Numerical Simulation of Integrated Mechanics of Drilling and Mechanical Cavitation in Coal Seam

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ABSTRACT: For coal and gas outburst and difficult extraction in soft, low-permeability, and high-gas seam, the integration technology of drilling and mechanical cavitation is put forward to relieve pressure and improve permeability of coal seam. Through the test of mechanical parameters of the coal body, the physical model of drilling and cave-making in coal seam is established, and the mechanical characteristics of drilling and mechanical cavitation are simulated numerically. The results show that the peak strength of coal increases linearly with confining pressure. When the drill bit just touches the coal, the maximum stress occurs at the center of the coal sample. With the increase in the drilling depth of the drill bit, the maximum stress point shifts to the depth. When the coal at the center of the sample is broken, the position of the maximum stress shifts to the surrounding. With the increase of drilling depth, the maximum contact number between the drill bit and coal body increases sharply. When the bit body basically enters the coal body, the maximum contact number between the drill bit and coal body remains unchanged. When the drill pipe rotates, the reaming tool collides with the hole wall at the reaming position on the axis. In general, the contact area increases with the opening of the reaming tool, but the contact between the reaming tool and the hole wall is random. As time increases, the contact force begins to increase and then basically stabilizes; at this time the reaming tool has been fully opened.

1. INTRODUCTION

Engineering practice shows that gas drainage is the most effective measure to solve coal mine gas accidents, energy saving, and environmental protection. However, China’s coal seam geology is usually complex, and coal seams damaged by structures are common. These coal seams have the characteristics of soft and broken coal and low permeability. According to statistics, more than 95% of China’s high-gas coal seams and outburst coal seams belong to low-permeability coal seams, with the permeability of only $10^{-4}$ to $10^{-3}$ mD, which is 3–4 orders of magnitude lower than that of the United States. The ubiquitous low-permeability coal seam leads to the problems of low extraction efficiency, difficult extraction, and high treatment cost.

In order to improve the permeability of coal seam, researchers had adopted a lot of antireflection measures and technologies. For example, the application of the mining protective layer greatly reduces the cost of gas control in low-permeability and high-outburst coal seam and achieves a good treatment effect. However, for coal seams without a protective layer or single coal seam, only other antireflection measures can be taken, for example, high-pressure hydraulic fracturing, deep-hole loose blasting, dense drilling, cross drilling, hydraulic slotting, hydraulic punching cavitation, and other antireflection measures. However, for soft and low-permeability coal seams such as structural coal, the measures such as high-pressure hydraulic fracturing and deep-hole loose blasting are not applicable because the cracks generated by such measures are difficult to maintain in coal seam, which leads to a poor antireflection effect and the risk of inducing outburst. Therefore, the most fundamental way is to take out the coal to achieve pressure relief effects, and the permeability of the coal will be greatly improved after pressure relief. However, the measures of pressure relief and antireflection through a large number of boreholes have huge quantities and high cost. The cavitation and antireflection technology was first applied in surface coalbed methane well completion. Mechanical, water jet, or other measures were used to take out coal near the bottom of the well to achieve the purpose of pressure relief and antireflection. However, the complex underground conditions and limited space greatly limit the use of large completion equipment. So far, the drilling-reaming only relies on high-pressure water jet. The pressure relief and antireflection effects caused by high-pressure water jet

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cavitation are remarkable, but the coal breaking by water jet has some disadvantages, such as low efficiency, large consumption of water resources, difficulty to guarantee the size of cavitation, and so on. This is because there are many constraints on the effective coal-breaking distance of high-pressure water jet. For example, according to construction experience, submerged jet is formed when there is water in the borehole, and the water resistance greatly reduces the coal-breaking distance. When the consistent coefficient of coal is lower, the punching effect is significant, and the punching efficiency decreases rapidly with the increase of coal hardness. The limitation of water jet coal breaking has become the main factor restricting the efficient reaming and pressure relief of soft and low-permeability coal seam. In order to solve this problem, a new technology of efficient hole reaming and pressure relief when the coal becomes hard, the coal seam reaming technology of mechanical reaming supplemented by high-pressure water jet is developed, which makes use of the high efficiency of mechanical coal breaking to make up for the shortcomings of hydraulic coal breaking and retains the advantages of hydraulic coal breaking. Compared with the original single high-pressure water jet reaming, the efficiency and distance have been significantly improved. Based on this, the integration of the drilling and mechanical reaming process is simulated by a borehole-mechanical reaming model of coal seam.

2. COMPUTATIONAL METHODS

2.1. Integration of Drilling and Cavitation in Coal Seam

2.1.1. Drilling-Cavitation-Integrated Equipment. The mechanical coal seam cavitation pressure relief device discharges a certain amount of coal in the gas outburst coal body, forming a hole around the borehole, providing space for the expansion deformation, pressure relief, and displacement of the coal body. At the same time, it causes the development of...
the coal fracture network, greatly increases the permeability of coal seam, promotes efficient gas drainage, realizes pressure relief and permeability enhancement of the gas outburst coal body, and carries out regional gas control. The cavitation device can realize the opening and closing of the mechanical reaming device through pressure switching. When the mechanical knife is opened, the coal seam is cut and cavitation is created. When the mechanical knife is closed, the normal drilling operation is carried out. In the construction process, the integrated drilling and reaming operation is realized without exiting the drill pipe.

The complete set of large-diameter variable-diameter hole-making equipment for coal mine is suitable for rapid drilling and mechanical hole making in coal and gas outburst coal seams, so as to achieve the purpose of unloading, increasing permeability, and increasing flow. It is widely used in the underground (high) drainage roadway of coal mine and gas drainage hole and hole-making hole in the construction of heading face of this coal seam. It is an integrated complete set of equipment for the efficient gas treatment of gas-bearing and low-permeability coal seams (as shown in Figure 1). It mainly consists of BLY800/2 mining crawler mud pump truck (Figure 2a), ZDY10000LPS mining crawler full hydraulic tunnel drill (Figure 2b), KFS-50/11 mining vibrating screen solid–liquid separator, high-pressure sealed drill pipe (Figure 2c), high-pressure rotary joint, drill bit (Figure 2f), and variable-diameter mechanical cavitation device (Figure 2d,e).

2.1.2. Integrated Coal Breaking and Cavitation Process of Drilling and Expanding. In order to achieve the function of drilling and reaming integration, it is necessary to realize the reaming without reaming in the process of drilling, and at the same time, it is necessary to successfully exit the drill pipe after reaming. (1) During drilling, the reaming tool is closed in the tool slot on the device, as shown in Figure 2d. At this time, the cooling water flows through the drill pipe through the drilling expansion-integrated equipment and flows out of the drill bit at the front side. While cooling the drill bit, the drill cuttings are discharged. (2) When reaming, the water supply pressure is increased. When the water pressure reaches 10 MPa, the low-pressure water flow channel is closed, the high-pressure water only flows into the inner channel of the tool, and the tool is gradually opened. As the coal around the cutter is cut and washed, the hole increases until the cutter is fully opened (as shown in Figure 2e), and the rotating cutter under the action of the propulsive force of the drill pipe cuts off the coal and jointly breaks the coal and enlarges the hole with the water jet. The effective reaming length of the open cutter is 200 mm, and the drilling hole can be directly expanded from about 100–500 mm during rotary coal breaking. The process is accomplished by varying the water pressure, creating a combination of drilling, mechanical, and hydraulic reaming.

2.2. Mechanics Theory of Borehole-Mechanical Cavitation in Coal Seam. 2.2.1. Stress Analysis of the Drill Bit. The drill bit is an integral drill bit composed of a blade and cutting teeth (Figure 2f). Therefore, the stress of cutting teeth determines the stress of the drill bit. Therefore, to analyze the force of the drill bit, the force of cutting teeth should be analyzed first. Under the action of axial thrust and torque provided by the drill bit, the drill bit rotates to cut and break coal. According to the action principle of force, the cutter is also subjected to coal reaction force, which is mainly composed of coal resistance to the cutter $P_1$ and friction resistance $F_1$ between the cutter and the coal surface. The reaction force of the cutter subjected to coal can be decomposed into positive pressure $F_{\alpha}$, tangential force $F_\varphi$ and lateral force $F_l$ in 3D space, as shown in Figure 3.

![Figure 3. Stress diagram of cutting teeth.](https://doi.org/10.1021/acsomega.1c06011)

The coal body corresponds to the cutting resistance $P_1$ of the cutting teeth

$$F_i = P_i = \frac{c b h \cos \varphi}{\cos(\gamma + \varphi + \psi) \cos \Psi}$$

In the formula, $h$ is the cutting depth, $b$ is the width of the cutting teeth, $c$ is the cohesive force, $\phi$ is the angle of internal friction, $\psi$ is the angle between the shear surface of the coal body and the direction of shear, $\varphi$ is the friction angle on the contact surface, and $\gamma$ is the rake angle of the cutting teeth.

The reaction force $F_i$ of the coal body on the cutting teeth corresponds to the cutting resistance $P_i$ of the cutting teeth. Also, reaction force $F_1$ can be expressed by the compressive strength ($\sigma_1$) of coal and the cutting area ($S$). The friction force $F_c$ distributes on the wear surface under the blade, and the friction coefficient between the wear surface and the coal body is $\mu$, then

$$F_1 = P_1 = \sigma_1 S$$

Assuming that the drill bit has $n$ cutting teeth, the axial thrust $F_n$ and cutting force $F_c$ of the drill bit can be expressed as

$$F_n = n[F_1 \sin(\gamma + \varphi) + F_1]$$

$$F_c = n[F_1 \cos(\gamma + \varphi) + \mu F_1]$$

Substitute eqs 1 and 2a into 3a, then

$$F_n = n[F_1 \sin(\gamma + \varphi) + F_1]$$

$$F_c = n[F_1 \cos(\gamma + \varphi) + \mu F_1]$$

The forces $F_\alpha$, $F_\varphi$, and $F_l$ of each cutter are decomposed into the axial, tangential, and radial parts of the drill bit, respectively, and the axial components $F_{\alpha}$, tangential components $F_\varphi$ and radial components $F_l$ of each cutter are obtained. The tangential component is the tangential force of the cutter, and the axial component and radial component are, respectively

$$F_i = F_n \cos \varphi$$

$$F_i = F_n \cos \varphi$$

$$F_c = F_n \cos \varphi$$

$$F_c = F_n \cos \varphi$$
If the cutter has a side angle $\beta$, the reaction of coal to the cutter will subject the cutter to an additional radial force $F_{r\alpha}$ as shown in Figure 4.

$$F_{r\alpha} = F_r \tan \beta$$  \hspace{1cm} (6)

The tangential component force and radial component force of the cutting teeth are decomposed and summed to the $x$ and $y$ coordinate axes, and then, the resultant force of the component force in the two coordinate directions is calculated, and the lateral force and the action direction of the drill bit can be obtained

$$F_l = \sqrt{F_x^2 + F_y^2}$$  \hspace{1cm} (7)

Among, $F_x = \sum_{i=1}^{n} [F_i \sin \theta_i - (F_i + F_{r\alpha}) \cos \theta_i]$ and $F_y = \sum_{i=1}^{n} [F_i \cos \theta_i + (F_i + F_{r\alpha}) \sin \theta_i]$.

$$\theta_i = 360^\circ - \arctan \left( \frac{F_{x\alpha}}{F_{y\alpha}} \right) \quad F_x \geq 0$$  \hspace{1cm} (7a)

$$\theta_i = 180^\circ - \arctan \left( \frac{F_{x\alpha}}{F_{y\alpha}} \right) \quad F_x < 0$$  \hspace{1cm} (7b)

Under the action of lateral unbalance force $F_{\alpha}$, the drill bit side surface contacts the hole wall. According to the action principle of force, the drill bit side surface receives the reaction force $F_N$ and friction $\mu F_c$ of the hole wall. When the reaction force $P_0$ on the coal block unit on the hole wall exceeds its cohesive force and frictional resistance, instability collapse occurs. The reaction force $P_0$ of hole-wall coal corresponds to the lateral force $F_c$. Therefore, the mechanical conditions of coal block instability collapse under the action of drill bit cutting disturbance are as follows.

$$F_N = F_c > \epsilon + f$$  \hspace{1cm} (8)

### 2.2.2. Mechanical Analysis of Mechanical Cavitation

When making a hole in the borehole, the coal body is subjected to a uniform initial stress $P_0$ and the initial hole radius is $r_0$. When the reaming pressure gradually increases from $P_0$, the borehole diameter gradually increases from $r_0$. With the increasing force exerted by the cutter on the borehole wall, the surrounding rock around the borehole begins to yield and destroy due to the circumferential cutting stress of the cutter and develops inward from the borehole wall. From the original elastic state to the elastic-plastic state, the small hole radius $r$ and the plastic zone radius $R$ also continue to expand. When the expansion pressure reaches a certain value, that is, when the water pressure of the reaming device is stable, the expansion pressure will remain unchanged and reach the maximum cavity radius. Figure 5 shows the circumferential stress model of hole making.

The basic theoretical equation of mechanical cavitation in coal seam can be expressed as

$$\frac{\partial \sigma_r}{\partial r} + \frac{(\sigma_r - \sigma_\theta)}{r} = 0$$  \hspace{1cm} (9)

In the formula, $\sigma_r$ and $\sigma_\theta$ are radial stress and circumferential stress, respectively.

The elastic stress-strain relationship is

$$\begin{align*}
\varepsilon_r &= \frac{E(1 - \nu^2)}{\sigma_r} - \frac{\sigma_\theta}{1 - \nu} \\
\varepsilon_\theta &= \frac{E(1 - \nu^2)}{\sigma_\theta} - \frac{\sigma_r}{1 - \nu}
\end{align*}$$  \hspace{1cm} (10)

In the formula, $E$ is the elastic modulus of the coal and $\nu$ is the Poisson’s ratio of the coal.

$P$ is the pressure on the borehole wall when the drilling pipe does not rotate and the reaming tool just touches the borehole wall. At this time, the borehole wall is in an elastic state, and the radial stress and circumferential stress are

$$\begin{align*}
\sigma_r &= P_0 + \frac{P - P_0}{(r_0/r)^2} \\
\sigma_\theta &= P_0 - \frac{P - P_0}{(r_0/r)^2}
\end{align*}$$  \hspace{1cm} (11)

When the tool rotates with the drill pipe, the tool begins to cut on the drilling surface, and the coal on the drilling surface begins to yield, reaching the yield limit, that is, failure. Suppose that the radius at the elastic-plastic interface is $R$ at a certain time and the critical plastic pressure acting radially at this point.
moment is $p_r$, then the radial and circumferential stresses at the elastic–plastic interface are, respectively

$$
\begin{align*}
\sigma_r &= P_0 + \frac{p_r - P_0}{(r_0/R)^2} \\
\sigma_\theta &= P_0 - \frac{p_r - P_0}{(r_0/R)^2}
\end{align*}
$$

(12)

In the process of reaming, the push rod is gradually compressed by the axial thrust; the piston pushes the gear and pushes the tool out of the rod body. The force of the tool on the direction perpendicular to the drilling wall gradually increases. When the push rod pushes the tool out completely, the vertical stress of the drilling wall reaches the maximum. At this time, the diameter of the largest reaming section reaches the maximum.

2.2.3. Coal Strength Failure Criteria. For coal under general force conditions, the ultimate shear strength of any force surface can usually be expressed by the Mohr–Coulomb law

$$
\tau_n = c - \sigma_n \tan \varphi
$$

(13)

In the formula, $\tau_n$ is the ultimate shear strength of the coal; $\sigma_n$ is the normal stress on the shear surface of the coal; and $c$ is the cohesion of the coal.

Equation 16 is a linear relationship on the $\sigma$–$\tau$ plane. In a more general case, the $\sigma$–$\tau$ curve can be expressed as a parabola, hyperbola, and other nonlinear curves, collectively referred to as the molar intensity condition.

The Mohr–Coulomb condition is expressed by principal stress $\sigma_1$ and $\sigma_3$ as

$$
\frac{1}{2}(\sigma_1 - \sigma_3) = c \cos \varphi - \frac{1}{2}(\sigma_1 - \sigma_3) \sin \varphi
$$

(14)

The general yield condition form is

$$
F = \frac{1}{2}(\sigma_1 - \sigma_3) + \frac{1}{2}(\sigma_1 - \sigma_3) = 0
$$

(15)

If $I_1$, $I_2$, and $\theta_\sigma$ replace $\sigma_1$ and $\sigma_3$, then

$$
F = \frac{1}{3} \sin \varphi + \left[ \cos \theta_\sigma - \frac{1}{3} \sin \theta_\sigma \sin \varphi \right] \sqrt{\frac{\pi}{2}} - c \cos \varphi = 0
$$

(16)

In the formula, $-\pi/6 \leq \theta_\sigma \leq \pi/6$.

The average stress can be obtained from the three principal stresses $\sigma_n$ generalized shear stress $\tau_\varphi$ and Cape lode $\theta_\sigma$.

Therefore, the Mohr–Coulomb criterion can be expressed as

$$
\tau_\varphi = -\sigma_n \tan \varphi \cos \theta_\sigma + c
$$

(17)

Equation 17 can be expressed in another form

$$
\tau_\varphi = -\sigma_n \tan \varphi + c
$$

(18)

In the formula, $\tan \varphi = \frac{3 \sin \varphi}{\sqrt{3} \cos \theta_\sigma - \sin \theta_\sigma \sin \varphi}$, $c = \frac{3 \cos \varphi}{\sqrt{3} \cos \theta_\sigma - \sin \theta_\sigma \sin \varphi}$.

Equations 9–11 consider the friction-type criterion of the friction component, which can summarize the Tresca condition, Von-Mises condition, generalized Von-Mises condition, and Drucker–Prager condition.

When $\varphi = 0$, it is the Tresca condition

$$
\sqrt{\frac{3}{2}} \cos \theta_\sigma - c = \sqrt{\frac{3}{2}} \cos \theta_\sigma - k = 0
$$

(19)

If $\theta_\sigma = 0$, the Von-Mises condition can be obtained

$$
\sqrt{\frac{3}{2}} - c = 0
$$

(20)

When $\theta_\sigma$ is constant, the yield function is no longer related to $I_2$, namely, the generalized Von-Mises condition can be obtained

$$
A_l + \sqrt{\frac{3}{2}} - k = 0
$$

(21)

Tensile damage at $\theta_\sigma = -\pi/6$ can be obtained

$$
A = \frac{2 \sin \varphi}{\sqrt{3}(3 + \sin \varphi)} = \frac{6 \cos \varphi}{\sqrt{3}(3 + \sin \varphi)}
$$

$$
\tan \varphi = \frac{6 \sin \varphi}{3 + \sin \varphi} = \frac{6 \cos \varphi}{3 + \sin \varphi}
$$

(22)

When tensile damage at $\theta_\sigma = \pi/6$ can be obtained

$$
A = \frac{2 \sin \varphi}{\sqrt{3}(3 - \sin \varphi)} = \frac{6 \cos \varphi}{\sqrt{3}(3 - \sin \varphi)}
$$

$$
\tan \varphi = \frac{6 \sin \varphi}{3 - \sin \varphi} = \frac{6 \cos \varphi}{3 - \sin \varphi}
$$

(23)

When tensile damage at $\theta_\sigma = -\pi/6$, it is the Drucker–Prager failure criterion

$$
A = \frac{\sin \varphi}{\sqrt{3}(3 + \sin \varphi)} = \frac{\tan \varphi}{\sqrt{9 + 12 \tan^2 \varphi}}
$$

$$
I_2 = \frac{\sqrt{3} \cos \varphi}{\sqrt{3}(3 + \sin \varphi)} = \frac{3 \cos \varphi}{\sqrt{3} \cos \theta_\sigma - \sin \theta_\sigma \sin \varphi}
$$

(24)

When the plastic strain value of the coal body reaches a certain limit value, the coal body will begin to damage and then fail and peel off from the coal body, that is

$$
e^p = \bar{e}^p
$$

(25)

In the formula, $\bar{e}^p$ is the equivalent plastic strain when the coal fails completely and $e^p$ is the equivalent plastic strain of coal.

The rock "damage factor" is an important parameter in damage mechanics. Since its development, more than 10 damage factor measurement methods have been formed. The most commonly used method is to define the damage factor $D$ through the change of the elastic modulus of the material, which is

$$
D = 1 - \frac{E'}{E} = \begin{cases} 0 & (e \leq \bar{e}^p) \\ 1 - \frac{e}{\bar{e}^p} & (e > \bar{e}^p) \end{cases}
$$

(26)

In the formula, $E$ is the elastic modulus of the undamaged coal; $E'$ is the macroscopic equivalent elastic modulus of the fractured coal; $e$ is the strain; $\sigma$ is the stress; $\bar{e}^p$ is the critical
plastic strain; $D$ is the damage factor of the coal; and $\bar{\sigma}$ is the extended value on the dotted line in Figure 6.

The stress–strain characteristic curve of the coal body during the failure process is shown in Figure 6. The solid line in the figure is the failure stress–strain curve, and the dashed line represents the corresponding nondestructive stress–strain curve. $\sigma_y$ and $\varepsilon_{pl}^f$ are the critical yield stress and critical plastic strain, respectively, when the coal body begins to fail, where the coal body damage factor $D = 0$; $\varepsilon_{pl}^f$ is the equivalent plastic strain when the coal body fails completely, where the rock damage factor $D = 1$. When the damage factor $D$ on the finite element is 1, the material is regarded as complete failure and spalling.

As the borehole size of coal seam is smaller than that of coal seam, according to the theory of elastic–plastic mechanics, the coal body around borehole is regarded as isotropic, homogeneous, and continuous medium, and the deformation of the coal body is small deformation. The deformation and crushing process of coal under the action of the drill bit is mainly divided into an elastic deformation stage, plastic deformation stage, and crushing stage. In the drilling process, the drill bit mainly uses the bit rotation to cut broken coal chips. According to the composition, structure, and stress characteristics of coal, the equivalent plastic strain of coal is selected as the judgment criterion of coal failure during drilling.

2.3. Mechanical Property Test of Coal. 2.3.1. Coal Sample Preparation. The test coal samples were taken from No. 3 coal seam (high metamorphic anthracite) in Xinjing Mine, Yangquan, with a burial depth of about 400 m and a thickness of 0.75–4.80 m with an average thickness of 2.26 m. The coal body of Xinjing Mine belongs to the soft coal body (firmness coefficient $f$ is between 0.44 and 0.50), and it is difficult to drill and prepare a standard-size raw coal sample of a diameter of 50 mm and a height of 100 mm. Therefore, briquette coal is used to test the mechanical and deformation characteristics of the soft coal body. The preparation of briquette mainly includes the following steps:

(1) Pulverize the bulk coal with a crusher and then screen out coal particles with a diameter of less than 1 mm as the base material for sample preparation;

(2) Mix coal particles and a small amount of distilled water in a clean container and stir them evenly, weigh them, and put them into a special mold (as shown in Figure 7a). The inner diameter of the mold is 50 mm;

(3) The axial pressure is loaded to 200 kN at a rate of 300 N/s, the pressure is stabilized for 3 h, and the coal sample is removed from the mold;

(4) The briquette sample is put into a vacuum drying oven and vacuum-dried at 60 °C for 2 h. The briquette sample is sealed for later use. The partially prepared soft coal and traditional briquette are shown in Figure 7b.

The processing accuracy of all coal samples is carried out in accordance with the “Rock Test Method Standard” (GB50218–94), that is, the unparallelism error of the two ends of the coal sample is not more than 0.005 mm, and the unevenness error of the end surface is not more than 0.02 mm. The diameter error along the height of the coal sample is no more than 0.3 mm. The end face is perpendicular to the axis of the samples, and the maximum deviation is not more than 0.25°.

2.3.2. Test Results and Analysis. The mechanical properties of coal under different confining pressures were tested by the triaxial compression test system (as shown in Figure 8), and

the strength parameters and deformation parameters such as uniaxial compressive strength, triaxial compressive strength (peak stress of the coal sample under each confining pressure), stress–strain curve, elastic modulus, Poisson’s ratio, cohesion, and internal friction angle can be obtained. After drilling, the stress state of coal changes and forms a new secondary stress distribution, which is manifested as tangential loading and radial unloading. It should be noted here that the axial load described in the laboratory corresponds to the maximum
principal stress on site, which is the tangential stress for the coal around the borehole; the confining pressure described in the laboratory corresponds to the minimum principal stress on site, which is the radial stress for the coal around the borehole. According to the evolution of the actual stress state of the coal around the borehole, the mechanical path of adding axial pressure (maximum principal stress) and unloading confining pressure (minimum principal stress) is selected. The stress—strain curves obtained from triaxial compression tests of coal samples under different confining pressures are shown in Figure 9.

Figure 9. Deviatoric stress—strain relationship curve of the coal sample in the triaxial (uniaxial) compression test.

In order to facilitate the regression analysis of the test data, the Mohr–Coulomb failure criterion is first transformed into the form of the main stress expression

\[ \sigma_i = \Psi + \zeta \sigma_3 \]  

(27)

\[ \Psi \text{ and } \zeta \text{ are the functions of cohesion } c \text{ and internal friction angle } \varphi, \text{ respectively} \]

\[ \Psi = \frac{2c \cos \varphi}{1 - \sin \varphi} \]  

(28)

\[ \zeta = \tan \left( 45^\circ + \frac{\varphi}{2} \right) \]  

(29)

The least-square method is used to fit the test data of coal sample loading, and the slope (\( \Psi \)) and intercept (\( \zeta \)) of the straight line can be calculated. The cohesion and internal friction angle of the coal sample under conventional loading and unloading confining pressure before peak can be further deduced from the physical significance of \( \Psi \) and \( \zeta \). The relationship between confining pressure and axial pressure in Figure 10 can be expressed as a linear relationship, with a correlation coefficient of 0.9987. Furthermore, the cohesion and internal friction angle of the coal sample can be calculated as shown in Table 1.

2.4. Numerical Simulation and Analysis of Drill Bit Drilling in Coal Seam. 2.4.1. Basic Assumptions. Drilling in coal and rock mass by the drill bit is a very complex process. There are many factors affecting drilling efficiency. The main factors directly related to the drilling process are coal and rock state, drilling depth, rotating speed, and so on. When using finite element analysis software to simulate the drilling process, the following assumptions shall be made:

1. The hardness and strength of the coal body are far inferior to the drill bit body. The drill bit is regarded as a rigid body in the model, and the wear of the bit and cutting teeth during drilling is not considered;
2. It is assumed that during the drilling process of the drill bit, the coal dust is removed sufficiently and does not affect the drilling process of the drill bit; and
3. The drill bit has a good hole trajectory, the drill bit penetrates the coal body vertically, and the drill bit does not shift during the drilling process.
4. Ignore the frictional hindrance of the hole wall and well wall to the rotation and advancement of the drill pipe and the drill bit.

2.4.2. Boundary Conditions and Load Application. According to the specific geological conditions of the drilling site, the coal body is infinite, and the drilling process has little impact on the surrounding coal body. The nonstress reflection total displacement constraint is adopted at the bottom boundary of the coal body model, while the nonstress reflection lateral displacement constraint is adopted at the surrounding boundary. For the drill bit, it has been assumed that the drill bit has a straight hole during the drilling process, and the radial displacement constraint is applied to the center line of the drill bit, which still has the freedom of rotation around the Z axis and Z-direction displacement. To simulate the process of drilling through the coal of the drill bit, bit pressure, torque, drilling rate, and speed can be applied to the drill bit, and pressure can also be applied to the coal body to simulate the process of deep drilling. According to the drill bit in Figure 2f, a drill bit model is established. The boundary conditions and load application of the overall model are shown in Figure 11.

In order to simulate the destruction of coal and the discharge process of coal chips in the drilling process, the birth and death element is used in the part where the coal model may contact with the drill bit. Under the bit pressure and rotation of the drill bit, the cutting teeth press into the coal and produce a cutting effect on the coal. When the element reaches...
the failure plastic strain, it is considered to complete coal breaking and chip removal, kill the element and associated nodes, and then automatically search the contact surface and redefine the contact. In this way, the dynamic simulation of rock breaking of the drill bit is completed.

2.4.3. Simulation of the Rock-Breaking Process of the Drill Bit.

The failure process of the coal body is very complicated, so all failure criteria cannot be taken into account in numerical simulation. Only one failure condition, namely, failure strain, is used in the simulation of the drill bit breaking coal. In the simulation of the rock-breaking process of the drill bit, the rigid body model is adopted for the drill bit and cutter, and the plastic follow-up strengthening model is adopted for the coal body. The material parameters are shown in Table 2.

Coal drilling by the drill bit is a dynamic process, and the continuous discharge of coal chips allows the drill bit to continue drilling. In this numerical simulation, the life and death unit is used to simulate coal crushing and chip removal. During the drilling process of the drill bit, the drill bit exerts mechanical action on the surrounding rock mass through the action of weight on bit and torque. When the effective plastic strain of the element reaches 1.0%, it is considered that the element has been destroyed. The element and the isolated node are killed, so that they do not participate in the subsequent analysis and calculation. When the unit is killed, the contact between the drill bit and cutting teeth and the rock mass will be redefined, and the contact unit and contact surface will be updated automatically.

The numerical simulation has a relatively large degree of nonlinearity and complexity. It includes not only the nonlinear characteristics of the material constitutive but also the nonlinearity of the contact problem between the drill bit and the coal body. At the same time, the life and death element is used in the model, and the calculation process is quite complicated. As a result, the data packet storage space is also relatively large. Figure 12 shows the failure of the drill bit and the rock unit at different moments under loading with an angular velocity of 4 r/s and a drilling speed of 2 cm/s. As cylindrical coal is symmetrical, the failure form is represented by a quarter diagram. It can be seen from Figure 12 that at 1 s, multiple units in the center of the coal body have failed, and then at 5 s, the second layer unit in the center also began to fail. Rock mass elements are failed and deleted layer by layer. With the advancement and rotation of the drill bit, at 10 s, most of the drill bit body has entered the coal body and formed a crushing pit in the coal body, while at 15 s, the drill bit body has completed entering the coal body and formed a final pore diameter in the coal body. The drill bit has no cutting teeth in the center of the top but three cutting teeth around it. The first failure unit on the coal body is the central part of the coal body, not the unit initially in contact with the coal body. Therefore, it can be inferred that the failure of the unit in the central part of the coal body is not caused by pressure but should be caused by shear.

Figure 13 shows the Mises stress distribution of rock mass at different drilling times under the loading of 10 kN weight and 180 N·m torsional torque. As can be seen from Figure 13, the cutting teeth at the top of the drill bit are the first to contact the rock unit.

| serial number | confining pressure/MPa | peak stress/MPa | ψ/MPa | ζ/deg | cohesion/MPa | internal friction angle/deg |
|---------------|------------------------|----------------|--------|--------|--------------|-----------------------------|
| 1             | 0                      | 1.66           | 6.60   | 3.70   | 1.72         | 35.06                       |
| 2             | 2                      | 13.72          |        |        |              |                             |
| 3             | 4                      | 21.90          |        |        |              |                             |
| 4             | 6                      | 28.57          |        |        |              |                             |
| 5             | 8                      | 36.14          |        |        |              |                             |

Figure 11. Boundary conditions and load loading.

Figure 12. Failure of drilling coal seam and the coal body unit.

Table 1. Mechanical Parameters of the Conventional Triaxial Compression Test of Coal Samples

| serial number | ρ (kg/m³) | E (GPa) | μ | G (GPa) | K (GPa) | f_s | f_d |
|---------------|-----------|---------|---|---------|--------|-----|-----|
| cutting teeth | 8390      | 200     | 0.25 | 0.21    | 123    | 0.12 | 0.10 |
| coal body     | 1430      | 0.23    | 0.50 | 0.25    | 3.43   | 0.18 | 0.15 |

Table 2. Mechanical Parameters of Cutting Teeth and the Coal Body
the coal body. However, the first unit to be damaged is not the unit in contact with the cutting teeth, but the central axis of the bit body. This is because the rock mass element on the central axis of the bit body bears the largest force and plastic deformation under the action of the cutting force of three cutting teeth pressure and torsion, so it reaches failure first. Then, the unit in contact with the top of the drill bit is damaged, and the cutting teeth begin to enter the coal body. The contact area between the coal body and the drill bit increases, and the friction resistance also increases. At 1s, the cutting teeth press into the coal body and shear the rock mass, forming a crushing pit on the surface of the coal body. With the increase of drilling time, the depth of the drill bit entering the coal body is also increasing. At 15 s, all the cutting teeth of the bit body have entered the coal body, forming a small section of drilling on the coal body. It can be seen from the Mises stress nephogram in Figure 13 that when the drill bit just contacts the coal, the maximum stress occurs in the center of the coal sample. With the increase of the drill bit drilling depth, the maximum stress point shifts to the depth. When the coal at the center of the sample is broken, the maximum stress point moves around.

Figure 14 shows the time history curve of the torsional moment on the drill bit under the loading of angular velocity 4 r/s and linear velocity 2 cm/s. As can be seen from Figure 14, the torsional moment on the drill bit generally increases with the drilling time. When the drill bit just contacts the coal body, the number of contact units between the coal body and the drill bit is very small, and the hindered torsional moment of the drill bit is also small. With the increase of drilling depth, the number of contact units between the drill bit and the coal body increases sharply, and the hindered torsional moment of the drill bit also increases rapidly. At 10 s, most of the bit body has entered the coal body. At this time, the torsional moment received by the drill bit has reached the maximum. Thereafter, with the increase of drilling depth, the torsional moment received by the drill bit will no longer increase. Due to the unit damage, in the actual drilling process, it is the formation of coal chips, and the torsional moment received by the drill bit also fluctuates greatly.

Figure 15 shows the variation curve of the vertical displacement of the drill bit with the drilling time. Due to the full displacement constraint imposed on the bottom boundary of the coal model, the vertical displacement of the drill bit is the drilling depth. It can be seen from Figure 15 that during the initial contact period between the drill bit and the rock mass, the cutting teeth on the drill bit do not break the coal but form friction on the coal body and produce a shear effect on the coal body surface. With the increase of vertical displacement, the friction between the drill bit and the coal body increases, and the shear effect of the cutting teeth on the coal body surface increases. When it reaches a certain degree, the units in the center of the coal body began to destroy. In the process of bit drilling, the vertical displacement of the drill bit does not increase gradually with time but the separation of coal and drill bit from time to time, that is, “rebound”. However, the overall trend of the vertical displacement of the bit with
time is to increase. At the drilling site, the bit will rebound, and the sound of clicking is often heard in the drilling process, which is generally caused by the hard coal body.

Figure 16 shows the time curve of the maximum number of contact units between the drill bit and the coal body under loading with an angular velocity of 4 r/s and a drilling speed of 2 cm/s. It can be seen from Figure 16 that the number of contact units (contact area) between the drill bit and the coal body is not constant, it changes with the drilling of the drill bit. Due to the adoption of the life and death unit, when some of the units are killed, the number of contact units between the drill bit and the coal body will decrease, and when it comes into contact with the coal body again, the number of contact units between the drill bit and the coal body will increase. Initially, when the drill bit first touches the coal body, there are only three units in contact. With the increase of the drilling depth, the maximum number of contacts between the drill bit and the coal body increases sharply. When the bit basically enters the coal, the maximum contact number between the drill bit and coal remains unchanged.

3. RESULTS AND DISCUSSION

3.1. Mechanical Hole Making in Coal Seam Drilling.
During mechanical cavitation, the water pressure of the water injection pump station is gradually increased to a high pressure state of 12 MPa. The mechanical knife arm is fully opened to cut coal and generate holes. The integration of drilling and cavitation is realized through the conversion of high and low pump pressure. The high- and low-pressure conversion mechanical cavitation device uses high-pressure water to open the mechanical tool handle to expand the hole and form a hole with a diameter of 500 mm.

3.2. Numerical Simulation Results and Analysis of Mechanical Cavitation.
During the simulation, the rod body of the cavitation device was set as the rigid body, and a reference point was established on the rod body. The rotational speed and axial thrust were applied on the reference point, the rotational speed and axial thrust were applied simultaneously, and boundary constraints in x and y directions were applied on the surface of the block body. ABAQUS finite element numerical simulation software was used to simulate the mechanical characteristics of the coal seam caving section at different times under confining pressure at 5 MPa. The model is shown in Figure 17.

An axial thrust of 1500 N is applied to the drilling machine in the coal seam, and the stress state of the coal body during the reaming process is shown in Figure 18. In the initial stage of cavitation, the cavitation tool is gradually opened (i.e., the diameter of the cavitation is gradually increased), until the cavitation tool is fully opened, the stress state shown by the coal body also has a certain difference, and as the diameter of

Figure 15. Variation curve of drilling depth with time.

Figure 16. Number variation of contact units between the drill bit and coal with time.

Figure 17. Drill pipe cavitation device and coal body.
the cavitation increases, the maximum stress of coal also gradually increased.

**Figure 19** is a cloud diagram of the cross-sectional stress distribution of coal at different times during the process of cave-making. It can be seen from Figure 19 that when the coal seam is cut by the cutter to reach the strength limit, it will be destroyed. The elimination of the mesh will be displayed in the software. The hexahedral mesh with higher calculation accuracy is used in the model. The quality is good, and the distribution is even. After the calculation is completed, how much the damage of the hexahedral mesh is eliminated was observed, and the software’s own query function to reflect the hole-forming effect of the cavity is used, which can be used as a reference to a certain extent. When there is no reaming ($t = 0$), the coal seam is drilled under confining pressure and local stress is generated. When $t = 2$ s, the contact part between the reaming tool and coal has produced a large stress. The maximum stress is at the contact point between the coal body and the reaming tool tip. The stress distribution is centered on the contact point and decreases layer by layer. When $t = 5$ s and $t = 10$ s, with the feed of the reaming tool, more and more parts are involved in cutting, and the stress value increases gradually with the drilling depth. When the maximum stress occurs, the maximum stress value tends to be stable until the cutting is completed. At $t = 15$ s, the cutting is basically completed, and some stress will occur due to the influence of coal properties.

### 3.3 Analysis of Contact Cutting between the Reaming Tool and Hole Wall

When the drill pipe rotates, the drill pipe may collide with the hole wall at any axis position, accompanied by energy loss, friction resistance, and resistance moment, which changes the motion state of the drill pipe and drill bit. **Figure 20** shows the contact area between the drill pipe and hole wall during drilling.

As can be seen from Figure 20, the drill pipe starts to contact the hole wall at 0.71 s, and the contact area is 0.45 mm$^2$. At 9.83 s, the contact area between the drill pipe and the hole wall reached a maximum of 141.54 mm$^2$ and then tended to be...
stable, but the contact between the drill pipe and the hole wall is random and had no obvious regularity.

When the drill pipe rotates, the reaming tool collides with the hole wall at the reaming position of the axis, accompanied by energy loss, friction resistance, and resistance moment, which changes the motion state of the drill pipe and drill bit. The X direction, Y direction, and normal contact force between the reaming tool and the hole wall are used to describe the contact process between the reaming tool and the hole wall in the drilling process. Figure 21 shows a graph of the contact force between the reaming tool and the hole wall during drilling.

As can be seen from Figure 21, the X and Y directions of the contact force between the reaming tool and the hole wall have changed. The reaming tool does not always maintain contact with the hole wall but constantly changes the contact point. After the reaming tool contacts the hole wall, the normal contact force is 351.76 N and the X direction contact force is 328.29 N. The X direction is negative, indicating that the reaming tool is in contact with the other side of the hole wall. With the increase of time, the contact force begins to increase.

Figure 20. Contact area between the reaming tool and hole wall.

Figure 21. Contact force between the reaming tool and hole wall. (a) Contact force in the X direction. (b) Contact force in the Y direction. (c) Normal contact force.
and basically tends to be stable. This is because with the gradual opening of the reaming tool, the area of the reaming tool in contact with coal increases, and the cutting force also increases accordingly. The X and Y direction contact force is gradually increasing and then tends to a certain stable state; at this time the reaming tool has been fully opened.

4. CONCLUSIONS

According to the characteristics of poor permeability and low extraction efficiency in soft coal seam, the integrated pressure relief and permeability enhancement technology of drilling and mechanical cavitation is proposed to achieve the purpose of permeability enhancement through pressure relief. By testing the mechanical properties of the coal body, the mechanical parameters of the coal body are obtained, the physical model of the drill bit drilling into the coal body and the reaming tool breaking the coal is established, and the coal-drilling tool mechanical characteristics of the drill bit drilling and reaming process are numerically analyzed. The conclusions are as follows:

1. Drilling through coal with the drill bit is a dynamic process. When the drill bit just touches the coal, the maximum stress occurs at the center of the coal sample. With the increase of drilling depth, the maximum stress point shifts to the depth. When the coal is broken in the center of the sample, the maximum stress point moves around.

2. With the increase of drilling depth, the torsional torque on the drill bit increases, and the maximum contact number between the drill bit and coal increases sharply. When the bit body basically enters the coal, the maximum contact number between the drill bit and coal body remains unchanged.

3. In the initial stage of cavitation, the cavitation tool gradually opens, and more and more coal parts are involved in cutting (the contact surface of the reaming tool is bigger and bigger). The stress value of coal increases gradually with the reaming time, and when the maximum stress occurs, the maximum stress value tends to be stable.

4. When the drill pipe rotates, the reaming tool colliders with the hole wall at the reaming position, but the reaming tool does not always keep the contact with the hole wall but constantly changes the contact point. As the reaming tool gradually opens, the cutting force increases correspondingly, and then, when the reaming tool is fully opened, the cutting force tends to a certain stable state.

### Notes

The authors declare no competing financial interest.

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