

Calculation of parameters of anchor-sprayed concrete support vertical mining operations

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Abstract. The issues of assessing the stability and fastening of horizontal and vertical mine workings, considering various mining and geological conditions, are relevant. The study of scientific papers related to this problem has shown that a fairly large number of works are devoted to developing methods for calculating and applying anchor-sprayed concrete support for the walls of horizontal mine workings. At the same time, there is no design model for using such a support for the trunks of vertical mine workings. In the proposed work, the method proposed in the previous work of the authors [1] is used to calculate the parameters of the anchor support of the trunks of vertical workings. To develop a methodology for calculating the thickness of the sprayed concrete coating, a model of a quadrangular plate was adopted, and methods of the theory of elasticity were applied, similar to the problem of calculating boiler walls reinforced with anchor bolts, first solved by academician A.S.Leibenzon. As a result, a new formula for determining the thickness of sprayed concrete for vertical shafts is proposed, taking into account the steps of installing anchors horizontally and vertically and the influence of the lateral rebound coefficient under the action of a gravitational stress field. The problem of determining the strength limit of anchors on a slice interacting with a sprayed concrete coating is solved. An expression is obtained for determining the minimum value of the shear stress for the applied anchors at depth in rocks with a density; a formula is derived that allows determining the upper limit of permissible distances between anchor belts vertically, different from previously known similar formulas in that it takes into account the effects of the radius of the zone of destroyed rocks, the thickness of the sprayed concrete and the ultimate strength of the sprayed concrete. In addition, in its structure, there is a factor of the angle of inclination to the horizon of the most dangerous sliding plane. Based on the results obtained, it can be concluded that a technique has been developed that allows the calculation of a combined anchor-sprayed concrete support for small vertical shafts, optimize the values of the parameters of such support and create a corresponding mathematical model.

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1 Introduction

Throughout the existence of preparatory and capital workings, methods for assessing their stability, oriented for use in various mining and geological conditions, are of paramount importance [1]. Despite this, the unsatisfactory accuracy of the created calculation methods to the present time causes an urgent need to develop new and improved methods and to make predictions about the stress-strain state of mine workings exposed to various force factors caused, in particular, by the action of rock pressure, blasting, gravitational and seismic forces, as well as forces of tectonic origin [2]. Numerous articles and monographs devoted to various aspects of this problem, various approaches and methods of its solution testify to the reality of the expressed idea.

One of the main problems during the passage of mine workings is the choice of the support most suitable to these mining and geological conditions, which plays an essential role [3] in increasing the stability of the rocks containing the mining. Therefore, creating new support structures with lower material consumption and increased load-bearing capacity and adapted to use for various operating conditions is an urgent task [4], which is of great importance when sinking vertical and horizontal mine workings. The new construction of the anchor-sprayed concrete support used in recent decades satisfies the conditions imposed on the above-mentioned new structures [5,6]. Such support has unique properties inherent in both anchor and sprayed concrete supports. On the other hand, it is known that the use of self-standing anchorage (without combination with other types of support) is accompanied by several geological and technical disadvantages [7], such as the inability to protect the walls of the workings from humidity and seeping water. Spray-concreting eliminates just such disadvantages of anchor support. Because, during spraying [3,8], under the pressure of the concrete mixture created by the concrete spraying machine, a mixture of cement with fine sand particles is driven into the voids and cracks of the surface of the mine. After concrete solidification, the load-bearing capacity of the layer formed as a result of the interaction of the area of destroyed rocks with the introduced mixture of cement and sand increases [9, 10].

In the case of sprayed concrete support, there is no fixed space; contact with the supported rocks is formed on the surface of the workings. Such support immediately after application (erection) is included in the work, involving the weakened rocks in work to maintain the workings and creating a single bearing system "support - rock", which perceives the loads arising in the zone of the destroyed rocks from the action of rock pressure, gravity and other stresses [1, 11]. Therefore, based on the properties mentioned above of sprayed concrete, it can be argued that the best insulation of rocks, when anchored, is provided by a layer of sprayed concrete [12]. At the same time, the combination of these two types of support, anchor and spray concrete, gives a completely new support design. In such a support, such properties as high strength and load-bearing capacity of anchor support and reliable insulation and adhesion to rocks on the concrete support are very successfully combined and work effectively. On the other hand, by doing so, she finds herself in more favorable conditions, which allow for the maintenance of workings by a light construction of a sprayed concrete support [13, 14]. In most studies, the support calculation is carried out based on an elastic model [15, 16]. Rigid contact conditions and general boundary conditions are formulated for the elastic-malleable supports used [17, 18]. Together with the creation of new support structures for vertical and inclined mine workings, researchers pay great attention to determining the stability of the native massif around them [19] and issues of dynamic calculation, taking the support as a reinforced [20] or multilayer [21] plate. Summing up the above, it can be noted that, despite the available results, the tasks of assessing stability and forecasting, as well as calculating the parameters of the anchor-sprayed concrete support for vertical mine workings for

various mining and geological conditions are far from being solved and are an urgent problem at present. This article is devoted to determining the values of the optimal thickness of sprayed concrete, the strength limit of anchors on the cut, and the distance between their belts vertically when using a combined anchor-sprayed concrete support of small vertical shafts.

2 Methods

2.1 Determination of the thickness of the sprayed concrete

The calculation of the spray concrete coating is based on the methods of the theory of elasticity used in the calculation of quadrangular plates. With sufficient accuracy, it can be assumed that the spray concrete coating design scheme is similar to the problem of calculating boiler walls reinforced with anchor bolts, first solved by academician A.S.Leibenzon [11]. In this problem, the stress-strain state of an elastic triangular plate with sides a , supported to the wall by anchor bolts at the vertices of the plate, is investigated. It is assumed that the plate is loaded with a uniformly distributed load of q . Bending stresses in the center of the plate were found according to S.P.Timoshenko [15] in the following form

$$\sigma = 0.25q a^2 / \delta^2, \quad (1)$$

where δ is plate thickness.

If the strength limit of the plate material is $[\sigma_s]$, then the thickness of the plate is easily determined from the above formula, i.e.

$$\delta^2 = 0.25q a^2 / [\sigma_{gs}] \quad (2)$$

or

$$\delta = 0.5 a \sqrt{q / [\sigma_{gs}]}$$

it is noted that the development of the greatest stresses in the material of the plate loaded with concentrated loads takes place in the area of application of these loads. In our case, the concentrated loads represent the reaction forces of the anchor bolts on the plate.

Concerning the walls of vertical shafts, the plate should be considered a quadrangular plate with sides a and h . Here a is the step of installing anchors horizontally along the circumference of the cross-section of the trunk; h is the vertical installation step of the anchors or the vertical distance between the anchor belts. Then formulas (1) and (2) can be written in the following form, respectively

$$\sigma = 0.25q a h / \delta^2.$$

and

$$\delta^2 = \frac{0.25q a h}{[\sigma_{gs}]} \quad (3)$$

We will write the last formula in the form

$$\delta = \sqrt{\frac{ahq}{[\sigma_{gs}]}}. \quad (4)$$

To calculate the greatest stresses in the plate material in the area of loading by concentrated forces, as in [6], we will use the results of S.P.Timoshenko's research, which allow us to determine the value of the bending moment M , near the anchor installation points in the form of

$$M = \frac{q(1+\mu)a \cdot h}{4\pi} \ln \frac{\sqrt{ah}}{r_a} \quad (5)$$

where μ is shift ratio; r_a is the radius of the cross-section of the reinforced concrete anchor. Since the highest stress value

$$\sigma_{\max} = \frac{M}{W}, \quad \text{and} \quad W = \delta^2 / 6$$

where w the moment of resistance of the plate section, then from the last equality, taking into account (5), we will have

$$\sigma_{\max} = \frac{3(1+\mu)qah}{2\pi\delta^2} \ln \frac{\sqrt{ah}}{r_a}$$

from here

$$\delta = \sqrt{\frac{3(1+\mu)qah}{2\pi[\sigma_{gs}]} \ln \frac{\sqrt{ah}}{r_a}}. \quad (6)$$

When calculating concrete plates, in most cases, a value of 0.15 is taken for the shear coefficient. Then the last formula can be written as

$$\delta = 0.74 \sqrt{\frac{aqh}{[\sigma_p]} \ln \frac{\sqrt{ah}}{r_a}} \quad (7)$$

The obtained formula for calculating the thickness of the sprayed concrete plate generalizes the well-known formula of work [6] by the presence of a multiplier h - at the logarithm and in its argument in the root expression.

When applying the sprayed concrete, small cracks in the contour zone are filled. As a result, a certain hardened layer of rock is formed, which has a bearing property and works together with a sprayed concrete coating. At the same time, the sprayed concrete coating and the formed hardened layer of rocks are in a mutually rigidly coupled position. Therefore, they jointly resist the destructive effect of rock pressure, seismic loads, and loads of another nature.

The joint work of a sprayed concrete coating with a hardened rock layer rigidly bonded to it will be taken into account, following [6], according to the methodology proposed by J.S.Yerjanov [2]. According to this method, the value δ found by equation (7) is

represented as the sum of the thickness of the sprayed concrete δ_{sc} and the hardened layer adjacent to it δ_t i.e.

$$\delta = \delta_{sc} + \delta_t.$$

Let us consider the layers of rock and sprayed concrete working together as a composite plate for which the condition is known [6]

$$\delta_t = \delta_{sc} \frac{E_t}{E_{sc}}, \quad (8)$$

where E_t and E_{sc} are elastic modulus of hardened rock and sprayed concrete, respectively. Then

$$\delta = \delta_{sc} + \delta_{sc} \cdot \frac{E_t}{E_{sc}} = \delta_{sc} \cdot \frac{E_{sc} + E_t}{E_{sc}}$$

from here, we have the formula

$$\delta_{sc} = \frac{E_{sc}}{E_{sc} + E_t} \cdot \delta$$

which, taking into account (7), takes the form

$$\delta_{sc} = 0,74 \frac{E_{sc}}{E_{sc} + E_t} \sqrt{\frac{aqh}{[\sigma_{gs}]}} \cdot \ln \frac{\sqrt{ah}}{r_a}. \quad (9)$$

In the literature, in particular, in the monograph [10], it is noted that for a vertically loaded, uniformly distributed load q , sprayed concrete plate with some margin, it can be assumed that

$$q = \frac{a_1 \gamma}{2tg\psi},$$

where a_1 is anchor installation step; γ is density of rocks containing the production; ψ is the angle of internal friction of rocks. In the case of vertical trunks, instead of a value of a_1 , we will install anchors vertically equal to $-h$. On the other hand, the load on the sprayed concrete coating caused by the action of rock pressure acts at an acute angle. Therefore, in this formula, it is necessary to consider the coefficient of lateral expansion in the gravitational stress field. Thus, for a sprayed concrete layer applied to the walls of a vertical shaft, the above formula can be written as

$$q = \frac{h\gamma}{2tg\psi} \lambda. \quad (10)$$

When $\lambda < 1$ according to the hypothesis of academician A.N.Dinnik, the distribution of gravitational stresses in the rock mass containing the mine is assumed to be equal to

$$\lambda = \frac{\nu}{1 - \nu} \quad (11)$$

where ν – Poisson's ratio of the breed. Taking into account (10) and (11), the formula (9) takes the form

$$\delta_{sc} = 0.74 \cdot h \frac{E_{sc}}{E_{sc} + E_t} \sqrt{\frac{a \nu \gamma_c}{2tg\psi(1-\nu)[\sigma_{gs}]} \ln \frac{\sqrt{ah}}{r_a}}. \quad (12)$$

Note that the state of the rock corresponding to the value λ according to the formula (11) is attributed to sections of the sedimentary rock mass at relatively shallow depths. Note that the state of the rock corresponding to the value according to the formula (11) is attributed to sections of the sedimentary rock mass at relatively shallow depths. According to the work's author [19], it can be confidently assumed that the stress distribution can occur at depths up to 500 m. At great depths, the probability of hydrostatic distribution of gravitational stresses increases, i.e. $\lambda=1$. However, there are currently no reliable experimental data on the limits of applicability of these hypotheses. Moreover, according to the cited work, the results of determining the core characteristics of deep and ultra-deep wells (up to 2-10km) indicate the absence of clear dependencies between the values of elastic properties and the depth of rocks [19].

It can be noted that the proposed formula for determining the thickness of the spray (12) for vertical shafts is new and differs from the known ones used for horizontal workings [3,6,10] in that it contains the values of the anchor installation steps; both horizontally and vertically. In addition, it considers the influence of the lateral rebound coefficient according to the hypothesis of academician A.N.Dinnik, under the gravitational stress field.

2.2 The ultimate strength of anchors on the cut

When anchoring the trunk walls on one side of the cross-section, the anchors will work on the cut [1]. Indeed, by installing anchorage in the trunk wall, the adhesion between the layers or structural blocks is increased to the limit of the strength of the anchors per cut. To determine the strength limit of anchors on the cut, i.e., for anchors with the desired shear strength, the minimum value of the tangential friction stress arising on the sliding plane should be determined. To solve the problem, we will use the inequality for the friction stress obtained in [19]

$$\frac{\sigma_3 - \sigma_1}{2} \cos 2\alpha (tg\alpha - tg\psi_{fs}) > \tau_{fs} + \frac{\sigma_3 + \sigma_1}{2} tg\psi_{fs},$$

where σ_3 , σ_1 are accordingly, the maximum and minimum compressive main stresses; α is the angle of inclination of the sliding plane to the line of action of the minimum main stress σ_1 ; τ_{fs} is the friction stress on the sliding surface.

We will assume that within the zone of rock destruction after the implementation of cleavage along all cracks, the minimum possible values of horizontal stresses will approach

zero. Then the stress state of rocks in the contour array, within the zone of destroyed rocks, with some margin, can be characterized by the following relations

$$\sigma_{zz} = \gamma \cdot H; \quad \sigma_{\theta\theta} = 0; \quad \sigma_{rr} = 0.,$$

where γ is density of rocks; H is the depth of the rock.

Taking into account these values, the above equation, transformed into equality for the limiting case, takes the form

$$\frac{\gamma H}{2} \cos 2\alpha (tg 2\alpha - tg \psi_{fs}) = [\tau_{fs}] + \frac{\gamma H}{2},$$

where ψ_{fs} is the angle of internal friction of the rock.

As is known, the angle of internal friction of the rock ψ_{fs} in magnitude does not exceed the 40^0 degrees. Taking the worst case of angle values $\alpha = \frac{\pi}{4} + \frac{\psi_{TP}}{2}$ and, assuming $\psi_{fs} = 40^0$, we find

$$[\tau_{fs}] = \gamma H \left(\frac{1}{2} \cos 40^0 + \sin^2 20^0 \right)$$

By the nature of the task, it is clear that the strength limit of the anchor on the cut $[\sigma_{cp}]$ should not be less than $[\tau_{fs}]_{\min}$. From here

$$[\sigma_{cp}] \geq \gamma H \left(\frac{1}{2} \cos 40^0 + \sin^2 20^0 \right). \quad (13)$$

The resulting expression makes it possible to calculate the minimum required shear stress for the anchors used at a depth of H in rocks with a density of γ .

For example, at a depth of 250 m in the walls of the trunk of fine-grained siltstones with clay-carbonaceous cement with a density of $\gamma = 2.18 \frac{m}{M^3}$.

$$[\sigma_{cp}] \geq 272.5 \frac{H}{CM^2}.$$

For different types of anchors, the shear strength determined during special tests has different, but usually very high, values [19]. Thus, reinforced concrete anchors with a rod diameter of 18mm can withstand shearing loads of over 100 kN. At the same time, the value of shear stresses in the anchor section reaches 80 kN/cm^2 , which is hundreds of times higher than the minimum required value of adhesion (0.2725 kN/cm^2 at a depth of 250 m) between layers and structural blocks. This shows that reinforced concrete anchors have an excessively large margin of strength, and it would be possible to use anchors with significantly lower strength characteristics. However, we must not forget that the decisive factor in fixing rocks in the contour area of the array is to ensure that the anchor rod adheres to the rock array along its entire length. Of the modern anchor designs, this is

characteristic only of reinforced concrete anchors and anchors fixed in the array with epoxy resins. Therefore, the use of reinforced concrete anchors is indisputable from the ease of manufacture.

2.3 Vertical distance between anchor belts

As already emphasized in the previous sections, the main function of the spray concrete coating is to isolate the trunk wall from weathering. Despite this, it is still advisable to at least approximate its bearing capacity, considering the interacting anchors. Therefore, let's assume that the sprayed concrete coating will work as a thin underground wall experiencing the pressure of a certain volume of rocks with a height h (corresponding to the distance between the anchor belts vertically), slipping along the most dangerous sliding plane inclined to the horizon at an angle

$$\alpha = \frac{\pi}{4} + \frac{\beta}{2}.$$

Then, taking into account the margin factor, the condition [22] must be fulfilled

$$[\sigma_{cp}^{sc}] \cdot \delta_{sc} = 2\gamma_c \cdot h_1 b \sin \alpha, \quad (14)$$

where $[\sigma_{cp}^{sc}]$ is the strength of the spray concrete coating on the cut, t/M^2 ; the thickness of the applied layer of sprayed concrete in meters - δ_{sc} ; h_1 is the maximum possible height of the rock layer at which sliding is not yet observed, in m; b is radius of the zone of possible dislocations (destroyed rocks); α is the angle of inclination of the sliding plane. At the same time, the anchor belts vertically should be installed so that there should be no sliding in the area (in space) between these belts, i.e., the distance between the anchor belts should not exceed h_1 , the height of the rock layer at which sliding does not occur. At a known value δ_{sc} from (14), we find

$$h_1 = \frac{[\sigma_{cp}^{sc}] \delta_{sc}}{2\gamma_c b \sin \alpha}. \quad (15)$$

Based on the above, we can conclude that the obtained formula allows us to determine the upper limit of the permissible distances between the anchor belts along the vertical. It follows from it that to determine h_1 the radius of the zone of destroyed rocks must be known – b , the thickness of the sprayed concrete – δ_{sc} and the strength limit of the sprayed concrete on the cut $[\sigma_{cp}^{sc}]$.

3 Results and Discussions

Summarizing the above, the following main results can be noted:

1. A new formula for determining the thickness of sprayed concrete for vertical shafts is proposed, which differs from the known ones used for horizontal workings [3,6,10] in that it takes into account the steps of installing anchors horizontally and vertically, as well as the influence of the lateral rebound coefficient under the action of a gravitational stress field (according to the hypothesis of Academician A.N.Dinnik);

2. The obtained expression of the anchor's shear strength $[\sigma_{cp}]$ makes it possible to calculate the minimum required shear stress for the anchors used at a depth of H in rocks with a density of γ .

Calculations made for various types of anchors to determine the strength limit on the cut shows that reinforced concrete anchors have an excessively large margin of safety, and it would be possible to use anchors with significantly lower strength characteristics. However, we must not forget that the decisive factor in fixing rocks in the contour area of the array is to ensure that the anchor rod adheres to the rock array along its entire length. Of the modern anchor designs, this is peculiar only to reinforced concrete anchors;

3. A formula is obtained that allows determining the upper limit of the permissible distances between the anchor belts vertically, from which it follows that to determine the vertical anchoring step, the radius of the zone of destroyed rocks - b , the thickness of the sprayed concrete must be known – δ_{sc} and the strength limit of the sprayed concrete on the cut $[\sigma_{cp}^{sc}]$.

4 Conclusions

The results obtained in this article, together with the results of work [1], allow us to make a complete calculation of the combined anchor-sprayed concrete support of small vertical mines, optimize the values of the parameters of such support and create a mathematical calculation model.

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