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METHOD FOR CALCULATION OF THE CARRYING CAPACITY OF THE BOTTOMHOLE ZONE OF A GAS-BEARING FORMATION

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Abstract: This paper presents a method for calculating vertical and horizontal stresses in gas-bearing coal seams based on a set of equations developed by the authors. The method describes the experimental curve of rock pressure as a convex quadratic function, with the initial value of the function equal to the normal stress at the top of the bottom hole crack. The method also considers the variation of gas pressure as the crack moves towards the interior of the formation. In addition, the method employs the relationship between active tangential stresses at points on the edges of the bottomhole crack, derived from Coulomb's strength criteria for brittle materials. The accuracy of the method was confirmed by experimental data on the maximum shear strength of marble and brown coal at various levels of confining pressure and pore pressure. The paper also presents analytical expressions for the strength limit of the bottomhole zone of gas-bearing coal seams as a function of gas pressure gradient.

Keywords*: *rock, strength limit, destruction, crack, bottomhole zone

1. INTRODUCTION

One important factor is not taken into account when evaluating the effectiveness of known methods for relieving gas-bearing coal seams. It has long been known (Olkhovichenko et al. 1982; Vasiliev et al. 2014) that the strength of coal increases as gas is removed from it. The authors indicate that as a result of undercutting or overcutting, the strength coefficient of coal samples increases by 1.2 times (Olkhovichenko et al. 1982).

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V.I. Nikolin (Sdvyzhkova et al. 2017) writes that from the experience of developing highly gas-bearing seams, it is known that in a gaseous heading, the bottom zone of the coal seam is destroyed by a pickaxe and other tools much easier than in the same heading with normal ventilation. Another experimentally established fact is that an increase in stress (driving workings in areas of support pressure from pillars left in the overlying horizons, driving workings in cross-cuts, etc.), an increase in gas content (an increase in helium content in the gas of the seam, an increase in gas release from boreholes, wells, etc.) leads to a reduction in the size of the safe unloading zone (a reduction in the area of ultimate stress), i.e., to a real increase in the probability of a blowout. It is well known that when carrying out mining operations on coal seams with low gas content (up to 6–8 m^3/t), signs of blowout hazard are absent even at depths of 800–000 m. The literature does not provide a mathematical description of the phenomenon of reducing the strength of coal when it is saturated with gas. Let's try to fill this gap. To do this, it is necessary to develop a method for calculating the bearing capacity of the bottom zone of gas-bearing coal seams, taking into account the internal gas pressure.

2. METHOD

In article (Sdvyzhkova et. al. 2017), a method for calculating loading parameters is presented, and a formula describing the epure of rock pressure in the form of a quadratic function is given (Fig. 1), the initial value of which is equal to the normal stress

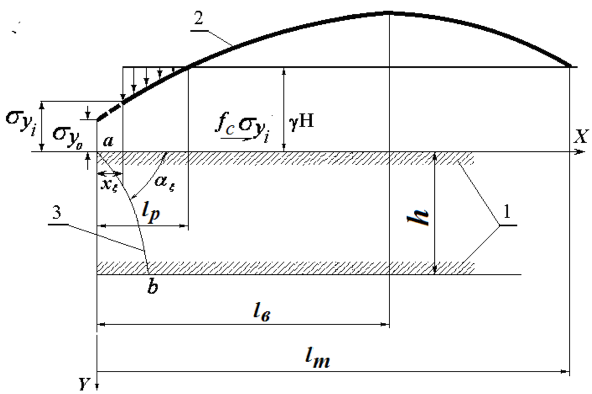


Fig. 1. Diagram of the development of the bottomhole crack in the relief zone of the bottomhole formation under rock pressure: 1 – formation, h – formation thickness, 2 – diagram of rock pressure, x and y – abscissa and ordinate of a point in meters, m, σ_{yi} – current value of rock pressure in Pa, $f_c\,\sigma_y$ – value of frictional contact in Pa, γH – specific rock pressure in Pa; 3 – bottomhole crack, a – angular point of the bottomhole zone, b – point of TMESS ξ exit onto the contact surface, α_ξ – angle of inclination of the tangent to the edges of the crack at its apex with respect to the horizontal stress, in radians

at the top of the bottom crack with the attenuation of the coefficient of friction along the seam (Vasiliev et al. 2018).

$$\sigma_{y_i} = \sigma_{y_\xi}\left(1 + f_c\left(1 - t_l \cdot l\right) \cdot l/h\right), \tag{1}$$

where:

σ_{y_ξ} – Vertical normal stress at the apex of the bottomhole crack, Pa;

f_c – contact friction coefficient;

l – the distance of the considered point into the depth of the formation from the face of the excavation, m;

$t_1 = \dfrac{1}{l_m}$ – the coefficient of attenuation of contact friction, 1/m;

l_m – support zone length, m.

Specific load-bearing capacity of the formation is equal to (Sdvyzhkova et al. 2017)

$$\sigma_c = \frac{\sigma_{y_\xi}}{l_m}\int_0^{l_m}\left(1 + f_c\left(1 - t_l \cdot l\right)l\right)dl = \sigma_{y_\xi}\left((l - x) + \frac{f_c(l_m - x)^2}{2h} - \frac{f_c t_l \cdot (l_m - x)^3}{3h}\right). \tag{2}$$

As we can see, it is necessary to know the value of the vertical normal stress at the apex of the bottomhole crack in a gas-bearing formation.

Let's try to answer this question based on the consideration of the change in the total shear resistance under the influence of rock pressure, taking into account internal and contact friction, with the presence of tensile normal stresses from the internal action of gas pressure at the crack apex. The method is based on Coulomb's criterion of maximum shear stress.

$$k = \tau_e = \tau_\alpha - \mu\sigma_\alpha, \tag{3}$$

where:

k – the shear strength limit of coal, Pa;

τ_e – trajectory of maximum effective shear stress (TMESS), Pa;

τ_α – active shear stress on TMECN, Pa;

$\mu = \tan g\,\rho$ – coefficient and angle (rad) of internal friction;

σ_α – the normal stress at the considered point on the trajectory of maximum shear stress (TMESS) ξ, Pa.

The book (Tomlenov 1972) presents a method for determining the vertical and horizontal normal stresses at the apex of a crack developed in a solid body according to Coulomb's strength criterion. The method is based on solving the differential equation of equilibrium at the apex of the bottomhole crack (Fig. 1) in the form of:

$$\frac{k+\mu\sigma_{\alpha_\xi}}{k_b+\mu\sigma_{\alpha_b}} = \exp\left(2\mu\alpha_{b_\xi}\right), \tag{4}$$

where:

k_b – shear stress on TMESS ξ in point *b*, Pa;

$\mu\sigma_{\alpha_b}$ – normal stress on TMESS ξ in point *b*, Pa;

α_{b_ξ} – rotation angle TMESS ξ between points *b* and current points on this, rad.

Normal stress on TMEESS ξ according to (Tomlenov 1972)

$$\sigma_\alpha = \frac{(\sigma_x+\sigma_y)\cos^2\rho}{2} - ksun\rho\cos\rho, \tag{5}$$

where σ_x – horizontal normal stress, Pa.

The horizontal normal stress σ_x as applied to the corner point (Fig. 1) is determined by the formula (Tomlenov 1972)

$$\sigma_x = \frac{(k+\mu C)\left(\sin\rho+\sqrt{1-b_\xi^2}\right)}{\cos\rho} + C, \tag{6}$$

where:

C – vertical normal stress at the bottomhole crack tip;

$b_\xi = \dfrac{f_c\left(1-\dfrac{2y}{h}\right)}{k+\mu C}$ – ratio of contact shear stresses to shear stresses inside the formation.

Now in formulas (5) and (6), it is necessary to take into account the gas pressure σ_g. Since the gas acts equally in all directions, its pressure counteracts the vertical and horizontal stress on TMESS ξ. We assume that the pressure σ_g of the gas along the plane of the formation changes linearly and is expressed by the formula

$$\sigma_g = g \cdot l, \tag{7}$$

where:

g – the gradient of gas pressure increase per unit distance from the free surface or the excavation face in the direction of the gas reservoir, Pa/m;

l – the distance from the excavation face to the considered point, m.

Hence, in the semi-sum formula (5), the value of the horizontal stress σ_x, the vertical stress in the form of C, and the vertical and horizontal stress σ_g due to the gas action should be taken into account. Then, the formula for the semi-sum of all stresses according to the principle of formula (5) will have the following form:

$$\frac{\sigma_x + C - 2\sigma_g}{2} = \frac{(k + \mu(C - \sigma_g))\left(\sin\rho + \sqrt{1 - b_\xi^2}\right)}{\cos\rho} + C - 0.5\sigma_g - \sigma_g \,. \quad (8)$$

Now let's find the stress σ_α on TMESS ξ' using expression (5),

$$\sigma_{\alpha_\xi} = \left(\frac{\left(k + \mu\left(C - \sigma_g\right)\right)\left(\sin\rho + \sqrt{1 - b_\xi^2}\right)}{\cos\rho} + C - 0{,}5\sigma_g - \sigma_g \right)\cos^2\rho - k\ \sin\rho \cdot \cos\rho \,. \quad (9)$$

From the formula (9) we have

$$\sigma_{\alpha_\xi} = \left(C - \sigma_g\right)\left(1 + \sin\rho\sqrt{1 - b_\xi^2}\right) + k\cos\rho\sqrt{1 - b_\xi^2} - 0.5\sigma_g\cos^2\rho \,. \quad (10)$$

After that, for equation (4), the expression for shear stress on TMESS ξ' will be

$$\tau_{\alpha_\xi} = \left(k + \mu\left(C - \sigma_g\right)\right)\left(1 + \sin\rho\sqrt{1 - b_\xi^2}\right) - 0.5\sigma_g\sin\rho \cdot \cos\rho \,. \quad (11)$$

Similarly, we obtain the formula for shear stress τ_{α_b} for point and *b*, using formula (5). To simplify the notation, we introduce the notation

$$A = 0.5\sigma_g \cdot \sin\rho \cdot \cos\rho, \quad (12)$$

$$\tau_{\alpha_b} = \left(k_b + \mu\left(\sigma_y - \sigma_g\right)\right)\left(1 - \sin\rho\sqrt{1 - b_b^2}\right) - A \,. \quad (13)$$

Let's now determine the constant *C*. According to A.D. Tomlenov (1972) the constant *C* at the angular point *a* is determined by the condition that the way of applying forces does not affect the distribution of stresses in sections sufficiently far from their application point. This condition is an extension of Saint-Venant's principle, applied in elasticity theory, to the stressed state. In the section $x = 0$, free of load,

$$\int_0^h \sigma_x dy = 0 \,, \quad (14)$$

Substituting the value of σ_x (6) into expression (13) at $x = 0$ and integrating, we obtain:

$$C = \frac{1}{2}k\arcsin\left(\frac{f_c\sigma_y\left(1 - \frac{2y}{h}\right)}{k + \mu\sigma_y} \right). \quad (15)$$

The parameter $\left(1-\frac{2y}{h_1}\right)$ determines the level of attenuation of shear stresses as they move away from the contact surface along the ordinate axis. To simplify notation in the future, we will introduce the following notation:

$$d=\frac{1}{2}\arcsin\left(\frac{f_c\sigma_y\left(1-\frac{2y}{h}\right)}{k+\mu\sigma_y}\right). \tag{16}$$

After solving Eq. (4) based on equalities (10), (11), and (14) for TMESS ξ, we obtain:

$$\sigma_{y_\xi}=\frac{1}{\mu}\cdot\left(\begin{array}{l}\frac{\left(\left(k\left(1+\mu d\right)-\mu\,\sigma_g\right)\left(1+\sin\rho\sqrt{1-b_\xi^2}\right)-A\right)\exp\left(2\mu\left(\beta_\xi+\beta_b\right)\right)}{1-\sin\rho\sqrt{1-b_b^2}}\\-\left(k_b-\mu\,\sigma_g-\frac{A}{\left(1-\sin\rho\sqrt{1-b_b^2}\right)}\right)\end{array}\right). \tag{17}$$

From the definition of the tangential stress k_b from point b in the direction of point a according to TMESS ξ we obtain that:

$$k_b=\frac{1}{\left(1+\mu d\right)}\frac{\left(k-\mu\sigma_g+\mu\sigma_y\right)\left(1-\sin\rho\sqrt{1-b_\xi^2}\right)-A}{\left(1+\sin\rho\sqrt{1-b_b^2}\right)\exp\left(-4\mu\beta_b\right)}$$

$$+\left(\mu\sigma_g+\frac{A}{\left(1+\sin\rho\sqrt{1-b_b^2}\right)}\right) \tag{18}$$

The formulas of the component parameters from (Tomlenov 1972):

$$b_\xi=\frac{f_c\left(1-\frac{2y}{h}\right)\sigma_{y_\xi}}{k+\mu\sigma_{y_\xi}}, \tag{19}$$

$$b_b = -\frac{f_c \sigma_{y_\xi}}{k_b + \mu \sigma_{y_\xi}}, \tag{20}$$

$$\beta_\xi = \frac{1}{2} \text{arctg} \frac{b_\xi \cos\rho}{\sin\rho - \sqrt{1 - b_\xi^2}}, \tag{21}$$

$$\beta_b = \frac{1}{2} \text{arctg} \frac{b_b \cos\rho}{\sin\rho - \sqrt{1 - b_b^2}}, \tag{22}$$

$$\alpha_{\xi'} = \frac{\pi}{4} + \frac{\rho}{2} + \beta_{\xi'_a} \cdot \tag{23}$$

First, let's calculate for gas-saturated samples presented in the book (Stavrogin et al. 1985). The specific pressure according to the contact stress distribution by L. Prandtl for TMESS ξ with the development of one crack is determined by the formula:

$$p = \sigma_{y_\xi} \left(1 + 0.5 f_c \left(a_1 - x_\xi\right) / h_1\right), \tag{24}$$

where a and h – length and height of sample, m.

The construction of limit curves is carried out using formulas

$$\sigma_c = \frac{p\left(a - x_\xi\right)}{a}. \tag{25}$$

Now let's confirm the fact that the pore pressure affects the values of necessary active tangential stresses on TMESS by using experimental data. We will verify the dependencies of these tangential stresses with direct experimental data on their changes with the lateral compressive and pore pressures (Fig. 2), presented in the book (Stavrogin et al. 1985).

We will create a simple system of equations for two points for marble (Fig. 2 a)

$$\begin{cases} 62 = k + 25 \cdot n, \\ 45.5 = k + 10 \cdot n, \end{cases} \tag{26}$$

where n – the coefficient of tangential stress change from external load.

Solving the first equation for the upper line 1, we find: n = 1.1, k = 34.25 MPa. Now let's determine the value of the tangential stress τ_α at $p_1 = 0$ and $\sigma_2 = 10$ MPa.

It is easy to verify that at these values, the stress τ_α or the middle line 2 at $g = 0$ is described by the formula:

$$\tau_\alpha = 34.25 + 10 \cdot 1.1 = 45.25, \text{ MPa}. \tag{27}$$

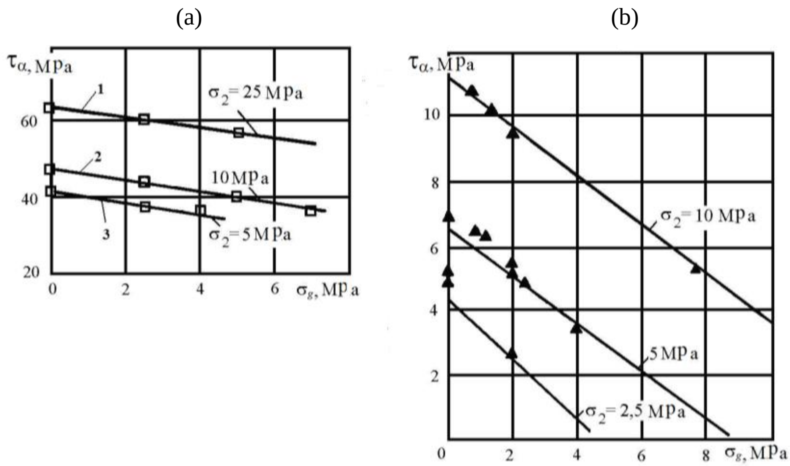


Fig. 2. Dependence of the maximum tangential stress of marble (a) and brown coal (b) on the pore pressure σ_g at different levels of lateral pressure

In the same way, for $\sigma_g = 0$ for line 3 we have:

$$\tau_\alpha = 34.25 + 5\cdot 1.1 = 39.75, \text{ MPa.}$$

From this analysis, it can be concluded that the straight lines presented in Fig. 2a for marble are described by the formula:

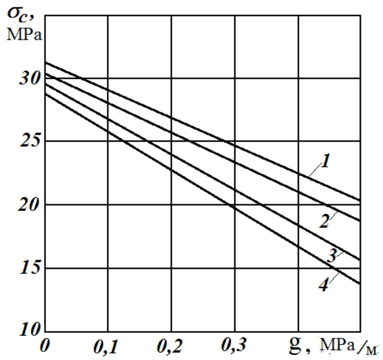
$$\tau_\alpha = k + \sigma_g \cdot n, \text{ MPa,} \tag{28}$$

where k = 34.25 MPa, n = 1.1 – is the coefficient of tangential stress change from external lateral load.

Similarly, when calculating the maximum tangential stress at the strength limit in the presence of lateral compressive stress σ_2 and tensile pore pressure, formula (28) is confirmed for brown coal (Fig. 2b) with k = 3.0 MPa and n = 0.8.

Returning to the coal seam. The bearing capacity – the strength limit of the seam – is described by formula (2). Here, based on formula (2), we will show how the strength limit of the bottomhole section changes over a length equal to the thickness of the seam (Fig. 3).

As can be seen, the internal gas pressure sharply reduces the load-bearing capacity of the bottomhole zone of gas-bearing coal seams. Thus, at a gas pressure gradient of g = 0.3 MPa/m the strength of the bottomhole zone decreases by 20%. g = 0.3 MPa/m – the strength of the bottomhole zone decreases by 30%. Based on this, it is planned to describe the mechanism of coal explosion during sudden release of coal and gas.



Seam: 1 – 1.35 m, 2 – 1.5 m, 3 – 1.8 m, 4 – 2.0 m

Fig. 3. Dependencies of the strength limit of the bottomhole part of gas-bearing coal seams with k = 1.5 MPa, ρ = 45°, f_c = 0.5 on the gas pressure gradient

Now let's compare the theoretical findings with experimental observations. Analysis of gas-bearing seam development gives an unambiguous answer to the question of the effect of gas pressure on the release hazard of coal seams. It has been established that the release hazard of coal seams of different deposits increases with increasing gas pressure (Fig. 4). In the past, research was conducted (Alekseev et al. 2010; Zykov 2010) to determine the "critical" gas pressure, above which the seam becomes hazardous due to sudden releases.

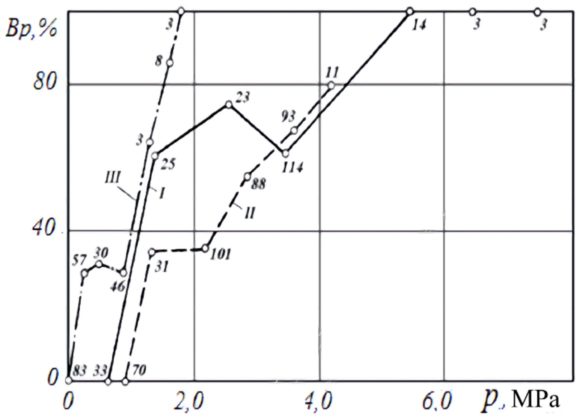


Fig. 4. The influence of gas pressure on the danger of gas emissions in coal seams:
I – Donbass, II – Vorkuta, III – Kuzbass.
The numbers near the points indicate the total number of investigated seams

According to the recommendations of the Central Research and Design Institute of the Coal Industry (McNII) (Vasiliev 2014), the critical pressure in low-power seams is 1.0 MPa, while for powerful seams it is determined by the formula of the Eastern Research and Design Institute (VostNII):

$$N_B = P_{\max} - 19f_n^2. \quad (29)$$

where:

$P_{\max}$ is the maximum measured gas pressure in the seam at the point of opening, in MPa;

f_n – the coal strength coefficient on the M.M. Protod'yakonov scale.

According to the All-Russian Scientific Research Institute of Mining (VNIMI) in St. Petersburg, critical gas pressure values, below which the protected seam becomes safe, are equal to 0.5–1.0 MPa (Alekseev et al. 2010).

Therefore, gas pressure acts as a "starter" for the transition of the limit stress state into a hazardous state by reducing the coal's resistance to shear. In conclusion, practical observations of many researchers (Olkhovichenko 1982; Alekseev et al. 2010) confirm our conclusions. The process does not end with the development of the near-wellbore fracture according to TMESS ξ. As soon as the near-wellbore fracture reaches the soil, the development of the so-called return fracture occurs, from bottom to top, according to TMESS η. The wellbore acquires an inclined shape. There are two ways for the process of destruction: to stop or to continue in the form of a chain reaction. The process of destruction can be stopped by the slope of the wellbore. The slope of the lateral plane of the body, as known (Stavrogin et al. 1985), sharply increases its load-bearing capacity. This task has not yet been solved for the near-wellbore part of the formation. We will try to solve it later. In addition, we note that the surfaces of the cavities in the formation after the blowout resemble the surfaces of the maximum effective tangential stresses, the theory of which we have used.

In conclusion, it should be noted that the mathematical model developed in the article has been repeatedly used in the development of methods for calculating the strength limit of rock samples (Vasiliev et al. 2018), the reliability of which was verified against numerous experimental data obtained on presses (Stavrogin et al. 1985).

3. CONCLUSION

A method has been developed for calculating the load-bearing capacity and stresses at the apex of the fracture at any point in the near-wellbore part of gas-bearing coal seams, which involves taking into account gas pressure values and a quadratic function of the supporting rock pressure, which allows determining the parameters of the near-wellbore fractures in gas-bearing coal seams and explaining the reduction in coal strength in the presence of pressurized gas.

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