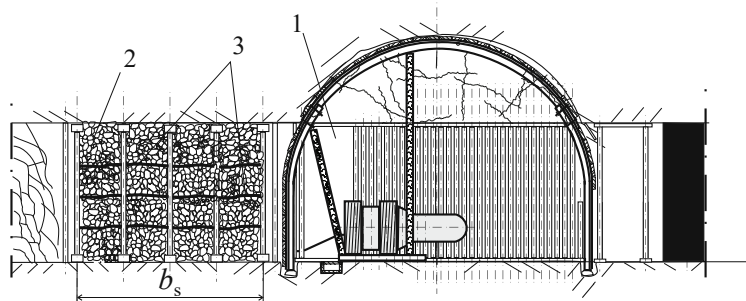

Fig. 1. Manufacturing scheme of protection of preparatory roadways behind a wall with a rubble strip having metal mesh partitions [31]:
1 — roadway; 2 — ordinary rock in a protection structure;
3 — partitions; b_s — strip width

Reduction of the pliability of the rock support was achieved when laying three partitions made of metal mesh [31]. However, parameters of metal mesh at which the process of their laying would be practically feasible and low-cost were not considered when designing and testing the method. Therefore, the question of determining parameters of the partitions made of metal mesh (diameter of rods, steel grade, size of mesh cells) remains open and requires scientific justification. Therefore, it is advisable to conduct additional studies to substantiate the efficiency and parameters of reinforcement of the rubble strips.

3. The aim and objectives of the study

The study objective was the substantiation of the efficiency and parameters of the rubble strip reinforcement. This would make it possible to consider reinforced rubble strips as effective resource-saving means of protection that can ensure operational condition in the preparatory roadways for their reuse. The study results can be used in designing the mining operations.

To achieve this objective, the following tasks were set:
– test reinforced rubble strips taking into account their geometric parameters and granulometric composition of the embedded material;
– develop a method of calculating parameters of partitions made of metal mesh.

4. Materials and methods used in the study

The rubble strip is a protective structure that is continuously built along the mine roadway behind the breakage face. In its width, the strip is a rockfill of limited size and in height, it is limited by the coal bed thickness. Guiding documents of branch research institute strictly define the width of rubble strips depending on the bed thickness. According to [32, 33], the strip should be at least $8m$ (where m is the thickness of the bed which is equal to the initial height of the fill h_s). This parameter is determined by the condition

of formation of a bearing core C (Fig. 2) in this fill by the consolidation of the rock pieces under the action of lateral resistance F in peripheral zones P.

As the load on the fill increases from the side of the roof, a bearing core (central zone) is formed and takes the main load. Reduction of the fill width leads to a decrease in the core and the degree of resistance to the applied load σ_c. An increase in height of the fill requires an increase in its width to ensure the stability of this structure.

As the width and height of the rock fill decrease, it is extremely difficult to ensure its stability because of the natural properties of the embedded material. This material is represented by a non-bound bulk medium and has the property to withstand significant compressive forces and be unresisting to tensile forces. Under the action of vertical forces, each rock piece behaves like a wedge, so there are horizontal forces that lead to the mobility of pieces of the rock body in the horizontal plane. Therefore, one of the solutions to reduce parameters of rubble strips and increase their bearing capacity is the use of special partitions with design features at which reduction in mobility of rock pieces is provided.
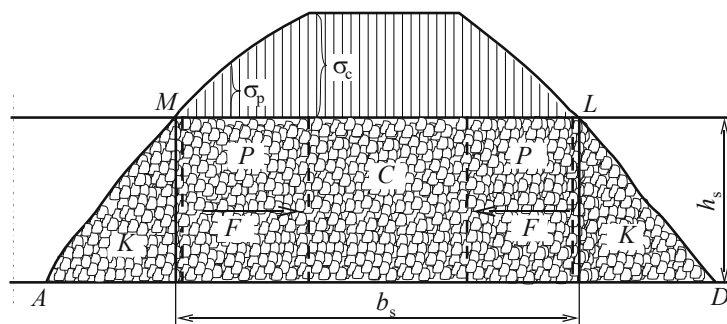

Fig. 2. Diagram of characteristic zones of free rock fill $AMLD$ [34]:
C — central zone (bearing core); P — peripheral zones; K — zones of free slopes; b_s — width of fill in contact with the roof; h_s — height of fill; σ_c and σ_p — stress in the central and peripheral zones, respectively

Geogrid [35–39] which resists to tensile stresses and does not resist to compressive stresses is widely used in construction. In compacted soils, the mesh adds to the stability of structures. In a loose medium, local tensile stresses are transmitted to geogrid resulting in their redistribution to neighboring areas. This principle forms the basis of rubble strips with partitions of metal mesh which divides this structure into separate layers, each being a separate fill.

The process of forming the reaction of rock supports with free slopes separated by rigid gaskets was studied in [23, 24]. The stability of each layer in the support between the gaskets is provided by its width b_s to height h_s ratio up to 5...7. At an assumption that the usual rubble strip is a single layer, the ratio b_s/h_s, equal to 8 [32, 33] is natural to ensure the stability of the strip.

When implementing this method, it is quite problematic to transport rigid gaskets to the place of laying. At insufficient coefficient of friction of rock, stability and bearing capacity of the structure are lost on the gasket. The gaskets become sliding planes for the bulk material. Therefore, this method needs to be improved while maintaining the basic principle: ordinary rock with bounding surfaces should be used. It is the bounding surfaces that must have such prop-

erties and dimensions at which a sufficiently stable rock structure is formed.

The effect of the use of flexible partitions should be provided by increasing the forces of friction and adhesion between the rock particles which will resist the horizontal forces leading to the mobility of particles in the fill (Fig. 3). The partition must be rough to provide fixation of rock particles that come into contact with it. An effective solution may be the use of mesh partitions of metal, geosynthetics, etc. Such structures are widely used in construction to strengthen weak soils.
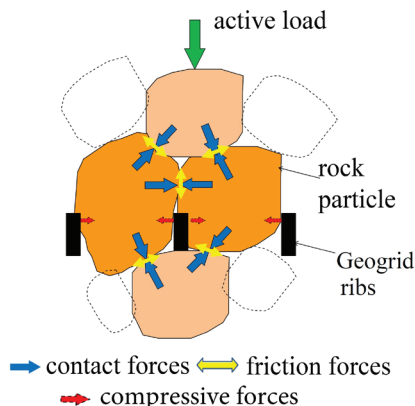

Fig. 3. Rock particles stuck in the geogrid block [38]

In conditions of protection of mine roadways, the reinforced rubble strip is built in layers between the roof and the floor of the coal seam. Partitions from metal grids are laid between layers. Due to the grid properties, blocking of rock particles in the protective structure and reduction of their mobility is ensured. Such properties include the roughness of partitions and their ability to change shape depending on the unevenness of the surface of the rock body with an increase in the contact area with the rock fractions. This solution has formed the basis of the utility model UA 137375 [40] shown in Fig. 1.

Analysis and generalization of present-day scientific and technical achievements in the field of protection of preparatory roadways by protective structures built of ordinary rock allow us to pass to determining the parameters of reinforcement of rubble strips. For this purpose, provisions of structural mechanics, soil mechanics, and bulk medium as the main foundation material will be used. To determine the effectiveness of reinforced rock structures, it is advisable to carry out physical modeling on natural materials.

5. The results obtained in studies on ensuring the stability of rubble strips

5. 1. The results obtained in testing reinforced rubble strips

The bearing capacity of the rubble strip depends on its width and the granulometric composition of rocks. When partitions from mesh structures are used, it is necessary to consider their roughness, rigidity, cell size, etc. Peculiarities of the process of load transfer in supports of ordinary rock were investigated and dependence of the width of the rubble strip on main influencing factors were established in [41] on a condition that balance in the geotechnical system "wall rocks-rubble strip" are satisfied.

$$b_s = h_s \frac{\text{tg}^2\left(45° - \dfrac{\rho_s}{2}\right)}{f_c} \ln \frac{k_o \gamma H}{R_w}, \qquad (1)$$

where h_s – height of the rock fill, m; ρ_s – angle of internal friction of rocks, deg.; k_o – coefficient of stress concentration at the contact of the fill and roof rocks; γ – volume weight of rocks, MN/m^3; H – depth of roadway placement, m; R_w – reaction of the peripheral zone and free slopes, MPa.

To establish parameters of rubble strips reinforced with metal mesh, laboratory tests of rock fills were carried out (Fig. 4) [42]. Structural models of rock-mesh structures with various parameters were prepared. Further, models were loaded in a press with the recording of load and shrinkage of each fill. Processing of load and shrinkage measurements has resulted in establishing quantitative dependences of bearing capacity and pliability of reinforced rock supports on influencing factors. Parameters, such as granulometric composition, height, width were changed in the process of testing a series of models.

The following similarity criteria were observed during preparation and testing of the structural models [43]:

1. Geometric similarity

$$\left(\frac{l_m}{l_n}\right) = \text{const}, \qquad (2)$$

where l_m and l_n are the linear dimensions in models and in kind, m, respectively.

2. Equality of the angle of internal friction of the model material (ρ_m) and crashed rocks (ρ_n)

$$\rho_m = \rho_n. \qquad (3)$$

3. Force similarity

$$P_m = P_n \left(\frac{l_m}{l_n}\right)^3 \cdot \left(\frac{\gamma_m}{\gamma_n}\right), \qquad (4)$$

where P_m and P_n – magnitude of the force in the models and in kind, respectively, kN; γ_m and γ_n – specific densities of the model material and rocks, respectively, N/m^3.

4. Similarity of mechanical characteristics

$$N_m = \left(\frac{l_m}{l_n}\right) \cdot \left(\frac{\gamma_m}{\gamma_n}\right) \cdot N_n, \qquad (5)$$

where N_m and N_n – are mechanical characteristics in the model and in kind, respectively, kPa.

A model was prepared on a modeling scale of 1:30. It was a welded steel structure from channel No. 10P measuring 0.55×0.4 m, to which rear and transparent front walls were attached (Fig. 4). Protective material with varied sizes of rock particles was placed inside the structure in turn without laying and with the laying of mesh partitions. The grid wire was 0.5 mm in diameter which corresponded to 0.015 m in kind and cell size was 6×6 mm (0.18×0.18 m in kind).

A series of models were tested at varied values (0 to 15 kN) of load acting on the protective material. Each model was tested in stages with a gradual increase in the load and the amount of the structure shrinkage was recorded.

It was found that the pliability of the 6 to 3 h_s wide fills with varied rock particle size was from 16 to 65 % in models

without a partition and from 13 to 42 % in models with a partition. Minimum values of pliability referred to $6\,h_s$ wide supports with rock particles of maximum size and maximum pliability were recorded in $3\,h_s$ wide supports with the smallest rock fraction.

Significant (65 and 62 %) vertical deformations were observed with $3\,h_s$ and $4\,h_s$ wide nonreinforced rock strips, respectively (Fig. 5). These deformations were accompanied

by horizontal displacements which amounted to 65...89 % of the vertical ones (Fig. 6). The granulometric composition had almost no effect on the result. Horizontal displacements measured 13...25 % of the vertical ones for a free $6\,h_s$ wide fill depending on the size of the rock fractions (Fig. 6). That is, we can assert that the rubble strip provides the least pliability at a given width, and the influence of the granulometric composition of rocks is insignificant in it.
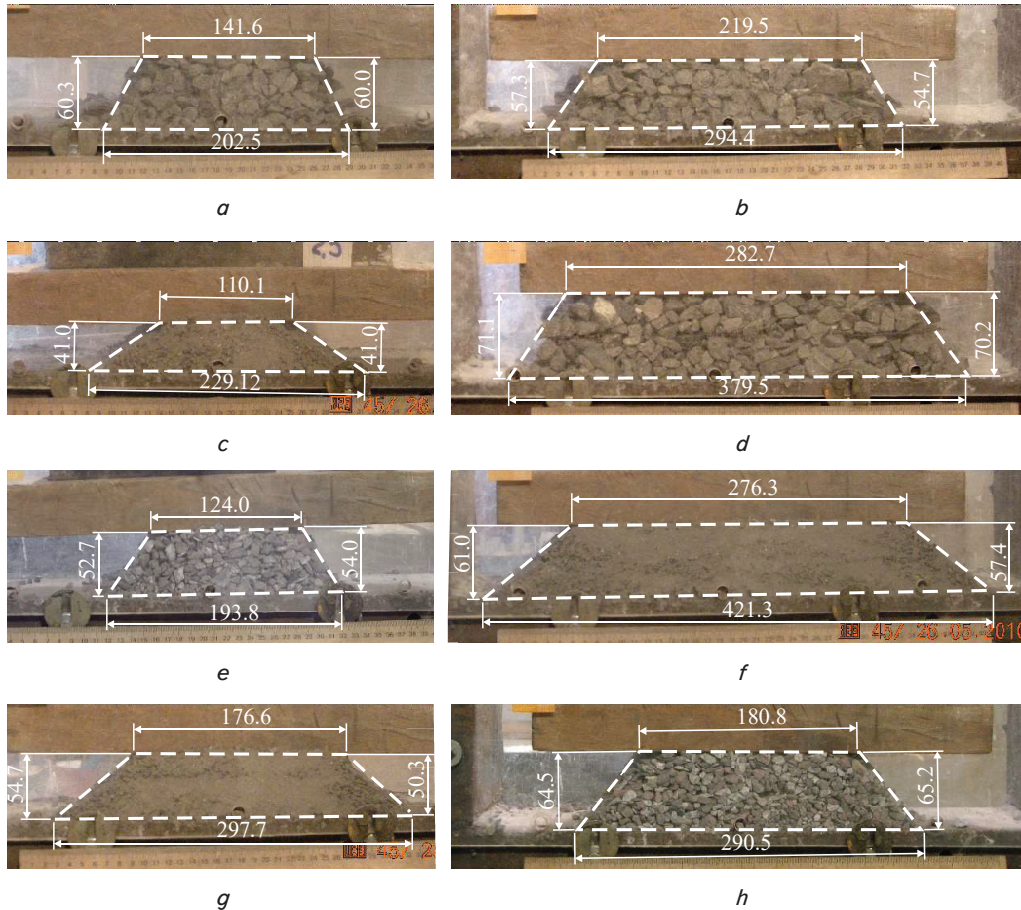

Fig. 4. General view of reinforced rock structures with current dimensions (mm) under loading at different fractions d_f and initial width b_s: $a - d_f=(0.15...0.27)\,h_s$, $b_s=3\,h_s$; $b - d_f=(0.15...0.27)\,h_s$, $b_s=4\,h_s$; $c - d_f<0.08\,h_s$, $b_s=3\,h_s$; $d - d_f=(0.15...0.27)\,h_s$, $b_s=6\,h_s$; $e - d_f=(0.08...0.14)\,h_s$, $b_s=3\,h_s$; $f - d_f<0.08\,h_s$, $b_s=6\,h_s$; $g - d_f<0.08\,h_s$, $b_s=4\,h_s$; $h - d_f=(0.08...0.14)\,h_s$, $b_s=4\,h_s$
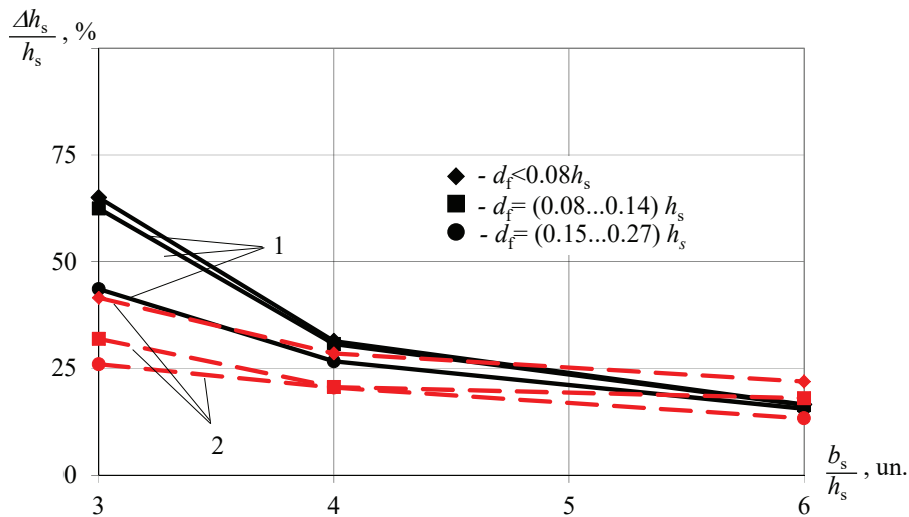

Fig. 5. Charts of dependence of relative shrinkage of the rock strip Δh_s on its width to height ratio b_s/h_s for various granulometric compositions d_f of the country rocks (1, 2: non-reinforced and reinforced strips, respectively)

Pliability was 42 %, for 3 h_s wide rock strips divided into two layers by a mesh partition and 32 and 26 % for 4 h_s and 6 h_s wide strips, respectively (Fig. 5). Ratios of horizontal and vertical shifts for the widths of 3 h_s, 4 h_s, and 6 h_s varied for different fractions in ranges 54...62 %, 36...60 % and 16...18 %, respectively (Fig. 6).

Thus, we can assert that presence of a partition is effective when the width of the rock strip is less than 6 h_s. Under the same conditions, the pliability of reinforced protective structures with a width of 6 h_s corresponds to the pliability of the rubble strip with a width of 6 h_s built by conventional technology. This width can be reduced to 3 h_s for reinforced strips with a coarse filler. Therefore, laying of a partition can reduce the width of the strip by 1.33 or more times without losing bearing capacity and, accordingly, reduce the volume of required rock. Change of granulometric composition in reinforced structures of different widths makes it possible to change pliability by 8...16 % including up to 8 % at a width of 6 h_s. Additionally, a decrease and stabilization of horizontal displacements (Fig. 6) and formation of a bearing core occurred with a fraction of 0.11 h_s.
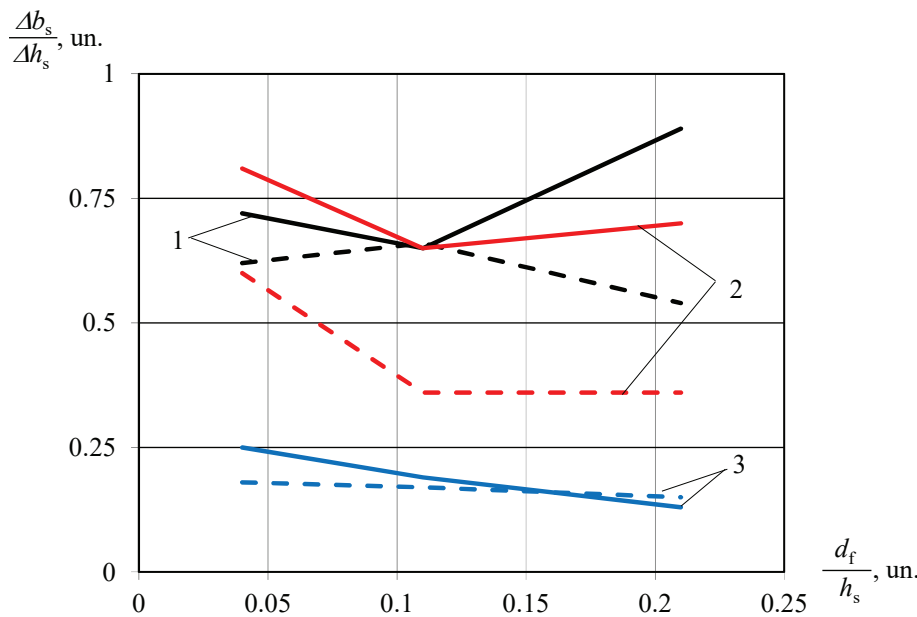

Fig. 6. Charts of dependence of the ratio of horizontal and vertical shifts of rock strips $\Delta b_s / \Delta h_s$ on the relative size of rock particles d_f / h_s (1, 2 and 3 — for the strip width of 3h_s, 4h_s and 6h_s, respectively; solid and dashed lines: nonreinforced and reinforced strips, respectively)

The obtained results indicate that the movement of rock particles in the non-reinforced rock strip is more intense and its bearing core is formed with a delay. The strip with a partition begins to withstand loads acting at an early stage.

5. 2. Development of methods for calculating the parameters of partitions made of metal mesh

Mesh structures are key elements in reinforced rock strips. They help reduce shear stresses in these layers in the contact zone between rock layers. The movement of adjacent moving particles is limited due to the engagement of rock particles in the mesh cells. Lateral expansion of the strip is prevented and its bearing capacity increases. That is, the main role in the strip is given to reinforcement.

As the results of numerical studies [39] show, the presence of reinforcement with a large rod diameter or high density of

reinforcement involving a larger mass of soil is the most important factor in reinforcement. The maximum distance between rods in any reinforcement should not exceed 8 rod diameters.

The diameter of the reinforcement rods determines the ability of the grid to withstand breaking loads and the size of the cells determines the quality of engagement of rock particles. Therefore, in addition to reinforcement density, the tensile strength of reinforcement should be included to main characteristics of mesh elements of the rock strip. Since reinforcement is made of round rods and must have sufficient tensile strength, the condition for its strength has the form

$$\frac{4F}{\pi d^2} \le \left[\sigma_p\right], \tag{6}$$

where F – the force tensioning the rod, H; d – the rod diameter, m; $[\sigma_p]$ – allowable stress in the rod during tension, MPa.

Flexible reinforcement is identified in the calculations with a thread, so to determine parameters of rods in the mesh partitions, we shall use provisions of the theory of flexible threads [44].

The action of vertical forces results in a partial spreading of the reinforced support and the rods are affected in any direction by the loads that decrease with depth. The vertical load applied to the upper surface of the rock support is maximum (Fig. 7). The forces of lateral pressure act in the horizontal plane. Since the tensile strength of the reinforcing bars is considered at maximum loads, it is necessary to take into account the load acting on the support from the roof rocks σ_c.

Under the action of the load q (N/m), the reinforcement rod sags by f (m) at a limited span length l (m). The action of the load will be accompanied by the occurrence of the force that tensions the rod F (H) and elongates it by Δl. Then tension of the rod is determined by the expression [44]

$$F = \frac{ql^2}{8f}, \tag{7}$$

and stress in the middle of the span

$$\sigma_1 = \frac{ql^2}{2f\pi d}. \tag{8}$$

A condition of tensile strength of the reinforcement is obtained

$$\frac{ql^2}{2f\pi d} \le \left[\sigma_p\right], \tag{9}$$

in which the rod sag in a segment of length l is unknown (Fig. 8). In the worst situation, this length for a dense rock filling will be equal to the diameter of the largest piece d_f, and the acting force is applied at the span center.
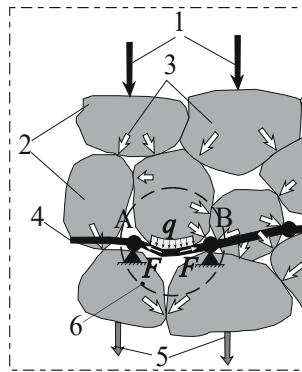
Fig. 7. Calculation diagram for determining the distribution of loads in the reinforced rock support: q — the load that affects sagging of the rod in the segment AB; F — the force tensioning the rod
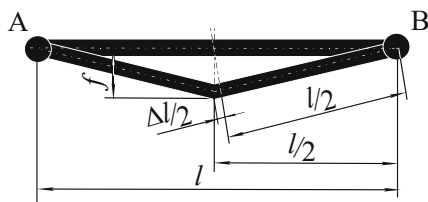

Fig. 8. Diagram of calculating the rod sag in the segment AB

According to the diagram (Fig. 8), the sag of the rod in the segment AB can be calculated from the expression

$$f = \sqrt{\left(\frac{l}{2} + \frac{\Delta l}{2}\right)^2 - \left(\frac{l}{2}\right)^2},$$

where Δl – the value of rod elongation under the action of the load that caused sag of the rod, m, equal to $\Delta l = \varepsilon_{ub} l$ (where ε_{ub} is ultimate relative deformation of the reinforcement elongation followed by the rod failure. It measures 0.014 to 0.02 corresponding to the reinforcement class [45]).

Then

$$f = \frac{l}{2}\sqrt{\varepsilon_{ub}\left(2 + \varepsilon_{ub}\right)}. \tag{10}$$

When $q = \sigma d$ (where σ is stress from the roof rock load), the strength condition (9) will take the form

$$\frac{d_f}{\sqrt{\varepsilon_{ub}\left(2 + \varepsilon_{ub}\right)}\pi d}\sigma \leq \left[\sigma_p\right]. \tag{11}$$

When condition (11) is met, mesh partitions will not be destroyed but will help maintain the stability of the rubble strip. Otherwise (if the condition is not met), there will be breaks in the reinforcement in the most loaded areas (Fig. 9). First of all, the structures in the center of the support will break as stresses in the rock support decrease from its center to the edges according to the exponential law [41]. However, at some distance from the support center, stress will not exceed the strength of reinforcement. Then the mesh structures will not collapse and will stay effective in marginal zones (peripheral zones and zones with free slopes).

Width of the zone of the possible destruction of the mesh partition bp (m) with (1) and (11) when $R_w = \sigma$ can be determined from the formula

$$b_p = h_s \frac{\text{tg}^2\left(45° - \frac{\rho_s}{2}\right)}{\text{tg}\rho_s}\ln\left(\frac{k_o \gamma H}{\left[\sigma_p\right]}\frac{d_f}{\sqrt{\varepsilon_{ub}\left(2 + \varepsilon_{ub}\right)}\pi d}\right). \tag{12}$$

Calculations according to this formula can show both positive ($b_p > 0$) and negative ($b_p < 0$) values which indicate destruction and preservation of the structural integrity, respectively.
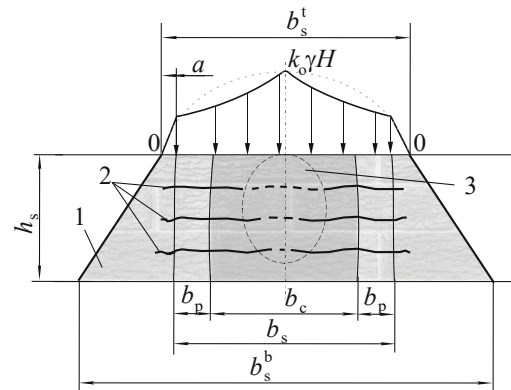

Fig. 9. Diagram of formation of zones in the rock support 1 with mesh partitions 2: h_s — height of the support; b_s^t and b_s^b — width of the support in a contact with the roof and sole, respectively; b_c, b_p — width of the core and peripheral zones, respectively; b_s — active width of the rock fill; a — width of the zone with free slopes at the contact of the support with the roof; 3 — the zone of the possible destruction of partitions

The issue of mesh cell sizes is well studied in the design of reinforced foundations for structures and buildings, so there is no need for a more thorough study of this issue. It was proved that corrugated reinforcement rods concentrate more friction force than smooth ones. The greatest efficiency of contact interaction is guaranteed by the geogrid [39]. The coefficient of friction of rock particles on the grids depends on the ratio of dimensions of their cells L_c and the average weighted particle diameter $\overline{d_f}$. Effective size of the cells should be determined by the condition [39]

$$2{,}2\overline{d_f} \leq L_c \leq 5\overline{d_f}, \tag{13}$$

and, as it was indicated earlier, must exceed 8 rod diameters.

6. Discussion of the results obtained in the study on determining the parameters of the rubble strip reinforcement

Based on the results obtained in determining the efficiency of reinforcement of rubble strips, it was found that the use of metal mesh for their reinforcement reduces shrinkage of the strip (Fig. 5). The strip width and volume of required rock can be reduced from $8h_s$ to $(3...6)h_s$, i.e. 1.33...2.66 times. It should be noted that the pliability of the reinforced $3h_s$ wide strip will be equal to the pliability of the $8h_s$ wide strip without reinforcement (which is regulated by guidelines) and will be about 60% (Fig. 5). Pliability will not exceed 18 % at the reinforced strip width of $6h_s$ (Fig. 5). The granulometric composition will not matter. By separating rock fractions with grain sizes from $0.08h_s$ to $0.2h_s$ and laying them in a $6h_s$ wide strip, a reduction in its pliability

from 16 to 8 %, respectively, can be achieved. Thus, the presence of metal mesh partitions in $3h_s$ to $6h_s$ wide rubble strips (where h_s is the initial height of the structure) makes it possible to provide pliability from $0.08h_s$ to $0.6h_s$, respectively, (Fig. 5). This confirms the effectiveness of the technology of reinforcement of strips by partitions made of metal mesh due to which bearing capacity can be raised by increasing adhesion and reducing displacements between the rock particles. The method scope is not limited by bed thickness and strength of the surrounding rocks because the reinforced rubble strip is relatively stable and does not require a large volume of rock at a significant bed thickness.

Parameters of metal grids should be determined taking into account the size of cells in partitions and according to the condition of the strength of reinforcement in grids (11) which was obtained in the studies. According to condition (11), the tensile strength of reinforcement is compared with maximum stresses in the grid which are determined by the magnitude of the load on the strip, diameter, and class of reinforcement, and diameter of maximum rock pieces. For example, let us consider the condition of the strength of steel reinforcement of class A600 (σ_p=630 MPa and ε_{ub}=0.02) with a diameter of 0.008 m. For a maximum piece size of 0.1 m and a load of 15 MPa, the left side of the condition (11) will be equal to 300 MPa for vertical stresses and 99 MPa for horizontal stresses. That is, condition (11) is fulfilled and the partition made of metal mesh can withstand existing loads without its destruction.

In certain cases, mesh partitions will be destroyed in local areas when the stresses acting in the reinforcement exceed their tensile strength [σ_p]. Then the width of the zone of the possible destruction of each partition (Fig. 9) should be determined by expression (12). According to (11), destruction of partitions can be caused by the action of excessive loads, insufficient diameter, and relative strain of the reinforcement as well as large size of the rock fractions in the strip.

The obtained results can be used in designing rubble strips reinforced with metal mesh partitions and can serve as a basis for substantiation of parameters of strips with geogrids and grids made of composite reinforcement.

Further development of this study may consist in determining the optimal density of reinforcement and the search for engineering solutions to raise the level of mechanization of works when building reinforced strips. Experimental and industrial verification of the technology in different mining and geological conditions is important, as it was tested only at one excavation site.

7. Conclusions

1. Rubble strips reinforced with metal grids were tested on physical models. Grids promote self-wedging of rock particles at the initial stage of strip loading, do not allow expansion of strips at the moment of formation of bearing cores, and essentially change loading and deformation characteristics of structures. Reinforcement will reduce structure width by 1.33...2.66 times which can be 3...6 times more than the height, regardless of fraction size. Then pliability of the reinforced strip will be 60...8 %, respectively. The main parameters that determine the efficiency of reinforcement of rubble strips include width and height of the structure, size of cells in partitions, tensile strength of reinforcement, and angle of internal friction of rocks.

2. A procedure for calculating parameters of partitions made of metal mesh was developed. It is based on the condition of reinforcement strength in grids when the tensile strength of reinforcement is compared with maximum stresses in the mesh. Maximum stresses are determined by the magnitude of the load acting on the structure, diameter, and class of reinforcement, and diameter of the largest rock pieces in the strip. The size of the mesh partition cells should be from 2.2 to 5 diameters of the largest rock piece in the structure and not more than 8 diameters of the reinforcement. Results of the performed studies can be used in designing effective resource-saving means of protection of preparatory roadways for their reuse.

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