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Study on Borehole Wall Real-Time Stability of Coal Seam With Coal Cleat When Underbalanced Drilling

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Abstract
Coal seam as the gas productive reservoir and gas-bearing reservoir, it is different from the conventional sandstone reservoir. On the one hand, coal cleat is well-developed in coal seam reservoir. Its characteristics are low porosity, small permeability, large specific surface area, low mechanical strength, strong heterogeneity, low reservoir pressure and so forth. These characteristics determine that drilling has more influence on coal seam reservoir than on conventional sandstone reservoir. In the process of drilling, therefore, in order to reduce or avoid the pollution to coal seam, usually adopt underbalanced drilling way to keep negative differential pressure and to reduce the damage of fluid in borehole flowing into the reservoir. At the same time, when underbalanced drilling, formation fluid flows into the borehole, leading to the formation pressure near the borehole to change. On the other hand, due to coal seam with low mechanical strength, great brittleness, and well-developed coal cleat, in the process of drilling especially underbalanced drilling, borehole wall is prone to collapse. Coal cleat exists in the coal seam and affects its mechanical property. When studying coal seam borehole wall stability, coal cleat must be considered. Considering time effect, the paper established the borehole wall stability model of coal seam with coal cleat when underbalanced drilling, obtained the collapse pressure distribution, and analyzed influence factors of coal seam borehole wall stability, providing theoretical guidance to prevent borehole wall instability.

Key words: Coal seam; Underbalanced drilling; Negative differential pressure; Borehole wall stability; Coal cleat

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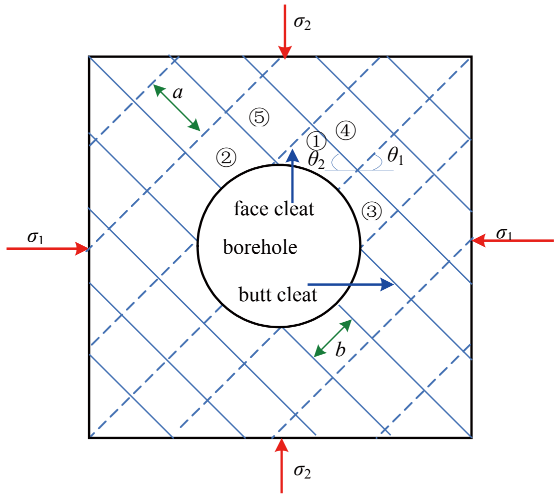
1. THE MODEL OF COAL SEAM BOREHOLE WALL INSTABILITY

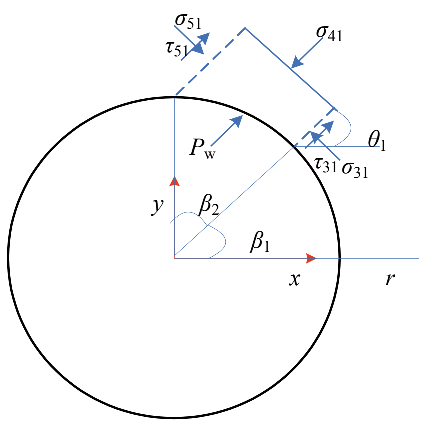
Two groups of approximately vertical coal cleats exist in coal seam. Face cleats develop better and extend up to hundreds of meters. Butt cleats develop between face cleats and communicate face cleats. Cleats cut the coal into small discontinuous cubes and destroy the coal seam integrity[1-2]. It is easy to slip and collapse along the cleat surface (Figure 1).

Coal lump ① sandwiched between two face cleats is most likely to collapse[3]. The stress analysis for coal lump ① is shown in Figure 2.



θ_1 is the inclination angle of face cleat. θ_2 is the inclination angle of butt cleat. σ_1 is the maximum horizontal in-situ stress. σ_2 is the minimum horizontal in-situ stress. a is the space between face cleats. b is the space between butt cleats.

Figure 1
Discretization Model of Coal Seam



β_1 is the polar angle at the right side of coal lump ①. β_2 is the polar angle difference between the left and right side of coal lump ①. σ_{31} is the compressive stress on contact surface between coal lump ① and ③. τ_{31} is the shear stress on contact surface between coal lump ① and ③. σ_{41} is the compressive stress on contact surface between coal lump ① and ④. τ_{41} is the shear stress on contact surface between coal lump ① and ④. σ_{51} is the compressive stress on contact surface between coal lump ① and ⑤. τ_{51} is the shear stress on contact surface between coal lump ① and ⑤.

Figure 2
Stress Analysis of Coal Lump ①

2. THE BOREHOLE WALL REAL-TIME STABILITY MODEL OF COAL SEAM WITH COAL CLEAT WHEN UNDERBALANCED DRILLING

Because coal seam gas reservoir usually adopts underbalanced drilling method[4], there is a negative differential pressure between borehole pressure and formation pressure. Under the action of negative differential pressure, formation fluid flows into the borehole when drilling, leading to the formation pressure near the borehole to change[5]. According to the theory of porous elastic medium mechanics, the effective stress at distance r from the center of borehole is:

$$\begin{cases} \sigma_r = \frac{r_0^2}{r^2}P_w + \frac{(\sigma_1+\sigma_2)}{2}(1-\frac{r_0^2}{r^2}) + \frac{(\sigma_1-\sigma_2)}{2}(1+\frac{3r_0^4}{r^4}-\frac{4r_0^2}{r^2})\cos 2\theta - \alpha P(r,t) + \delta\left[\frac{\alpha(1-2v)}{2(1-v)}\left(1-\frac{r_0^2}{r^2}\right)-\phi\right](P_w-P_p) \\ \sigma_\theta = -\frac{r_0^2}{r^2}P_w + \frac{(\sigma_1+\sigma_2)}{2}(1+\frac{r_0^2}{r^2}) - \frac{(\sigma_1-\sigma_2)}{2}(1+\frac{3r_0^4}{r^4})\cos 2\theta - \alpha P(r,t) + \delta\left[\frac{\alpha(1-2v)}{2(1-v)}\left(1-\frac{r_0^2}{r^2}\right)-\phi\right](P_w-P_p) \\ \tau_{r\theta} = -\frac{(\sigma_1-\sigma_2)}{2}(1-\frac{3r_0^4}{r^4}+\frac{2r_0^2}{r^2})\sin 2\theta \end{cases} \tag{1}$$

Where, σ_r, σ_θ and $\tau_{r\theta}$ are respectively for the radial stress, circumferential stress and shear stress, MPa; r_0 is the borehole radius, mm; P_w is fluid column pressure, MPa; α is the effective stress coefficient; φ is the porosity; v is the Poisson ratio of coal seam; δ is the permeability coefficient, $\delta = 1$ when borehole wall is permeable, $\delta = 0$ when borehole wall is impermeable; $P\ (r,t)$ is the pore pressure at the distance r from the center of borehole at the time t.

Basic differential equation of unstable planar radial flow:

$$\frac{\partial^2 P_p}{\partial r^2} + \frac{1}{r}\frac{\partial P_p}{\partial r} = \frac{1}{\eta}\frac{\partial P_p}{\partial t} \tag{2}$$

Where,

$$\eta = \frac{K}{\mu\phi C} \tag{3}$$

According to the empirical formula：

$$C = \frac{2.587\times 10^{-4}}{\phi^{0.4358}} \tag{4}$$

The initial condition:

$$P(r,0) = P_p \tag{5}$$

The inner boundary condition：

$$P(0,t) = P_w \tag{6}$$

The outer boundary condition：

$$\lim_{r\to\infty} P(r,t) = P_p \tag{7}$$

Where, r is the distance from the center of borehole; φ is the porosity; K is the permeability; μ is the fluid viscosity; C is the fluid compressible coefficient.

According to the initial condition, boundary conditions and basic differential equation:

$$P(r,t) = P_p - (P_p - P_w)e^{-\frac{1}{2}} \cdot \left[e^{-\frac{\eta t}{4r}} erfc\left(\frac{r}{2\sqrt{\eta t}}\right) + \frac{1}{4r^2}\int_0^{\eta t} e^{-\frac{\xi}{4r^2}} erfc\left(\frac{r}{2\sqrt{\xi}}\right) d\xi\right] \tag{8}$$

Where, $erfc(x)$ is Gaussian Error Function, which is an elementary function, $erfc(x) = 2/\sqrt{\pi}\cdot\int_0^x e^{-t^2}dt$.

Taking the direction of σ_1 and σ_2 respectively as the direction of axis x and y, the stress components in rectangular coordinate system can be obtained by the stress components in polar coordinate:

$$\begin{cases} \sigma_x = \dfrac{\sigma_r + \sigma_\theta}{2} + \dfrac{\sigma_r - \sigma_\theta}{2}\cos 2\theta - \tau_{r\theta}\sin 2\theta \\ \sigma_y = \dfrac{\sigma_r + \sigma_\theta}{2} - \dfrac{\sigma_r - \sigma_\theta}{2}\cos 2\theta + \tau_{r\theta}\sin 2\theta \\ \tau_{xy} = \dfrac{\sigma_r - \sigma_\theta}{2}\sin 2\theta + \tau_{r\theta}\cos 2\theta \end{cases} \tag{9}$$

According to Formula (9), σ_{31}, σ_{51} and σ_{41} can be expressed as:

$$\sigma_{51} \text{ or } \sigma_{31} = \sigma_y\cos^2\theta 1 + \sigma_x\sin^2\theta_1 - \tau_{xy}\sin 2\theta_1 \tag{10}$$

$$\sigma_{41} = \sigma_y \cos^2\theta_2 + \sigma_x \sin^2\theta_2 + \tau_{xy}\sin 2\theta_2 \tag{11}$$

When the coal lump ① collapses, the shear stress is equal to the maximum static friction force:

$$\begin{cases} \tau_{31} = \tan\varphi_m(\sigma_{31} - p_w) \\ \tau_{51} = \tan\varphi_m(\sigma_{51} - p_w) \end{cases} \tag{12}$$

Where, φ_m is the friction angle of face cleat, (°).

Because the borehole size is far greater than the cleat space[6], the stress at the centre of contact surface can replace the average stress on the contact surface. Thus, σ_{41} is equal to the stress at the centre of contact surface between coal lump ① and ④:

$$\begin{cases} \sigma_{41} \approx c_{41}p_w + f_1(\sigma_1, \sigma_2, a, b, \theta_1, \theta_2, \beta_1, r_0) \\ c_{41} = \left(\dfrac{r_0}{r_{41}}\right)^2 (\cos^2\theta_{41} - \sin^2\theta_{41})\sin^2\theta_2 + \left(\dfrac{r_0}{r_{41}}\right)^2 \cdot \\ (\sin^2\theta_{41} - \cos^2\theta_{41})\cos^2\theta_2 + \left(\dfrac{r_0}{r_{41}}\right)^2 \sin 2\theta_{41}\sin 2\theta_2 \\ r_{41} = r_i + b \\ \theta_{41} = \beta_1 + \dfrac{a}{2r_i} \end{cases} \tag{13}$$

In Formula (13), the function f_1 can be obtained by Formula (11) combined with the Formula (1) and (9).

In the same way,

$$\begin{cases} \sigma_{31} \approx c_{31}p_w + f_2(\sigma_1, \sigma_2, a, b, \theta_1, \theta_2, \beta_1, r_0) \\ c_{31} = \left(\dfrac{r_0}{r_{31}}\right)^2 (\cos^2\theta_{31} - \sin^2\theta_{31})\sin^2\theta_1 + \left(\dfrac{r_0}{r_{31}}\right)^2 \cdot \\ (\sin^2\theta_{31} - \cos^2\theta_{31})\cos^2\theta_1 - \left(\dfrac{r_0}{r_{31}}\right)^2 \sin 2\theta_{31}\sin 2\theta_1 \\ r_{31} = r_i + b/2 \\ \theta_{31} = \beta_1 \end{cases} \tag{14}$$

$$\begin{cases} \sigma_{51} \approx c_{51}p_w + f_3(\sigma_1, \sigma_2, a, b, \theta_1, \theta_2, \beta_1, r_0) \\ c_{51} = \left(\dfrac{r_0}{r_{51}}\right)^2 (\cos^2\theta_{51} - \sin^2\theta_{51})\sin^2\theta_1 + \left(\dfrac{r_0}{r_{51}}\right)^2 \cdot \\ (\sin^2\theta_{51} - \cos^2\theta_{51})\cos^2\theta_1 - \left(\dfrac{r_0}{r_{51}}\right)^2 \sin 2\theta_{51}\sin 2\theta_1 \\ r_{51} = r_i + b/2 \\ \theta_{51} = \beta_1 + a/r_i \end{cases} \tag{15}$$

In Formula (14) and (15), the function f_2 and f_3 can be obtained by Formula (10) combined with the Formula (1) and (9).

According to the equilibrium of radial force, the premise condition for coal lump not collapsing is:

$$(\sigma_{41} - p_w)a - (\tau_{31} + \tau_{51} + 2C_m)b \le aS_{td} \tag{16}$$

Where, C_m is the cohesion of face cleat, MPa; S_{td} is the tensile strength of butt cleat, MPa.

Inserting Formula (12), Formula (13) - Formula (15) in Formula (16), collapse pressure p_c should satisfy:

$$\begin{aligned} &(a - ac_{41} + b\tan\varphi_m c_{31} - 2b\tan\varphi_m + b\tan\varphi_m c_{51})p_c \\ &= cp_c \ge af_1 - 2bC_m - b\tan\varphi_m f_2 - b\tan\varphi_m f_3 - aS_{td} \end{aligned} \tag{17}$$

The borehole wall stability coefficient c is related to face cleat space, butt cleat space, the friction angle of face cleat, the location of coal lump and so on. And the value will determine the relationship between borehole pressure and borehole wall stability.

If c is positive everywhere in the borehole, the safe mud pressure should be greater than the maximum p_c. If c is negative everywhere in the borehole, the safe mud pressure should be less than the minimum p_c. If there are both positive and negative for c, p_c is shown in Formula (18). In this case, it not only needs to adjust the density of drilling fluid, but also use drilling fluid with plugging performance to improve the resistance to pressure of formation. The location of the negative maximum $\boldsymbol{c}$ would be sensitive and prior to collapse.

$$p_c\left(c > 0, |c|_{\max}\right) \le p_i \le p_c\left(c < 0, |c|_{\max}\right) \tag{18}$$

3. INFLUENCE STUDY OF BOREHOLE WALL REAL-TIME STABILITY OF COAL SEAM WITH COAL CLEAT WHEN UNDERBALANCED DRILLING

With Qinduan block in Qinshui basin, China as an example[7], the basic calculation parameters: the bit diameter in coal seam φ215.9 mm, the coal seam depth 795 m, the minimum horizontal in-situ stress 11 MPa, the maximum horizontal in-situ stress 17 MPa, the initial formation pressure P_p 5 MPa, elastic modulus E 24.5 GPa, Poisson ratio μ 0.24, the porosity φ 4%, the cohesion of face cleat C_m 1.03 MPa, the friction angle of face cleat φ_m 33°, the tensile strength of butt cleat S_t 1.4 MPa, the inclination angle of face cleat θ_1 55°, the inclination angle of butt cleat θ_2 35°.

3.1 Time Effect

According to Formula (8), formation pressure P_p at coal lump ① changed over time, as shown in Figure 3.

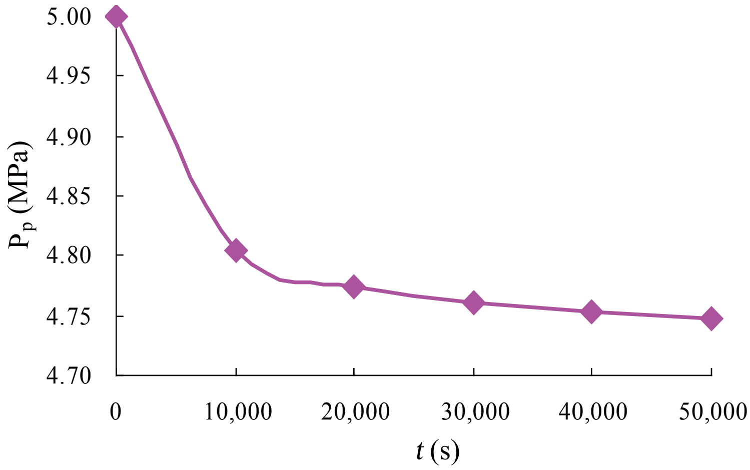


Figure 3
The Change of Formation Pressure at Coal Piece ①

Adopt the method in the paper to calculate the distribution of the borehole wall stability coefficient c around the borehole wall when $a = 4b$ and $\triangle P = 0.3$ MPa, as shown in Figure 4. From Figure 4, when β_1 was at the interval of 25° - 36° and 74° - 85°, c was close to 0. It implied that at the location, the borehole wall stability had nothing to do with borehole pressure, thus:

$$p_c\big|_{\beta_1=0^\circ} \le p_i \le p_c\big|_{\beta_1=55} \tag{19}$$

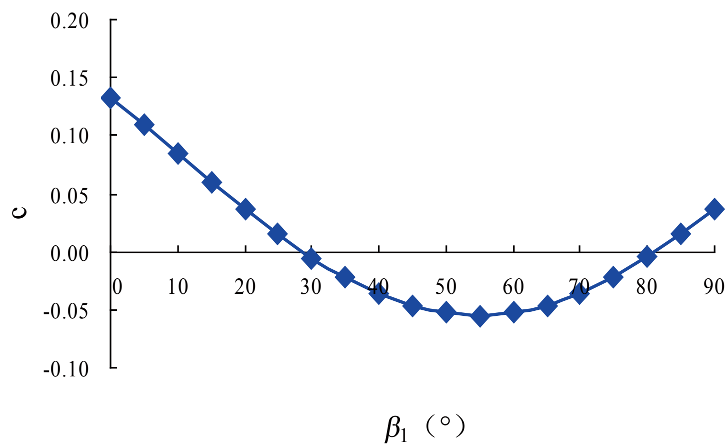


Figure 4
The Distribution of Borehole Wall Stability Coefficient *c* Around the Borehole Wall When *a* = 4*b* and △*P* = 0.3 MPa

Table 1
The Change of Collapse Pressure Over Time When *a* = 4*b* and △*P* = 0.3 MPa

t (s)		Collapse pressure (MPa)
0	$\beta_1 = 0°$	0.307
	$\beta_1 = 55°$	2.761
10,000	$\beta_1 = 0°$	0.313
	$\beta_1 = 55°$	2.775
20,000	$\beta_1 = 0°$	0.314
	$\beta_1 = 55°$	2.777
30,000	$\beta_1 = 0°$	0.314
	$\beta_1 = 55°$	2.778
40,000	$\beta_1 = 0°$	0.314
	$\beta_1 = 55°$	2.778
50,000	$\beta_1 = 0°$	0.314
	$\beta_1 = 55°$	2.778

From Figure 3, with the fluid flowing into borehole, the pore pressure near borehole would be less than 0.5 MPa. From Table 1, after drilling the borehole, the collapse pressure increased with time gradually. That was to say, the change of pore pressure may lead to borehole wall instability after drilling the borehole.

3.2 The Influence of Negative Differential Pressure

Adopt the method in the paper to calculate the distribution of the borehole wall stability coefficient c around the borehole wall when $t = 0$ and $a = 4b$, as shown in Table 2.

Table 2
The Collapse Pressure When t = 0 and a = 4b

Negative differential pressure (MPa)		Collapse pressure (MPa)
0.1	$\beta_1 = 0°$	0.314
	$\beta_1 = 55°$	2.777
0.3	$\beta_1 = 0°$	0.307
	$\beta_1 = 55°$	2.761
0.5	$\beta_1 = 0°$	0.300
	$\beta_1 = 55°$	2.745

3.3 The Influence of Cleat Size

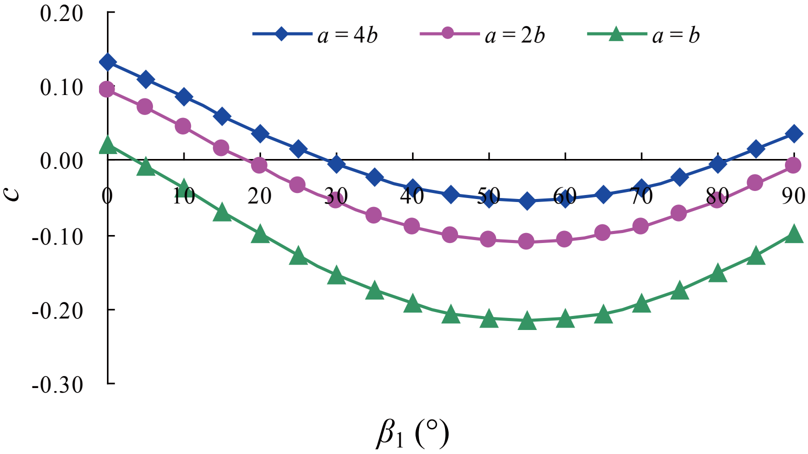


Figure 5
The Distribution of Borehole Wall Stability Coefficient c Around the Borehole Wall

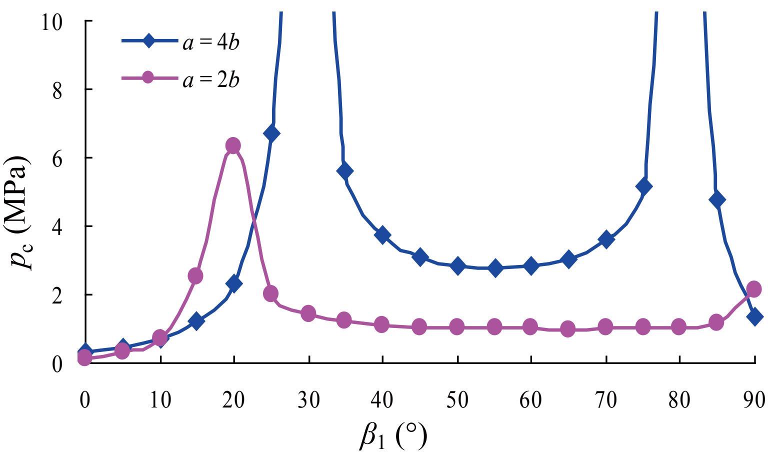


Figure 6
The Collapse Pressure When t = 0 and △P = 0.3 MPa

The distribution of the borehole wall stability coefficient c around the borehole wall when t = 0 and △P = 0.3 MPa was shown in Figure 5. From Figure 5, when a = b, borehole wall stability coefficient c near β_1 = 0 ° was 0. Namely at the location, borehole wall stability had nothing to do with borehole pressure. At other locations, borehole wall stability coefficient c was negative. In the case, the collapse pressure should be less than the minimum p_c. When a = 4b and a = 2b, there were both positive and negative for borehole wall stability coefficient c. The collapse pressure calculation result was shown in Figure 6. Table 3 was shown for the collapse pressure calculation result when t = 0 and △P = 0.3 MPa.

Table 3
The Collapse Pressure When t = 0 and △P = 0.3 MPa

Cleat size		Collapse pressure (MPa)
a = 4b	$\beta_1 = 0°$	0.307
	$\beta_1 = 55°$	2.761
a = 2b	$\beta_1 = 0°$	0.116
	$\beta_1 = 55°$	1.008
a = b	$\beta_1 = 55°$	0.103

CONCLUSION

(a) After drilling the borehole, with formation fluid flowing into the borehole, pore pressure near borehole would decrease and collapse pressure would increase gradually. It may lead to borehole wall instability.

(b) The greater negative differential pressure, the smaller collapse pressure. Thus maintaining a certain negative differential pressure is beneficial to the borehole wall stability.

(c) The cleat size has great influence on borehole wall stability. The greater a/b, the grater collapse pressure at the sensitive location, and the more easily borehole wall collapse. It needs to use drilling fluid with plugging performance and adjust the density of drilling fluid to avoid borehole wall instability.

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