

Some approaches to coal pillar strength calculation

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Abstract

Introduction. *Reliable forecasts of pillars geomechanical state are required to ensure rhythmic and safe work when mining a coal bed.*

Research aim *is to construct a state model of the coal pillar located between the headways, based on the fundamental methods of elasticity theory and mechanics of a granular media, carry out a computational experiment within the model, and analyse the results.*

Methodology. *The stress field in the coal pillar has been constructed in the course of solving the elastoplastic problem. By replacing the ultimately stressed marginal zone of the bed with the stresses which act within the zone, the problem has been reduced to the second exterior boundary value problem of elasticity theory and has been solved by the boundary element method. Ordinary and special Coulomb–Mohr criteria simultaneously fulfilled for the coal bed and rock mass contact are the criterion of the limit state onset. Actual pillar load is determined by integrating the vertical stress curve along the bed roof, which has been obtained from elastoplastic problem solution, while the ultimate load is determined from the condition that the whole pillar is in ultimately stressed state.*

Results. *The dependence between the safety factor of the pillar between two identical headways, determined by V. D. Shevyakov method, and the growth of its width represents a graph in the form of a monotonically increasing curve. The curve flattens as soon as the depth increases.*

Summary. *The results from the developed model of coal rock mass geomechanical state can be successfully used as coal pillar strength forecasts.*

Key words: *rock mass; coal bed; pillar; mine working; ultimately stressed zones; Coulomb–Mohr strength criteria.*

Introduction. The most important stage of developing and operating coal producers by an underground method is the selection of various pillars. Theoretically grounded dimensions of pillars ensure rhythmic, safe and high-performance work of any mine.

Pillar strength analysis includes the determination of its safety factor which is found as a ratio of ultimate (cracking) load upon the pillar and actual load [1]. Depending on the pillar type, mining and geological conditions of a deposit, mine and engineering conditions of its development, the safety factor is set within the limit of 1.5 to 4 units.

In order to determine ultimate and actual load, various approaches are used which can be broken down into engineering and fundamental (theoretical). Engineering approach is based on experimental methods and the methods of strength of materials [1–5]. The fundamental approach is based on the methods of solid mechanics: the methods of elasticity theory, plasticity theory, theory of granular media and rock ultimate behavior [2, 3, 6–15].

Fundamental calculation methods assume that both enclosing rock mass and coal beds in natural conditions (in virgin soil) are in elastic state. However, in the course of mining the marginal sections of the coal bed are the first to transfer into plastic (inelastic) state. Their state can be described by the methods of plasticity theory.

In the classical plasticity theory, the criteria of the material's transfer into the plastic state is either Tresca–Saint-Venant criterion or Huber–Mises criterion, and the diagram of material conventional stresses in plastic media are most frequently accepted as corresponding to Prandtl diagram for ideal plastic material (ignoring its strengthening) [11].

In actual shaft conditions the bed does not show the properties of ideal plastic material. Firstly, based on the results of numerous experiments on coal samples it has been determined that their ultimate load diagrams are qualitatively close to the diagrams obtained when testing the samples of various rock which manifest brittle behavior. Secondly, the state model of ideally plastic rock mass does not take into account the conditions of slip during its deformation at the contacts with enclosing rock, and this circumstance plays important role in estimating its stress state.

When calculating rock masses which enclose workings, the general criterion of Coulomb–Mohr and the special criterion of Mohr–Kuznetsov are used as the criteria of their transfer into the ultimate stress (inelastic) state. The special criterion is used to calculate the strength of the rock mass in its weakest parts, along the planes of weakness, as well as when constructing the uniformity-loss zones (ULZ), the present of which is a kind of a criterion of mine working stability [12, 13].

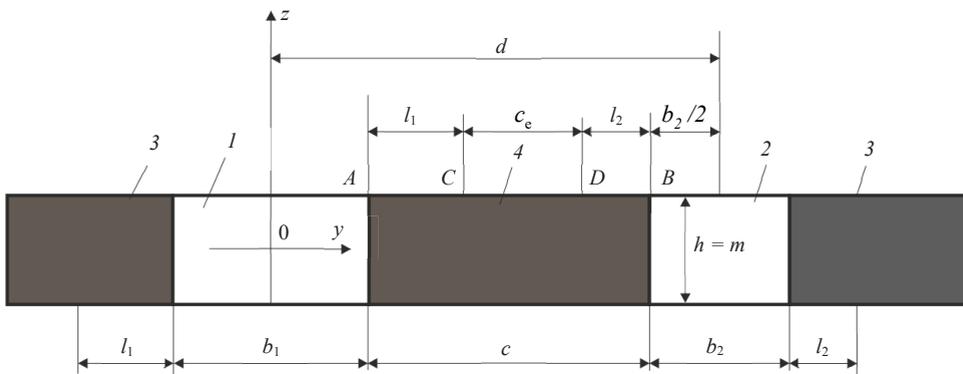


Fig. 1. Diagram of a headway:

1, 2 – headways; 3 – coal bed; 4 – pillar between the headways

Рис. 1. Расчетная схема пластовой выработки:

1, 2 – пластовые выработки; 3 – угольный пласт; 4 – целик между выработками

As soon as the characteristics of bed strength differ from the characteristics of strength at its contact with the enclosing rock mass, it is necessary to apply both general and special criteria of strength at the same time when calculating the coal mass with headways.

In this regard, the development geomechanical state model of the coal mass which encloses the headways and its application when calculating coal pillars strength is an important scientific and production problem. The problem solution makes it possible to conduct large-scale theoretical investigation ensuring the choice of safe dimensions of pillars and the conditions for effective work of a mining enterprise when mining a coal field.

Problem setting and its solution. In the rock mass at the depth H across the coal bed with thickness m two development openings with rectangular cross-section have been cut, their dimensions are the following: the span the first working b_1 , the second – b_2 (fig. 1).

The height of workings h is equal to the thickness m of the bed. The characteristics of the coalbed strength σ_0 , C , ρ (σ_0 – compression strength of the bed; C – cohesion coefficient; ρ – angle of shear resistance) are lower than main rock mass strength characteristics, but exceed the coefficient of cohesion C' and the angle of shear resistance ρ' along the contacts of bed and rock mass. The distance between the edges of the workings (the width of the pillar) is equal to c . The workings are long, so the rock in their vicinity are subject to plain strain. Coordinate system yOz is situated in gravitational

center of the cross-section of the first mine working. Ultimately stressed zones in the edges of the first mine working have a size of l_1 ; the edges of the second – l_2 . The width of the elastic part of the pillar (its elastic core) is c_e , and the load upon the pillar is conditioned by the weight of the undermined rock of d width. Points A, B denote the edges of the mine workings; points C, D denote the borders of the ultimately stressed zones of the pillar.

Dimension d is determined from fig. 1 in the following way:

$$d = c + \frac{b_1 + b_2}{2}. \tag{1}$$

Assuming that the traces of mine workings are parallel, their dimensions along the x coordinate significantly exceed the dimensions in yOz plane, and the strength of the bed is significantly lower than the strength of the enclosing rock, but it is higher than along its contact with the surrounding rock. The coal mass can be represented by the following design diagram. Elastic plane is loaded by the gravitational pressure γH from above and below, and by pressure $\lambda\gamma H$ (λ – lateral pressure coefficient) on either side.

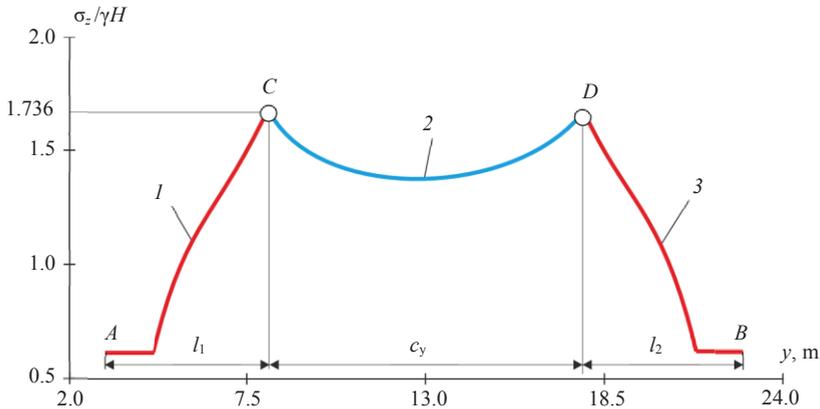


Fig. 2. Curve of vertical stresses σ_z along the roof of the pillar in elastoplastic state
 Рис. 2. Эпюра вертикальных напряжений σ_z вдоль кровли целика, находящегося в упругопластическом состоянии

It encloses the layer, physical and mechanical properties of which differ from the properties of the plane’s material; it has two rectangular cuts in this layer. The layer is subject to inelastic deformations in the marginal part of the mine working.

With the assumptions, the stress field in the rock mass, particularly in the pillar, can be constructed with the help of solid mechanics methods in two steps.

At the first stage, the problem of stresses distribution in the ultimately stressed marginal zone of the bed is solved. The problem should be solved by the methods of V. V. Sokolovsky who developed them to calculate granular media and cohesive soils [14]. As applied to the coal bed the solution to the problem is presented in [15].

To describe the state of the bed from the point of view of the solid mechanics, two criteria of its transfer into the ultimate state should be used: general Coulomb–Mohr criterion for the bed itself, and special Mohr–Kuznetsov criterion for its contact with the surrounding rock mass (the condition of bed slide). These conditions together with equilibrium differential equations make up the system of resolving equations of coal bed marginal zone stress state. In the two-dimensional system this system is reduced to one nonlinear differential equation of hyperbolic type which can be solved with the

method of characteristics. This method integrates the differential equations with rather simple structure at the characteristic lines which coincide with the lines of material slide [14]. However, despite relatively simple form of these equations, their integration in the closed form is possible only under particular conditions. As applied to the coal bed, solution in the closed form is successful only at bed sections adjacent to its outcrop. In the remaining parts, the solution is possible only by means of subsequent numerical solution of a range of marginal problems of granular media statics.

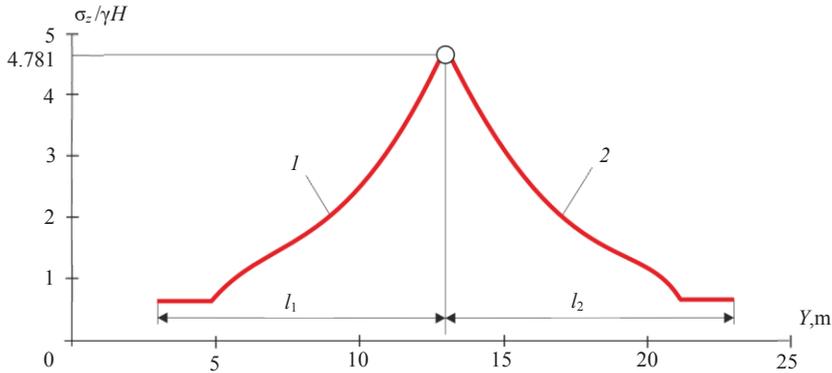


Fig. 3. Curve of vertical stresses σ_z along the roof of the ultimately stressed pillar
Рис. 3. Эпюра вертикальных напряжений σ_z вдоль кровли предельно напряженного целика

In research [15], by the methods of V. V. Sokolovsky, the stress state of bed marginal zone has been calculated at a depth equal to five depths of the bed. It has been shown that stress curves in bed roof and along its axis represent the combination of alternating section types. Some sections have constant stresses, while others have nonlinearly growing stresses.

At the second stage the elastoplastic problem is solved. By replacing the ultimately stressed marginal part of the bed with normal and tangential stress, it is reduced to the second external boundary value problem of elasticity theory. It can be solved by the method of boundary integral equations (boundary elements) [12, 13].

So, the design diagram of the coal mass based on the methods of granular media mechanics, plasticity theory and elasticity theory represents the physical and mathematical model of coal bed geomechanical state with a system of headways; within the limits of the model, in particular, the strength of the coal pillar situated between the mine workings can be evaluated.

Ultimate load P_p upon the pillar is determined from the condition that the pillar is in the ultimate state. Consequently, in order to determine the load it is required to use solutions for stresses obtained by the methods of granular medium [15]. The load itself is calculated by means of integrating the stresses in the ultimately stressed zone:

$$P_p = \int_{y^A}^{y^B} \sigma_z(y) dy = \int_0^c \sigma_z(y) dy = \int_0^{c/2} \sigma_z(y) dy. \quad (2)$$

Expression (2) has taken into account that in ultimately stressed state of stress tensor vertical component σ_z is symmetric relative to the center of the pillar, i. e. independently of mine workings dimensions, curves σ_z are equal from the edge of the each mine

working into the depth of the pillar and intersect in a point above the center of the pillar. If in ultimately stressed zone the stress curves are approximated by analytical expressions, for example by polynomial with various degrees [15], the integral is easily calculated.

Actual load acting upon the pillar can be determined in two ways.

The first method determines the actual load P_{f1} with the help of formula (2) where loads σ_z are the result of elastoplastic problem solution. As soon as this problem is reduced to the elastic problem solved by the method of boundary integral equations numerically, then integration of expression (2) should also be carried out by means of one of the numerical methods.

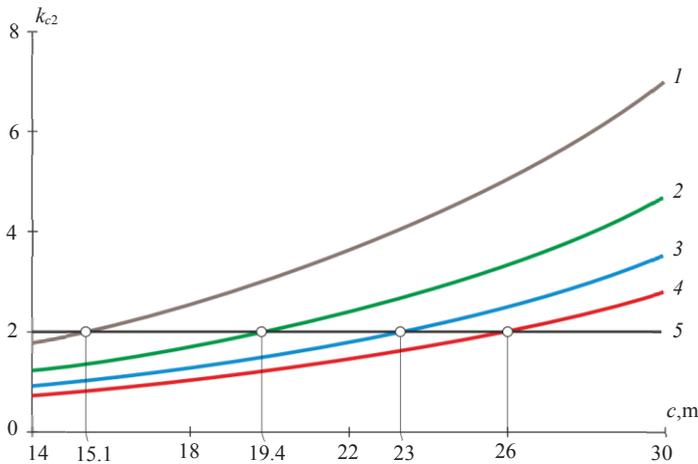


Fig. 4. Dependence between the safety factor and the width of the pillar
 Рис. 4. Зависимость коэффициента запаса прочности от ширины целика

In the second method, the actual load P_{f2} upon the pillar is determined according to L. D. Sheviakov approach [1, 2] by means of calculating the weight of the column of the undermined part of the rock mass according to the formula:

$$P_{f2} = \gamma Hd. \tag{3}$$

Safety factor k_c of a pillar by two methods is determined according to the formula:

$$k_{ci} = \frac{P_p}{P_{fi}},$$

where i is the number of actual load calculation method.

Results and their analysis. Here are the results of the on pillar stress state problem solution. The following rock mass and bed parameters are accepted as input information: $H = 800$ m; $\gamma = 25$ kN/m³; $\sigma_0 = 10$ MPa; $\rho = 20^\circ$; $C' = 0$; $\rho' = 10^\circ$; $b_1 = b_2 = 6$ m; $c = 20$ m.

Fig. 2 shows bearing pressure curve (vertical stresses curve σ_z) in the pillar along $ABCD$ line (see fig. 1) which has been constructed in the course of solving the elastoplastic problem. The curve represents the total of three graphs. *Graphs 1, 3* – the curve of stresses σ_z in the edges of the first and second mine workings. *Graph 2* – curve σ_z in the elastic part of the pillar (between point C and D).

In the course of solving the problem, the following values of ultimately stressed zones dimensions and maximum stresses in the pillar have been obtained: $l_1 = l_2 = 5.2$ m; $c_e = 9.6$; $\sigma_{z_{\max}} = 1.736\gamma H$. By integrating stress curves σ_z according to the trapezoidal method, the actual load upon the pillar is determined by the first method: $P_{f1} = 469.8$ MN/m. By the second method, under the same parameters of mine workings and pillar, dimension d is 26 m and the actual load is $P_{f2} = 520$ MN/m. Both loads are determined for 1 m of the pillar, and the difference between these loads is 9.65%.

Fig. 3 presents bearing pressure curve in the ultimately stressed pillar.

As it has already been mentioned, bearing pressure curve represents two symmetric curves (*curve 1* and *2*) of ultimate stresses σ_z along the bed roof. The said curve integration according to formula (2) makes it possible to determine the value of the cracking load P_p , which is obtained as equal to 785.3 MN/m.

The values of the safety factor of the pillar, determined by the two methods are the following:

$$k_{c1} = \frac{P_p}{P_{f1}} = 1,672; \quad k_{c2} = \frac{P_p}{P_{f2}} = 1,51.$$

Based on the obtained values, L. D. Sheviakov's formula provides an increased result as compared to the theoretical method. In this connection the engineering method of pillar calculation leads to a certain safety factor.

At fig. 4 a sequence of dependency graphs between k_{c2} coefficient and pillar width c for a number of depths H .

Curve 1 was constructed under $H = 400$ m, *curve 2* corresponds to the dimension of the pillar $H = 600$ m, *curve 3* has been obtained under $H = 800$ m, *curve 4* – under $H = 1000$ m. It follows from fig. 4 that all graphs represent smooth incremental concave curves; with the growth of depth H , curves growth rate decreases. *Line 5* corresponds to the safety factor, which is equal to 2. X coordinates of this line intersection with curves *1–4* are equal to the dimensions of the pillar, which correspond to the value of this coefficient. It should be noted that with the growth of mining depth, the growth of pillar width reduces. So, with depth H increasing by 2.5 times (from 400 to 1000), the pillar width grows only by 1.72 times from 15.1 to 26.0 m.

Summary. The developed model of the geomechanical state of the coal bed with the systems of headways, which has been constructed based on the fundamental methods of solid mechanics, ensures the fulfillment of theoretical research and reliable evaluation of cracking and actual load upon the pillar.

Actual load upon the pillar which has been obtained within the limits of the developed model differs from the load which has been calculated according to L. D. Sheviakov's method for less than 10%. So, the pillar with the width found by an engineering method has a certain additional safety factor.

Graphs of the safety factor corresponding to the actual load found according to L. D. Sheviakov's method, become smooth monotonously increasing curves with the growth of the pillar's width. With the growth of mining depth they become gently sloping lines.

So, with the growth of mining depth the rate of pillar safe width growth reduces.

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О некоторых подходах к расчету прочности угольных целиков

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Реферат

Введение. Для обеспечения ритмичной и безопасной работы при отработке угольных пластов необходимы надежные прогнозные оценки геомеханического состояния целиков.

Цель работы. Построение модели состояния угольного целика, расположенного между пластовыми выработками, на основе фундаментальных методов теории упругости и механики сыпучих сред, проведение в ее рамках вычислительного эксперимента, анализ результатов.

Методология. Поле напряжений в целике построено в ходе решения упругопластической задачи. Путем замены предельно напряженной краевой зоны пласта действующими в ней напряжениями она сведена ко второй внешней краевой задаче теории упругости, которая решена методом граничных элементов. Критерием наступления предельного состояния является одновременное соблюдение обыкновенного и специального критериев Кулона–Мора по пласти и по контакту с массивом. Фактическая нагрузка на целик определяется интегрированием эпюры вертикальных напряжений вдоль кровли пласта, полученной из решения упругопластической задачи, а предельная находится из условия, что целик полностью пребывает в предельно напряженном состоянии.

Результаты. Зависимость коэффициента запаса целика между двумя одинаковыми выработками, определяемого способом В. Д. Шевякова, с ростом его ширины представляет собой график в виде монотонно возрастающей кривой. С увеличением глубины кривая становится пологой линией.

Выводы. Результаты, полученные в рамках разработанной модели геомеханического состояния углеродного массива, могут быть с успехом использованы в качестве прогнозных оценок прочности угольных целиков.

Ключевые слова: массив горных пород; угольный пласт; целик; горная выработка; предельно напряженные зоны; критерии прочности Кулона–Мора.

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