Study on the mechanism of “separation stratum water-inrush” induced by impact energy of the key stratum sudden breaking

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Abstract: Subsidence deformation of the bottom rock stratum of the bending belt was different due to deflection difference; the separation stratum space was easy to form between the soft and hard rock stratum, and the separation stratum water formed under the water supplies. Based on catastrophe theory and the mechanics theory, the pointed catastrophic model of key stratum (the rock beam structure overlying the separation stratum space) was established. The impact energy released by the key stratum breaking was calculated. The "crushing" modes and "cleavage" modes of separation stratum water-inrush were proposed under the impact energy of key stratum. The periodic step distance of two kinds modes of separation stratum water-inrush was calculated. At last, separation stratum water-inrush of extra-thick coal of Guo Jiahe mine was taken as an example to study, and the aim was to provide technical reference for the prevention and treatment of separation stratum water-inrush.

1. Introduction
With the increase of the depth of coal, separation stratum water-inrush was becoming one of the main water hazards threatening the safety of mine production. Separation stratum water-inrush had the characteristics of large instantaneous water volume, no obvious water-inrush symptom and enormous damage. The prevention and treatment of separation stratum water-inrush were difficult problems that need to be solved in deep mining. Especially the study on the mechanism of separation stratum water-inrush was particularly important.

Many scholars had made a lot of research achievements in the mechanism and prediction of separation stratum water-inrush. Teng Yonghai et al.[1] studied the development law of overburden layer during coal mining. Jing Jidong et al.[2] studied and confirmed that the water inrush from the roof of NO.4 coal in huafeng mine was the water inrush from the separation stratum, and believed that there was a close relationship between separation stratum water-inrush, the impact pressure and the line of spot cracks. Qiao Wei et al.[3], based on separation stratum water-inrush of NO.2 coal in Ji-ning mine, proposed the type of "hydrostatic water inrush", and discussed the formation mechanism of "hydrostatic water inrush" of separation stratum water-inrush. Feng Qiyan et al.[4] used RFPA numerical simulation software to study and explain the periodicity of separation stratum water-inrush of NO.3 coal of the sixth mine area in Ji Ning mine.

However, there was relatively little theoretical research on the mechanism of outlying water inrush. Based on catastrophe theory, mechanics of structure and mechanics of materials el at., this paper used the catastrophe theory to explain and establish fracture mechanics model of the key stratum. The impact energy induced by the key stratum sudden breaking was calculated, the two kinds modes of the
"crushing" and the "cleavage" of separation stratum water-inrush were proposed, and the water-inrush distance of separation stratum was calculated. The last, separation stratum water-inrush of extra thickness coal in Guo Jiahe mine was taken as an example to study.

2. The formation and periodicity of separation stratum water-inrush
After mining, "bending belt" at the bottom of the rock stratum happened bending and subsidence deformation. Due to deformation differences between different rock formations, the closed separation stratum space between soft and hard rock stratum was formed (figure 1). Under water supply, the closed separation stratum water was formed[5].

When the key stratum top of the separation stratum space broken suddenly[6], the accumulated energy in the key stratum was released, the released energy was enough to cause cracks through-aquifer which was bottom of the separation stratum space, the separation stratum water entered the working face through cracks and fracture zone and the caving zone.

After separation stratum water inrush, with the advance of the working face and water supply, the closed separation stratum water was reformed. The key stratum regather energy until the next break occurred, the periodicity of separation stratum water-inrush was presented[7].

3. Pointed catastrophe model of the key stratum of the separation stratum

3.1. Simplification of the mechanical model of the key stratum
The key stratum of the separation stratum can be simplified as a simply supported the rock beam structure. The force system of the structure was shown in figure 2. The two ends of the simply supported the rock beam structure were subject to the horizontal axial force $F$, and the upper part was subject to the distribution pressure of overburden rock, while the lower part was subject to the uniform distribution pressure of off-layer water.

$$\delta = \frac{q_0 s}{E_0 H}$$

Figure 2. Simplified model of the rock beam structure mechanics

3.2. Determination of the potential function of the key stratum
It was assumed that under the force system of the rock beam structure, the subsidence bending deformation in the middle of the rock beam was $\delta$, the elastic modulus was $E_0$, the height of the rock beam was $H$, the moment of inertia of the section was $I_0$, and the displacement along the length of the rock beam was $s$, The vertical displacement of the rock beam structure can be expressed as:

$$\omega = f(s) = \delta \sin\left(\frac{\pi s}{L}\right)$$

(1)
The curvature of the rock beam structure was expressed as:

\[ k = \frac{M(s)}{E_0 I_o} = \frac{f'(s)}{1 + f^2(s)} \approx \frac{f'(s)}{\sqrt{1 + f^2(s)}} \]  

(2)

The strain energy accumulated in the rock beam structure can be expressed as:

\[ U = \frac{E_0 I_o}{2} \int [f'(s)\sqrt{1 + f^2(s)}] \, ds = \frac{E_0 I_o \pi^6 \delta^4}{16L^5} + \frac{E_0 I_o \pi^4 \delta^2}{4L^3} \]  

(3)

The contraction deformation at both ends of the rock beam structure was expressed as:

\[ \Delta = \int_0^L (1 - \sqrt{1 - f^2(s)}) \, ds \]  

(4)

Because of \( |f'(s)| \ll 1, \ f^2(s) \ll 1 \), therefore:

\[ \sqrt{1 - f^2(s)} = 1 - \frac{1}{2} f^2(s) \]  

(5)

\[ \Delta = \frac{1}{2} \int_0^L f^2(s) \, ds \]  

(6)

The energy made by horizontal force can be expressed as:

\[ W_f = -F \Delta = -\frac{F}{2} \int_0^L f^2(s) \, ds = -\frac{F \pi^2 \delta^2}{4L} \]  

(7)

The energy made by vertical force can be expressed as:

\[ W_q = (q_0 - q_o) \int_0^L f(s) \, ds = \frac{2(q_0 - q_o)L}{\pi} \]  

(8)

The total potential energy of the rock beam structure\[8-9\] can be expressed as:

\[ E = U + W_f - W_q = \frac{E_0 I_o \pi^6}{16L^5} \delta^4 + \frac{\pi^2}{4L} \left( \frac{E_0 I_o \pi^2}{L^2} - F \right) \delta^2 - \frac{2(q_0 - q_o)L}{\pi} \]  

(9)

3.3. Establishment of pointed catastrophe Model of the key stratum

According to the catastrophe theory\[10\], the standard expression of potential function of pointed catastrophe model of the key stratum was:

\[ V(x) = \frac{x^4}{4} + \frac{a}{2} x^2 + bx \]  

(10)

In equation (10): \( V(x) \)—a potential, that was the energy stored in the system when the state was \( x \).

\( x \)—state variables;

\( a \) and \( b \)—control parameters.

The total potential energy equation (9) in accordance with the standard equation (10) of potential function of pointed catastrophe model. \( x \), \( a \) and \( b \) can be written:

\[ x = \frac{\pi}{L} \left( \frac{E_0 I_o \pi^2}{4L} \right)^{\frac{1}{4}} \delta \]  

(11)

\[ a = \frac{L}{2} \left( \frac{4L}{E_0 I_o \pi^2} \right)^{\frac{1}{4}} \left[ \frac{E_0 I_o \pi^2}{L^2} - F \right] \]  

(12)

\[ b = -\frac{2L^2}{\pi^2} (q_0 - q_o) \left( \frac{4L}{E_0 I_o \pi^2} \right)^{\frac{1}{4}} \]  

(13)

According to the catastrophe theory and equation (9) \(~ (13), the potential function of the key stratum of the separation stratum can be interpreted by pointed catastrophe model. Before and after the breaking of the key stratum, it was in the state of mechanical balance. For the mechanical system in the state of balance, the potential function of the system must have stationary values, and that were to say, equation (10) must have stationary values. Therefore, the equation of the first partial derivative of
the potential function \( V(x) \) was:
\[
x^3 + ax + b = 0 \tag{14}
\]

Equation (14) was the equation of balance surface. In the \( a-b-x \) space coordinate system, the balance surface was the spatial geometry shape of upper, middle and lower leaves (Fig.3). The discriminant with real root was [12]:
\[
\Delta = 4a^3 + 27b^2 \tag{15}
\]

In the \( a-b \) plane coordinate system, the discriminant equation (15) was a semi-cubic parabola, which there was a bifurcation set on the projection of mutant points (figure 3), and an catastrophe point \((0,0)\).

\[\text{Figure 3. Balance surface and control variable plane}\]
\[q_0 - q_w > 0, \text{ therefore } b^2 > 0; \text{ while } \Delta = 0, \text{ there must be:} \]
\[
L > \frac{E_t I_0}{F} \tag{16}
\]

\[q_0 - q_w > 0 \text{ and equations (15) and (16) were sufficient and necessary conditions of the key stratum breaking.} \]

While \( \Delta = 0 \), the three solutions of the equation of balance surface:
\[
x_1 = \frac{2b}{a}, \quad x_2 = x_3 = -\frac{3b}{2a}
\]

When it was jumped from the \( x_2=x_3 \) lower leaves to the \( x_1 \) upper leaves, the energy released by sudden breaking of rock girder structure can be expressed as:
\[
\Delta E = \frac{175L^3E_tI_0(q_0-q_w)^4}{\pi^6(L^2-F)^4} + \frac{35L^3(q_0-q_w)^2}{\pi^4\left(\frac{E_tI_0\pi^2}{L^2}-F\right)} \tag{17}
\]

4. The two kinds mechanism of separation stratum water-inrush

According to the mechanical properties of soft rock aquiclude, this paper thought that there were two kinds mechanism of separation stratum water-inrush. The first kind of separation stratum water-inrush was “crushing”, the conditions of happening “crushing” was that soft rock aquiclude had certain brittleness and had further sinking deformation space. When the key stratum broke suddenly, the released impact energy can make soft rock aquiclude crack from the bottom, and rapidly develop upward to space of the separation stratum, separation stratum water-inrush occurred suddenly. The second kind of separation stratum water-inrush was "cleavage", the conditions of happening
“cleavage” was that soft rock aquiclude had certain plasticity and had small the sinking deformation space. When the key stratum broke suddenly, the released impact energy can make soft rock aquiclude happen cleavage from the top, and rapidly develop downward to bottom of the separation stratum, separation stratum water-inrush occurred suddenly [11-13].

4.1. The "crushing" mechanism of separation stratum water-inrush

Before the "crushing" occurred, the soft rock aquiclude was pure bending deformation, when the key stratum broke suddenly, the released impact energy can make soft rock aquiclude crack from the bottom, the tensile stress at the bottom exceeded the tensile strength of the key stratum, the bottom of the soft rock aquiclude was cracked.

The soft rock aquiclude can be simplified as a simply supported rock beam structure. It was assumed that the length of the soft rock beam structure was 2l, the height was 2h, the elastic modulus was $E_1$, and the section inertia moment was $I_1$. The stress state of the soft rock beam structure in the coordinate system was shown in figure 4 and overlapped with the main stress state, therefore, $\sigma_y = \sigma_z = \tau_{xy} = \tau_{yz} = 0$, $\sigma_x = \sigma_1$, $\sigma_z = \sigma_2$.

![Figure 4. Mechanical model of the soft rock aquiclude](image)

According to the first strength theory of material mechanics, the failure criterion of the soft rock aquiclude was expressed as:

$$[\sigma_1]_{\text{max}} = \sigma_b$$

When the failure occurred at the bottom of the soft rock aquiclude:

$$[\sigma_1]_{\text{max}} = \left[\frac{q}{6I_1} (l^2 - 3x^2) y\right]_{\text{max}} = \frac{ql^2}{4h^2} = \sigma_b$$  \hspace{1cm} (18)

$$q = \frac{4h^2}{l^2} \sigma_b$$

Because of $\varepsilon_y = \frac{1}{E_1} [\sigma_y - \mu(\sigma_x + \sigma_y)] = 0$, therefore $\sigma_x = \mu \sigma_y$;

$$\varepsilon_x = \frac{1}{E_1} [\sigma_x - \mu(\sigma_y + \sigma_x)] = \frac{1 - \mu^2}{E_1} \sigma_x$$  \hspace{1cm} (19)

The deformation ratio energy of the soft rock aquiclude can be expressed as:

$$\nu = \frac{1}{2} \sigma_y^2 e_y^2 = \frac{1 - \mu^2}{2E_1} \sigma_y^2 $$  \hspace{1cm} (20)

The maximum principal stress along the y-direction was expressed as:

$$\sigma_y = \frac{M(x)}{I_1} y = -\frac{q}{6I_1} (l^2 - 3x^2) y$$  \hspace{1cm} (21)

When the "crushing" of separation stratum water-inrush occurred, the total energy required for the fault of the soft rock aquiclude was expressed as:

$$U = \int \int_{\Omega} \nu e dxdy = \frac{q^2 (1 - \mu^2)}{72E_1 I_1} \left[ (l^2 - 3x^2) y^2 \right]_{\Omega} dxdy = \frac{16h^7 (1 - \mu^2)}{135E_1 I_1^2} \sigma_b^2$$  \hspace{1cm} (22)

When the key stratum broke suddenly, the impact energy was released on the soft rock aquiclude. This paper considered energy loss and calculation; the high order term of the impact energy expression
was ignored. The periodic step distance $L$ was calculated when the "crushing" of separation stratum water-inrush:

$$L = \left( \frac{\sqrt{F^2 + 140E_0 l_0 \pi / k - F}}{k} \right)^{\frac{1}{2}}$$  \tag{24}

$$k = \frac{8\pi^4 h^2(1-\mu^2)}{135EI^2(q_0-q_w)} \sigma_b^2$$  \tag{25}

4.2. The "cleavage" mechanism of separation stratum water-inrush

Before the "cleavage" of separation stratum water-inrush occurred, enough plastic deformation had taken place on the soft rock aquiclude. The impact energy of the key stratum acted on the soft rock aquiclude through water in separation stratum space, the tensile stress on the top surface of the soft rock aquiclude exceeded its tensile strength, and the soft rock aquiclude was split, the stress state can be simplified as plane strain, therefore, $\sigma_y = \sigma_y = \tau_{xy} = \tau_{yz} = 0$, $\sigma_x = \sigma_i = \sigma_b = \text{const}$, $\sigma_z = \sigma_2$, $\sigma_z = \mu \sigma_x$. It was assumed that the deformation amount of the length direction of the soft rock aquiclude $2\Delta l$, the maximum principal stress was expressed as:

$$\sigma_1 = \sigma_b = \frac{E_i \Delta l}{(1-\mu^2)l}$$  \tag{26}

When the "cleavage" of separation stratum water-inrush occurred, the total energy required for the fault of the soft rock aquiclude was expressed as:

$$E = \int_{D_1} \int_{D_2} \int_D v_i dxdydz = \frac{\sigma_b^2(1-\mu^2)}{2E_1} \int_{D_1} \int_{D_2} \int_D 2h\mu(1-\mu^2)\sigma_b^2$$

When the key stratum broke suddenly, the impact energy was released on the soft rock aquiclude. This paper considered energy loss and calculation; the high order term of the impact energy expression was ignored. The periodic step distance $L$ was calculated when the "cleavage" of separation stratum water-inrush:

$$L = \left( \frac{\sqrt{F^2 + 140E_0 l_0 \pi / k - F}}{k} \right)^{\frac{1}{2}}$$  \tag{28}

$$k = \frac{\pi^4 h^2(1-\mu^2)}{E_i(q_0-q_w)} \sigma_b^2$$  \tag{29}

5. Case application

NO.3 coal in Guo Jiahe mine belonged to extra-thick coal. Separation stratum water-inrush occurred repeatedly in the process of coal mining, it was taken as an example by this paper to study.

5.1. Mine geological conditions

At present, NO.3 coal was being mined in Guo Jiahe mine, NO.3 coal thickness was 1.10~26.55m and average thickness was about 14.80m, which was belonging to extra-thick coal, The overlying Stratum of NO.3 coal was shown in table 1.

| Geologic time        | Stratum       | Thickness/(m) | average thickness/(m) | main rocks                        |
|----------------------|---------------|---------------|-----------------------|-----------------------------------|
| Middle Jurassic      | Yanan group(J2y) | 0~95.58       | 48.50                 | sandy mudstone, silty ~ coarse sandstone, carbonaceous mudstone, coal |
|                      | Zhihuo        | 5.63~76.63    | 39.44                 | sandy mudstone, silty ~           |
5.2. Determination of the development location of the separation stratum

5.2.1. Numerical simulation of the development position of the separation stratum

In this paper, UDEC numerical analysis software was used to simulate the development position of the separation of NO.3 coal overlying stratum [14-16]. According to the geological conditions of the mine and mining conditions of the working face, the model size was selected as 500m×210m. The bottom boundary of the model was fixed boundary, the left and right boundary were horizontal supporting boundary and the upper boundary was stress boundary. The overburden from the upper boundary to the ground was equivalent to vertical load acting vertically on the boundary. The vertical stress value was 6.24mpa. Considering the gravity gradient of the rock mass itself and the stress experienced by the unit in the horizontal direction, the magnitude of the stress was vertical stress times the pressure coefficient. According to the indoor mechanical experiment, the mechanical parameters of various overlying stratum were shown in table 2.

Table 2. Mechanics parameter of NO.3 coal overlying rock

| rocks                     | Mass (N/m³) | bulk modulus(GPa) | Shear modulus(GPa) | internal friction angle (°) | Cohesive (MPa) | Joint normal stiffness (GPa) | Joint shear stiffness (GPa) |
|---------------------------|-------------|-------------------|--------------------|----------------------------|----------------|-----------------------------|----------------------------|
| Medium sandstone          | 2330        | 2.27              | 1.77               | 34                         | 11.12          | 2.1                         | 1.7                        |
| Fine sandstone            | 2435        | 3.64              | 3.05               | 38                         | 13.02          | 3.2                         | 2.6                        |
| Powder sandstone          | 2449        | 2.89              | 2.16               | 33                         | 9.22           | 2.1                         | 1.9                        |
| Sandy mudstone            | 2490        | 1.35              | 1.14               | 28                         | 5.5            | 1.2                         | 1.0                        |
| muddystone                | 2580        | 1.66              | 1.47               | 30                         | 3.81           | 1.6                         | 1.2                        |
| NO.3 coal                 | 1340        | 1.36              | 1.1                | 30                         | 3.52           | 1.2                         | 1.1                        |
| Coal mudstone             | 2520        | 1.66              | 1.47               | 30                         | 3.81           | 1.6                         | 1.2                        |
The numerical simulation results were shown in figure 5, it can be found from the Fig.5 that the development position of the separation stratum developed between the medium sandstone aquifer and the sandy mudstone, and the development position of the separation stratum was about 168m away from the top of NO.3.

5.2.2. Field observation of the development position of the separation stratum
In order to further confirm the development position of the separation stratum, the development position of the separation stratum was observed by the TV observation method of borehole drilling. Two boreholes were arranged on the ground above 1305 working face, and development position of the separation stratum of NO.3 coal was determined to be located in the top area of the fracture zone, which was a small range above 164m of the vertical distance from the top of NO.3 coal. Figure 6 shown the top section of the separation stratum space observed by the TV observation method of borehole drilling.

The vertical distance from the top of NO.3 coal was about 168m, which was larger than 164m observed by the TV observation method of borehole drilling in the field, the development position of the separation stratum identified by the two methods were the same basically.

Finally, according to the comprehensive judgment of numerical simulation and the TV observation method of borehole drilling, the development position of the separation stratum was between the medium sandstone and sandy mudstone [17], and the vertical distance from the top of NO.3 coal was about 164m.

5.3. The mechanism of separation stratum water-inrush and step distance
The medium sandstone of the top of the separation stratum space was a key stratum with the thickness of 19~26m and average thickness of about 22m, the sandy mudstone of the bottom of the separation stratum space was thickness of 11~16m and average thickness of about 14m. The sandy mudstone had
certain brittleness and further subsidence deformation space. At last, it belonged to the "crushing" mechanism of separation stratum water-inrush.

The relevant mechanical parameters of the medium sandstone and sand mudstone were substituted into equations (21) and (22), and the periodic step distance of the "crushing" was calculated to be 55.4~58.9m and average about 53.7m, the measured step distance was 58m, the result of theoretical calculation was basically consistent with the actual situation.

6. Conclusions
The sudden breaking of the key stratum of separation stratum water-inrush was jump energy; the released impact energy was expressed by pointed catastrophe model of the key stratum of the separation stratum.

Based on the mechanical property of the soft rock aquiclude, the two mechanisms of the "crushing" and "cleavage" of separation stratum water-inrush were proposed. The energy need and the periodic step distance of the "crushing" and "cleavage" were calculated.

The NO.3 coal of Guo Jiahe mine was taken as a case application. The development position of the separation stratum was determined by numerical simulation and the TV observation method of borehole drilling. Separation stratum water-inrush was determined as "crushing", and the periodic step distance of the "crushing" was calculated to be 55.4~58.9m and average about 53.7m; the measured step distance was 58m; the result of theoretical calculation was basically consistent with the actual situation.

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