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A Review of the Fracture Extension Mechanism and Mechanical Analysis around the Perimeter of the Extraction Borehole

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Abstract

With The development and utilization of coalbed methane (gas) is an important way to adjust my country's energy structure. At the same time, coalbed methane extraction is also an important technical means to control outstanding gas accidents. In order to improve the extraction utilization rate, it is necessary to improve the gas pre-draining effect, then the gas in the coal seam needs to be extracted by using the extraction drilling and its permeability enhancement technology, and the gas resources are used to ensure the safe production of the mine. In this paper, the stress distribution around the borehole of the mining hole is combed with rock mechanics. Through the analysis of the related mechanism of injecting high-pressure liquid nitrogen into the cracked coal rock in the extraction borehole, we learned that the impact force of liquid nitrogen generated by high-pressure fluid, liquid nitrogen gasification expansion force, water-ice phase change frost expansion force and low temperature liquid nitrogen pair fractured coal rock under the combined action of coal body damage. Through the analysis of the influencing factors of the stress distribution of the borehole and the assumption of the stress study, combined with the relevant theory of the plastic zone distribution, it will lay down for the subsequent construction of the mechanical model of the extracted borehole and the systematic study of the high-pressure liquid nitrogen-induced fractured coal rock basis.

Keywords

Drainage Drilling; Rock Mechanics; Fissure Propagation; Permeability; Liquid Nitrogen; Coal Seam.

1. Introduction

The volume of China's coal consumption market is huge, and the main position of coal in energy consumption is difficult to change in a short time. The precise extraction of coal mine gas is the main technical means of mine gas prevention and control, and in order to improve the extraction utilization rate, it is essential to improve the gas pre-pumping effect. One of the important issues facing the extraction of gas from coal seams using extraction boreholes is to increase the coal seam permeability, thus promoting the discharge of gas from the coal seam and achieving the effect of abatement and utilization of gas resources.

The main mechanical factors affecting the stability of extraction boreholes include ground stress, mechanical properties of coal rock, deformation characteristics of coal rock (elastic, elastoplastic, plastic, viscoelastic, etc.), mining stress and temperature disturbance stress. In this paper, we discuss the stress distribution and fracture expansion mechanism around the perimeter of the extraction borehole in the context of rock mechanics, and discuss and analyze the mechanism of fracturing coal rock by injecting high-pressure liquid nitrogen into the extraction borehole. The factors influencing the stress distribution in the borehole, the assumptions for the study of the stress around the borehole and the theories related to the distribution of the plastic zone are discussed and analyzed, aiming to provide theoretical support for the construction of the mechanical model of the extraction borehole and the study of the pore structure evolution characteristics and permeability enhancement mechanism of the fractured coal body by the injection of liquid nitrogen in the extraction borehole in the future.

2. Current Status of Research on Peripore Fracture Extension in Extraction Boreholes

2.1 Theory of Stress Distribution around the Perimeter of Extracted Boreholes

The fracture extension mechanism of extraction borehole is an important part of extraction borehole research. Early scholars believed that the mechanical model of extraction borehole is extremely similar to that of the roadway, so they mostly adopted the calculation method of roadway surrounding rock stress to carry out stress research around the borehole.

Academician Qian [1] and other pioneer scholars theoretically gave the stress distribution in the surrounding rock of the roadway, and combined with the theory of limit equilibrium conditions to derive the radial stress and tangential stress in the fracture zone of the surrounding rock, as shown in equations (1) and (2). By studying the limit equilibrium theory, the classical stress and plastic zone calculation method is established, and most of the subsequent studies are carried out based on this idea.

$$\sigma_r = C\cot\varphi[(\frac{r}{r_1})^{\frac{2\sin\varphi}{1-\sin\varphi}} - 1] \tag{1}$$

$$\sigma_t = C\cot\varphi[\frac{1+\sin\varphi}{1-\sin\varphi}(\frac{r}{r_1})^{\frac{2\sin\varphi}{1-\sin\varphi}} - 1] \tag{2}$$

Where: σ_r, σ_t are the radial and tangential stresses, respectively, MPa; C is the cohesion of the coal rock body, MPa; φ is the angle of internal friction, °; r, r_1, is the pole diameter of the study point and the radius of the roadway, m.

Wang [2] applied this theoretical derivation process to the study of stress distribution around the perimeter of the extraction borehole, and used the residual plastic softening model combined with the Mohr-Coulomb strength criterion to establish the destabilization mechanics model of the borehole bottom in the "three zones" (i.e., fracture zone, plastic zone, and elastic zone), and gave the destabilization conditions of the borehole wall in the elastic zone, plastic zone, and fracture zone as equations (3)-(5).

$$\sigma_r + \alpha p_r \delta_{ij} = \frac{1+\sin\varphi}{1-\sin\varphi}(\sigma_r - \alpha P_r \delta_{ij}) + \sigma_c \tag{3}$$

$$\sigma_r + \alpha p_r \delta_{ij} = \frac{1+\sin\varphi}{1-\sin\varphi}(\sigma_r - \alpha P_r \delta_{ij}) + \sigma_c(\varepsilon_1^p) \tag{4}$$

$$\sigma_r + \alpha p_r \delta_{ij} = \frac{1+\sin\varphi}{1-\sin\varphi}(\sigma_r - \alpha P_r \delta_{ij}) + \sigma_c^* \tag{5}$$

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Where: σ_r is the radial stress, MPa; σ_c is the uniaxial compressive strength, MPa; σ_c^* is the residual compressive strength, MPa; α, δ_{ij} is the equivalent pore pressure coefficient and Kroneker sign; P_r is the radial gas pressure, MPa; ε_1^p is the plastic softening strain component.

Zheng [3] used the classical elastic theory to solve the problem by using the superposition principle to simplify the three-dimensional stress field around the borehole to a planar stress superposition problem, and obtained the relative displacement expression near the borehole, as shown in equation (6).

$$\left.\begin{aligned} u &= \frac{(1+v)r}{E}\left\{\frac{p_x+p_y}{2}\frac{a^2}{r^2}+\frac{p_x-p_y}{2}\left[-\frac{a^4}{r^4}+4(1-v)\frac{a^2}{r^2}\right]\cos 2\theta\right. \\ &\quad +p_{xy}\left[-\frac{a^4}{r^4}+4(1-v)\frac{a^2}{r^2}\right]\sin 2\theta \\ v &= -\frac{(1+v)r}{E}\left(\frac{p_x-p_y}{2}\sin 2\theta - p_{xy}\cos 2\theta\right)\left[\frac{a^4}{r^4}+2(1-2v)\frac{a^2}{r^2}\right] \\ w &= \frac{2(1+v)r}{E}(p_{yz}\sin\theta + p_{zx}\cos\theta)\frac{a^2}{r^2} \end{aligned}\right\} \tag{6}$$

Where: u, v, w, are the x, y, z three-way displacements, m; p_x, p_y, p_{xy}, p_{zx}, p_{yz} are the distal uniform loads, MPa; in the polar coordinate system θ are the polar angles and r are the polar diameters in ° and m ; a are the borehole radii, m; E are the moduli of elasticity, MPa.

Wang [4] et al. studied the mechanical mechanism of destabilization of loose and soft particles in the surrounding rock based on the elasticity theory, and gave the criterion of collapse of loose and soft coal rock holes, as shown in equation (7).

$$\left|\frac{1+\lambda}{2}q_0\left(1+\frac{r_1^2}{r^2}\right)+\frac{1-\lambda}{2}q_0\left(1+3\frac{r_1^4}{r^4}\right)\cos 2\theta\right| > |R_t| \tag{7}$$

Where: r_1 is the radius of the borehole, m; λ is the lateral stress coefficient in the original rock stress field; q0 is the vertical self-weight, MPa; R_t is the tensile strength of the borehole wall of the surrounding rock, MPa.

Sun [5] studied the mechanical mechanism in the drilling process of loose coal seams and investigated the influence of drilling depth on the stability of the borehole. Based on this, Li [6] studied the expression of stress in the elastic-plastic zone of the borehole by combining the generalized Hoke-Brown strength criterion, and concluded that the geological strength index and the imbalance coefficient have a greater radius of influence on the plastic zone.

$$\left.\begin{aligned}\sigma_r &= \frac{\sigma_{ci}}{m_b}\left\{\left[\left(m_b\frac{\sigma_R-\alpha P_p}{\sigma_{ci}}+s\right)^{1-a}+m_b(1-a)\ln\frac{r}{R}\right]^{\frac{1}{1-a}}-s\right\}\\ \sigma_\theta &= \frac{\sigma_{ci}}{m_b}\left\{\left[\left(m_b\frac{\sigma_R-\alpha P_p}{\sigma_{ci}}+s\right)^{1-a}+m_b(1-a)\ln\frac{r}{R}\right]^{\frac{1}{1-a}}-s\right\}\\ &+\sigma_{ci}\left[\left(m_b\frac{\sigma_R-\alpha P_p}{\sigma_{ci}}+s\right)^{1-a}+m_b(1-a)\ln\frac{r}{R}\right]^{\frac{a}{1-a}}\end{aligned}\right\} \tag{8}$$

where: , σ_r, σ_θ, σ_R and σ_{ci} are the radial stress, circumferential stress, plastic zone boundary stress and uniaxial compressive strength of intact rock mass, MPa, m_b, a, and s are functions of GSI index; P_p is the gas pressure at the distance from the center of the borehole, MPa; r and R are the pole diameter and plastic zone radius, m, respectively.

Sun [7] used the effective stress principle and the effective stress coefficient, combined with the Mohr-Coulomb strength criterion, to calculate the stress distribution and the range of plastic region in the coal body.

$$L=\frac{h(\lambda-\frac{P_r}{q}-\frac{b}{h}\tan\varphi)}{\tan\varphi+\frac{C_c}{q}} \tag{9}$$

Where: L is the range of plastic zone, m; λ is the lateral pressure coefficient; h is the thickness of coal seam, m; q is the vertical stress, MPa; b is the radius of the roadway, m; C_c is the cohesion of coal rock body, MPa; φ is the angle of internal friction, °; P_r is the support resistance in front of coal seam, MPa.

Wang [8] analyzed the evolution characteristics of the fracture zone of the borehole envelope with time and gave the stresses in the air leakage zone, softening zone, and elastic-viscous zone based on the Poying-Thomson rheological model.

$$\sigma^{\mathrm{c}}=p_0\pm\frac{R_p^2}{r^2}\bullet\frac{p_0(M-1)+\sigma_{\mathrm{c}}}{M+1} \tag{10}$$

Where: σ^{c} is the elastic zone stress, MPa; $M=\dfrac{1+\sin\varphi}{1-\sin\varphi}$, p_0 is the hydrostatic pressure, MPa; R_p is the radius of plastic zone, m; r is the pole diameter, m; σ_{c} is the uniaxial compressive strength of coal body, MPa.

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$$\left.\begin{aligned}&\sigma_\theta^p = M\sigma_r^p + \sigma_c - j_c A(t)\left[(\frac{R_p}{r})^2 - 1\right]\\&\sigma_r^p = \frac{2}{M+1}(\frac{r}{R_p})^{M-1}(p_0 + \frac{A(t)j_c + \sigma_c}{M+1} + j_c A(t)\left[\frac{1}{M+1}(\frac{R_p}{r})^2 - \frac{1}{M-1}\right] - \frac{\sigma_c}{M-1}\\&A(t) = \frac{p_0(M-1)+\sigma_c}{2(M+1)} \bullet \left\{\frac{1}{G_\infty}\left[1-e^{(\frac{1}{\eta_{ret}})}\right] + \frac{1}{G_0}e^{(\frac{1}{\eta_{ret}})}\right\}\end{aligned}\right\} \tag{11}$$

Where: σ_r^p and σ_θ^p are the radial and tangential stresses in the softening zone, respectively, MPa; p_0 is the hydrostatic pressure, MPa; R_p is the radius of the plastic zone, m; r is the pole diameter, m; σ_c is the uniaxial compressive strength of the coal body, MPa; η_{ret} is the rheological delay time of the coal body, s; t denotes the stress action time, s; G_0 , G_∞ is the original and long-time shear modulus of the coal body, MPa, j_c respectively; is the softening coefficient.

$$\left.\begin{aligned}&\sigma_r^x = (p_r + \frac{\sigma_c^*}{M-1})(\frac{r}{r_0})^{M-1} - \frac{\sigma_c^*}{M-1}\\&\sigma_\theta^x = M\sigma_r^x + \sigma_c^*\end{aligned}\right\} \tag{12}$$

Where: σ_r^x and σ_θ^x are the radial and tangential stresses in the air leakage zone, respectively, MPa; p_r is the active support, MPa; σ_c^* is the residual strength, MPa; r_0 is the radius of the air leakage zone, m.

2.2 Fracture Extension Mechanism of Coal Rock Body around Extraction Drill Hole

The stress distribution around the extraction borehole is the basis for studying the distribution of cracks around the extraction borehole, however, what really causes the decrease of extraction borehole concentration is that the extraction borehole causes a large amount of damage to the coal and rock body around the borehole during the drilling process, which is inevitably accompanied by the generation of a large number of cracks. Cracks in the sealing section are harmful and seriously affect the extraction seal, leading to a decrease in gas extraction concentration; while cracks at depth are beneficial and can play a role in increasing the coal seam permeability. In order to solve the problem of sealing, it is imperative to seal the fissures in the sealing section as much as possible. To do purposeful sealing, it is necessary to master the fissure distribution law.

To study the development law of peripore fissures in coal rock bodies containing boreholes, Liang [9] conducted a theoretical analysis for the stability of boreholes and established a mechanical model for borehole instability. Xiao [10, 11] used a triaxial test system and an acoustic emission monitoring system to conduct compression tests on the borehole-containing specimens, obtained the damage characteristics and acoustic emission properties of the borehole-containing specimens, established a theoretical model of solid-gas coupled instability in gas extraction boreholes, and obtained the relationship between the borehole inclination angle and the plastic zone by calculation. Wong[12] crack expansion during the destruction of rocks, and the test found that holes affect the development of fractures, which in turn affects the destruction of the whole specimen.Jin [13] et al. conducted uniaxial compression tests of coal rock bodies using the observation methods of acoustic emission and electromagnetic waves to reveal the damage evolution of coal rock bodies from the perspective of damage. Zhu [14] carried out uniaxial compression tests on sandstone containing pores, but was limited by the research angle and only obtained the relationship between fracture dip angle and damage type at the macroscopic level. Hu [15] studied the formation of the roadway loosening circle, the borehole loosening circle, and concluded that air enters the borehole loosening circle from the roadway loosening circle and finally flows into the borehole under the action of the negative pressure of extraction. Lin [16] analyzed the damage process of gas extraction borehole by numerical simulation calculation and came up with the law of extraction borehole damage. Wang [17] established a mathematical model of the borehole considering gas leakage, established the equation of gas leakage cross-sectional area and gas leakage volume, and obtained the relationship between extraction concentration and fracture width by using this model calculation. Gao [18] studied the damage characteristics of perforated coal bodies through experiments, obtained the rupture evolution process of perforated coal rock bodies by using acoustic emission detection, and revealed the damage mechanism of perforation damage from the perspective of energy release. Zhang [19] conducted uniaxial compression on the raw coal specimens containing boreholes and studied the law of coal body rupture around the borehole, and concluded that the damage was first at the horizontal boundary of the borehole, while the inclination angle would affect the strength of the coal body. Kang [20] studied the law of fracture expansion by hydraulic fracturing, and concluded that the fracture expansion is random when the fracture surface is formed, while the fracture surface formation will guide the fracture expansion along the dominant surface.

3. Analysis of the Mechanism of Fracturing Coal Rock by High Pressure Liquid Nitrogen Injection in Extraction Borehole

Through the above analysis of the fracture extension mechanism around the hole, combined with the research direction to discuss the mechanism of fracturing coal rock by injecting high-pressure liquid nitrogen into the extraction hole, I think it is mainly divided into three aspects: fracturing and increasing permeability of coal rock by high-pressure fluid (liquid nitrogen), fracturing coal rock by liquid nitrogen vaporization and expansion, and fracturing coal rock by liquid nitrogen freeze-thaw damage.

3.1 High Pressure Fluid Fracturing Coal Rock

One of the mechanisms of coal rock destruction by injecting high-pressure liquid nitrogen into the extraction borehole is similar to hydraulic fracturing technology. When the speed of the injected high-pressure fluid exceeds the absorption capacity of the oil and coal seam, it will form a high impact force within the borehole, thus destroying and stripping the coal body within the range of action, forming a large hole around the borehole, and the coal body around the hole will move toward the hole under the action of ground stress, and the coal body will be expanded and deformed, and the coal body will be fully decompressed, and the permeability of the coal seam will be greatly increased.

The decompression of the coal body within the influence range of hydraulic fracture punching creates favorable conditions for the desorption and discharge of large amount of gas, which enhances the permeability of the coal seam, while the discharge of gas makes the coal body contraction and deformation, which inevitably leads to the redistribution of stress in the coal body. Meanwhile, because the coal body is composed of many coal molecules, and the whole coal body is divided by longitudinal and transverse laminae, joints and fissures, thus the contraction and deformation of the coal body will inevitably cause the further increase of these fissure systems [21], which further increases the permeability of the coal body.

3.2 Liquid Nitrogen Vapor Expansion Fracturing Coal Rock

Under normal pressure, the temperature of liquid nitrogen can reach -196°C. 1 cubic meter of liquid nitrogen can be expanded to 696 cubic meters of pure gaseous nitrogen at 21°C, which means it has 696 times expansion rate, then the rapid expansion of liquid nitrogen in the limited space of extraction borehole can produce huge air pressure, i.e. expansion stress. When the expansion stress exceeds the

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capacity of the coal body, the coal rock body will undergo shear and fracture damage, generating a large number of microfractures, while causing the primary fractures to connect, further significantly increasing the permeability of the coal body. Damage occurs in the unitary coal body, and the unitary elastic modulus of damage occurs can be expressed as:

$$E_{\mathrm{i}} = (1-D)E_0 \tag{13}$$

Where: E_{i} is the damage unit modulus of elasticity, MPa; E_0 is the non-damage unit modulus of elasticity, MPa; is the damage factor.

When the coal body is subjected to high-energy gas, the coal body is damaged when the expansion stress σ_{t} exceeds its own tensile strength σ_{b} damage threshold, i.e $\sigma_{\mathrm{t}} > \sigma_{\mathrm{b}}$, when the coal body is damaged. When the coal body unit is subjected to tensile stress, the damage factor D can be expressed as [22, 23].

$$D = \begin{cases} 1 & \varepsilon \ge \varepsilon_{\mathrm{t1}} \\ \dfrac{1-\sigma_{\mathrm{br}}}{\varepsilon E_0} & \varepsilon_{\mathrm{t0}} \le \varepsilon \le \varepsilon_{\mathrm{t1}} \\ 0 & \varepsilon \le \varepsilon_{\mathrm{t0}} \end{cases} \tag{14}$$

where: σ_{br} is the residual tensile strength; ε is the strain; $\varepsilon_{\mathrm{t0}}$ is the elastic tensile ultimate strain; $\varepsilon_{\mathrm{t1}}$ is the tensile ultimate strain.

When the coal body unit is subjected to compressive stress, the damage factor D can be expressed as:

$$D = \begin{cases} 1-\dfrac{\sigma_{\mathrm{cr}}}{\varepsilon E_0} & \varepsilon > \varepsilon_{\mathrm{r}} \\ 0 & \varepsilon \le \varepsilon_{\mathrm{r}} \end{cases} \tag{15}$$

Where: σ_{cr} is the compressive residual strength; ε_{r} is the residual strain.

The effective stress intensity factor can be used to measure the expansion of fractures in the coal rock body after damage occurs by the action of high-energy gases, which can be expressed as:

$$\delta_1 = \frac{\delta_0}{1-D} \mathrm{or} D = 1-\frac{\delta_0}{\delta_1} \tag{16}$$

Where: δ_1 is the effective stress intensity factor; δ_0 is the stress intensity factor. It can be seen that the damage factor increases with the increase of the effective stress intensity factor, and the damage factor increases, and the damage degree of the coal body increases, thus increasing the coal seam fracture development.

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3.3 Liquid Nitrogen Freeze-thaw Damage Fractured Coal Rock

In extraction boreholes, liquid nitrogen vaporization can absorb a large amount of surrounding heat, and most of the coal body boreholes contain pore water, when the coal rock comes in contact with liquid nitrogen, the water in the coal rock voids will freeze rapidly with the heat absorption process of liquid nitrogen vaporization. The water freezes and its volume will increase, and the water-ice phase change will produce a volume expansion of about 9%, which T. Sandström found to be theoretically capable of producing a freezing expansion force of up to 207 MPa [24]. The resulting expansion stress then causes the void volume of the coal body to increase, which promotes the connectivity of coal fractures and thus makes the coal seam more permeable.

By injecting high-pressure liquid nitrogen into the extraction borehole, the coal body, under the joint action of the impact force generated by high-pressure fluid, the expansion force of liquid nitrogen vaporization, the freezing and swelling force of water-ice phase change, and the damage of low-temperature liquid nitrogen to the coal body, promotes the expansion and connection of coal body pore fissures around the borehole and generates new fissures to increase the coal seam permeability, and the method of injecting high-pressure liquid nitrogen into the extraction borehole to cold soak the coal seam for fracturing can provide a method to unload the pressure and increase the permeability of low-permeability coal seam, thus eliminating the risk of coal seam protrusion.

4. Characterization of the Stress Distribution around the Perimeter of the Extraction Borehole

4.1 Factors Influencing the Stress Distribution around the Perimeter of the Extraction Borehole

By itself, its microstructure directly affects the macroscopic material properties, which results in complex and variable mechanical properties [25, 26]. In contrast, the coal rock body near the perimeter of the extraction borehole is often more susceptible to damage due to the multi-field coupling of gas, water, and stress [27]. When studied from the perspective of the entire coal seam recovery workings, the coal seam mining height, overburden lithology, coal seam inclination and workings geometry parameters all have non-negligible effects on the macroscopic characteristics of the coal rock body. In addition, both the key layer and composite key layer above the coal seam will affect the mechanical characteristics of the coal seam, resulting in several different force states of the coal seam. Therefore, the objective factors affecting the deformation of gas extraction borehole mainly include the following three aspects.

(1) Coal rock body fine view structure: the influence of coal rock body fine view structure will affect the macro mechanical behavior, such as at the texture will show the slip. Dislocation theory suggests that coal rock body damage is due to the existence of dislocations within the fine microstructure, and the continuous development of dislocations between lattices eventually leads to the generation of microcracks, which in turn produce macroscopic cracks. This factor needs to be observed inside the coal rock body.

(2) Coal seam stress state: Gas extraction boreholes in this seam usually run through coal bodies with different stress states around the roadway, and there are huge differences in stress states within each area, resulting in different mechanical behavior of gas extraction boreholes within each zone. At the same time, the deformation of the borehole is directly influenced by the overburden conditions of the coal seam. As the workings are retrieved, the mining stresses are continuously redistributed, and there exist overburden stress states in different situations such as coal wall support influence zones and off-set zones [28]. This forms coal seams with different overburden rock layers, resulting in complex and variable coal seam stress states, which in turn affects the deformation of the borehole walls.

(3) Water content of the coal seam: in high gas loose coal seams, the coal body encountering water usually produces softening and mudification, and is accompanied by dangerous processes such as volume expansion of the borehole and disintegration of the borehole wall. Such factors need to be

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studied for the problem of water content of coal rock body, which can be studied by using the damage test of coal rock body with different water content.

All the above three influencing factors can affect the stress distribution around the borehole, but the fine structure of the coal rock body needs to be studied at the fine and even microscopic level. Among them, the stress state of the coal body itself is an important part of the link between the fine and macroscopic view, and the water content affects the mechanical characteristics of the coal body. Therefore, this paper starts from the stress state of the coal rock body itself, establishes the stress distribution model around the extraction borehole, and then investigates the influence of water content on the damage of the coal rock body in the subsequent study.

4.2 Basic Assumptions for Peripore Stress Studies in Extraction Boreholes

(1) Continuity: Assuming that the coal body is continuous, the displacement, deformation and stress of the coal body can be expressed as a continuous function.

(2) Isotropic and homogeneous gas extraction borehole and roadway are in the coal seam, so the perimeter of extraction borehole can be considered as coal body. Assuming that these coal bodies are the same type of homogeneous material, the mechanical properties of the medium at each point in the perimeter coal body of the extraction borehole are the same, and the variation properties in each direction in space are the same at each point. In other words, the physical parameters characterizing the perimeter coal body of the hole do not change with the change of the perimeter coordinates of the hole.

(3) Small deformation assumption: Although the deformation of the perimeter of the gas extraction borehole under different loading conditions has a large difference, the deformation of the perimeter of the gas extraction borehole is much smaller than the extraction borehole size. Therefore, it is assumed that the deformation of the perimeter of the gas extraction borehole is small, and the dimensional changes caused by the deformation of the perimeter of the borehole can be disregarded.

5. Theory of the Distribution of the Initial Plastic Zone of the Original Coal Seam after Drilling and Excavation

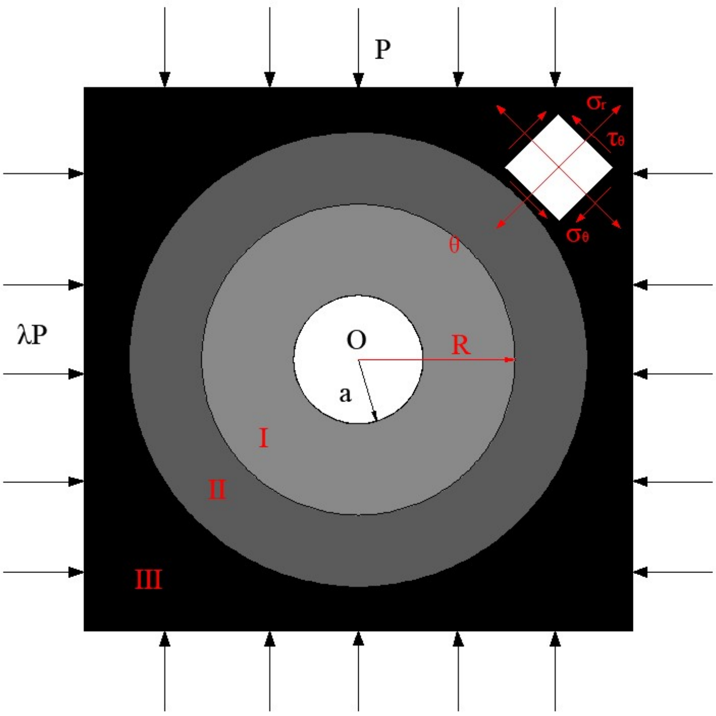

Figure 1. The stress states and stress zones of the surrounding coal are divided[29]

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When a borehole is excavated in a coal seam, the original stress state of the seam is changed by the disturbance of external conditions, and the stresses around the excavation are redistributed to produce stress concentrations around the seam slot or at the tip. If the magnitude of the concentrated stress is greater than the mechanical strength of the coal rock body, the material undergoes plastic deformation; if the stress is less than the mechanical strength of the coal rock body, the coal rock body undergoes only elastic deformation [29]. The stress zones of the coal seam around the drill hole can be divided into: original stress zone (III), elastic deformation zone (II) and plastic deformation zone I, as shown in Figure 1.

The stress solution on any tiny cell in the elastic deformation zone around the seam slot in polar coordinates can be expressed by the following equation [30, 31].

$$\begin{cases} \sigma_r = \frac{1}{2}p(1+\lambda)(1-\frac{R^2}{r^2}) - \frac{1}{2}p(1-\lambda)(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4})\cos 2\theta \\ \sigma_\theta = \frac{1}{2}p(1+\lambda)(1+\frac{R^2}{r^2}) + \frac{1}{2}p(1-\lambda)(1+3\frac{a^4}{r^4})\cos 2\theta \\ \tau_{r\theta} = \frac{1}{2}p(1-\lambda)(1+2\frac{a^2}{r^2}-3\frac{a^4}{r^4})\sin 2\theta \end{cases} \tag{17}$$

where: σ_r is the radial stress, MPa; $\tau_{r\theta}$ is the shear stress, MPa; σ_θ is the annular stress, MPa; λ is the lateral pressure coefficient; a is the radius of the borehole, m; r and θ is the polar coordinate.

The maximum and minimum principal stresses at any point around the borehole after converting the polar coordinates to right-angle coordinates by coordinate transformation can be expressed as:

$$\begin{cases} \sigma_1 = \frac{\sigma_r+\sigma_\theta}{2} + \sqrt{(\frac{\sigma_r-\sigma_\theta}{2})^2+\tau_{r\theta}^2} \\ \sigma_3 = \frac{\sigma_r+\sigma_\theta}{2} - \sqrt{(\frac{\sigma_r-\sigma_\theta}{2})^2+\tau_{r\theta}^2} \end{cases} \tag{18}$$

Where σ_1 and σ_3 are the maximum and minimum principal stresses, MPa, respectively.

When the coal body is converted from the elastic deformation state to the plastic deformation state, the stress conditions should satisfy the Moore-Coulomb damage criterion. The equilibrium condition is generally defined using the σ_1 and σ_3 Moore-Coulomb damage criterion consisting of the ultimate principal stress and the expression as follows.

$$\sigma_1 - \sigma_3 = (1+\sin\varphi)\sigma_1 + 2C\cos\varphi \tag{19}$$

Where: φ is the internal friction angle, C is the cohesion force, MPa.

The size of the plastic zone around the seam can be derived by combining the given coal seam mechanics and stratigraphic parameters with the relevant calculation equations, and then the effective plastic zone formed by different boreholes and the pressure relief range.

6. Conclusion

(1) Through the analysis of the elastic-plastic stress distribution law and fracture expansion mechanism around the extraction borehole, we understand that the mechanical models of extraction

borehole and roadway are extremely similar, and the calculation method of roadway envelope stress is mostly used to carry out the stress study around the borehole. A large number of cracks will be produced during the drilling of extraction boreholes, which will promote the development of coal fissures, but the development of fissures during the drilling and sealing of extraction boreholes will affect the sealing of extraction and lead to the decrease of gas extraction concentration, so the research on the fissure development law of extraction boreholes is of great significance.

(2) The discussion and analysis of high-pressure liquid nitrogen injection in the extraction borehole shows that the fracture damage of coal rock is mainly divided into three aspects: damage by the impact force generated by high-pressure fluid, fracture of coal rock by the expansion force of liquid nitrogen vaporization, and promotion of coal body pore enlargement and connectivity by the freezing expansion force of water-ice phase change. High-pressure fluid mainly relies on the impact force of high-pressure fluid and gas emission to make the coal contraction and deformation, thus enhancing the permeability of the coal seam; the expansion stress generated by liquid nitrogen vaporization is the damage of the unit coal body; the freezing and thawing of liquid nitrogen makes the pore water freeze and generates the freezing and expansion stress to increase the pore volume and fracture connectivity.

(3) Through the analysis of the influencing factors of the stress distribution around the perimeter of the extraction borehole and the theoretical discussion of the distribution of the initial plastic zone of the original coal seam after the borehole excavation, we understand that the stress state of the surrounding coal seam changes with the drilling of the borehole, and when the concentrated stress of the coal body around the excavation exceeds the ultimate stress of the coal body, the coal seam will produce plastic damage. After the borehole excavation reaches stability, high pressure liquid nitrogen is injected into the borehole, and the borehole will be destabilized and deformed again. With the borehole deformation and fracture development, new support stress will be generated, which makes the borehole stable again, and the above theoretical analysis provides the theoretical basis for the subsequent research.

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