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Research Article

Study on Catastrophe Theory of Activation-Induced Prominence of Faults under Dynamic Disturbance

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In view of the phenomena of coal and gas outburst induced by fault activation under dynamic disturbance, a mechanical model of faults and surrounding rock mechanics was established based on the theory of fold catastrophe. Moreover, the dynamic disturbance factors were introduced and analyzed to analyze the influencing factors of outburst coal rock outburst. Through theoretical analysis, it shows that the thinner the fault medium is, the more energy the external input is required for system instability, and the external energy can reflect the stability of the system. When the width of fault media is fixed, the stronger the mining disturbance, the less energy the external input is required for system instability; on the contrary, the weaker the mining disturbance is, the more energy the external input is required for system instability. In addition, through the equation of conservation of kinetic energy, it can be seen that the stronger the mining disturbance, the greater the critical value of the surrounding rock thickness. The paper introduces the dynamic disturbance parameters through the catastrophe theory and analyzes the influence of the existence of faults on coal and gas outburst in detail, which provides a new theoretical basis for the prediction and prevention of coal and gas outburst disasters.

1. Introduction

Coal gas outburst is a complex, short-term dynamic phenomenon caused by many factors, including geological structure, mechanical properties of coal, gas pressure, and external force. The role of gas is to generate tensile stress. The influence of faults on the coal and gas outburst in the belt is a major dynamic disaster affecting the safe mining of coal mines. The cause is often induced by fault activation caused by dynamic disturbance during mining [1–5]. Faults are common in coal mines, and there is an important link between dynamic disturbances and the activation of structural planes (weak faces) with faults and coal and gas outburst accidents. Both the depth of draw and the increase in gas pressure will increase the risk of protrusion, and gas also plays an important role in the process of coal and gas outburst [6, 7]. The existing research shows that coal and gas outburst are the dynamic instability phenomena of the corresponding gas-bearing coal-rock system under external disturbance. In the process from prominence to stimulation and development, the interaction between various elements within the system and its interaction with external systems have obvious nonlinear characteristics [8–11]. The nature of faults is of great significance to coal mine gas occurrence and mine disaster research such as coal and gas outburst and coal mine production. The current study qualitatively analyzes the influence of the tectonic stress field on the fault properties [12, 13]. At the same time, based on the actual engineering analysis, the researchers also proposed that coal and gas outburst are mainly affected by small geological structures, coal thickness and its changes, and the occurrence of coal and gas in the mining area and the corresponding outstanding law [14, 15].

At present, Li [16] believe that the fault is conducive to the accumulation of gas and can prevent the migration of gas. Cui and Yao [17], through the example of coal and gas outburst and the numerical simulation experiment results of gas drainage in longwall mining face, found that low permeability faults may form impermeable fault zone, which may lead to excessive gas pressure difference between the two coal seams; Song and Zhang [18] used the rock stress state analysis system software to analyze the mechanism of the tectonic stress field on coal and gas outburst. It is pointed out that the tectonic stress field caused by fault distribution provides dynamic conditions for the occurrence of gas outburst. Wang et al. [19] studied the dynamic response characteristics of the layered system and its whole process. Through analysis, it is believed that the existence of the weak surface of the fault is conducive to the occurrence of gas outburst. It can be seen that the study of the influence of faults on coal and gas outburst in the belt has obviously attracted people's attention.

In addition, many experts and scholars have analyzed and summarized the coal and gas outburst mechanism based on the catastrophe theory, which greatly promoted the theoretical research process of coal and gas outburst accidents. Xiao et al. [20] established a cusp catastrophe model of coal and gas outburst and made a systematic theoretical analysis of the prominent gestation and prominence process, which proposed a new theoretical basis for highlighting the prevention and prediction of disasters. Zhao et al. [9] proposed that the failure of coal (rock) under the joint action of ground stress and gas pressure is a nonlinear process. The traditional deterministic linear theory is difficult to explain the nonlinear behavior of gas outburst in essence. The catastrophe theory is an important branch of nonlinear dynamics, and its main method is to generalize various discontinuities into different types of topologies and discuss the discontinuous morphological features near various critical points. Ma and Ju [21] introduced the correspondence between the parameters of coal and gas outburst and the parameters in mathematical model by using the mathematical model of safe rheological-mutation. Pan et al. [22] established a sudden model of instability of a single coal shell and provided a basis for studying the three processes of ground stress, gas pressure, and coal medium in the disintegration of coal shell, gas energy release, and high pressure gas flow to the protruding process of coal injection.

Many experts and scholars have proposed the seepage field equation of gas flow in coal and rock mass, the deformation field equation of coal and rock mass and the coupling equation of damage and gas permeability coefficient evolution of coal and rock mass under disturbing stress and the mathematical model of gas-solid coupling during the rupture of gas-bearing coal rock mass considering coal rock deformation damage and gas seepage [23–28]. Xu et al. [29] established a fluid-solid coupling RFPA2D–flow coupling model for gas-rock fracture process and gave a numerical solution based on the rock fracture process analysis system (RFPA2D). Yang et al. [30] carried out the stress-strain full-process penetration test and established a piecewise stress-permeability relationship equation that reflects the rock structure change characteristics before and after the peak, which provides a reliable experimental basis for establishing a coupled stress-permeability numerical model for rock failure process. Wang et al. [31, 32] established a catastrophic model of coal-shell instability and disintegration, gave the expression of the off-stress strain energy released by the moment of instability, the expression of the volumetric strain energy release of the coal-rock system, and the description of the gas-gas pulverized coal two-phase flow formed by the coal-containing gas pulverized coal and the coal-bed gas seepage are obtained, which deepened the understanding of the comprehensive role of coal and gas evolution law.

The mechanism of coal and gas outburst accidents caused by fault activation under dynamic disturbance is complex, and the occurrence of prominent accidents is also affected and restricted by many factors. This is not only related to geology, mechanics, gas seepage, etc., but also to many uninfluenced factors, such as tides. From the gestation to the excitation, the starting process has the characteristics of abrupt changes. It is the disturbance of the gas-bearing coal-rock system under the open conditions, due to the disturbance of the external mining activities, and controlled by the nonlinear dynamic mechanism inside the system. The research content mainly focuses on the static or quasistatic action. The theory of catastrophe induced by fault activation under dynamic disturbance needs further study. Based on the specific conditions, this paper introduces the concept of mining disturbance through macroscopic mechanics and discusses the relationship between dynamic disturbance and fault width, width of fault surrounding rock, and external energy through the catastrophe equation. In addition, many scholars have done a lot of research work on the phenomenon of faults caused by faults, such as the theory of fault-induced earthquakes [33] and the pressure of fault activation induced by fault activation [34, 35]. Therefore, some of the theories cited in this paper are mostly based on rock, but the physical and mechanical properties of coal and rock mass are quite different, and further research is needed.

2. Modeling

2.1. Mechanical Model. Considering that the occurrence of coal and gas outbursts is mostly related to fault activity, the fault activation mechanism mainly consists of sliding faults and normal faults, and the former is more than the latter. Therefore, we focus on the study of coal and gas outbursts induced by fault-induced instability during dynamic mining. To facilitate the analysis, we establish the mechanical model shown in Figure 1 and make the following assumptions:

The fault is defined as an infinitely uniform strike-slip fault. As shown in Figure 1, the fault medium and its surrounding rock mass are homogeneous and have isotropy. The width of the fault zone is $2b$, the horizontal distance of the fault from the boundary of the rock mass is B, the fault height is L, the displacement (lateral displacement) of the two plates of the fault is μ, the tangential displacement of the rock mass boundary is ν, and the dip angle of the fault is 90°. Due to the seepage softening effect of gas, the constitutive relation of fault media has the property of weaker displacement. The existing researches on gas seepage problems are based on the study of the relationship between the permeability coefficient and the damage of coal and rock

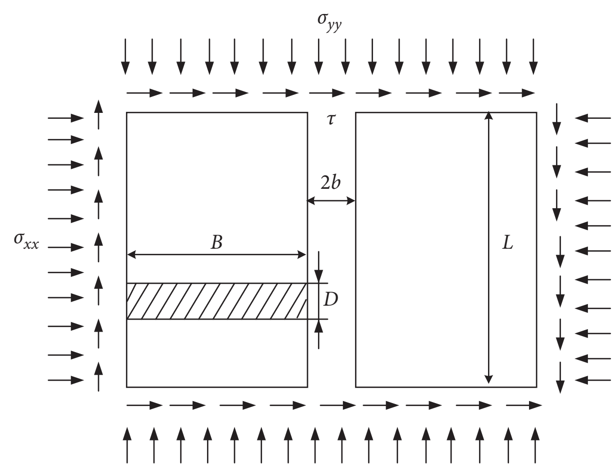

Figure 1: Mechanical model of surrounding rock failure instability.

microscopic units, but there is a lack of analysis of macroscopic parameters. This article focuses on macroscopic system instability. It ignores the use of gas-related parameters in derivation and explores the theoretical derivation of fault activation induced by dynamic disturbances in high gas environments.

In Figure 1, a two-dimensional mechanical model is established. The surrounding rock is affected by the lateral stress σ_{xx}, and at the same time, it is affected by σ_{yy} in the vertical direction. Due to the complexity of geological conditions and the influence of mining disturbances, σ_{xx} and σ_{yy} are not equal in the general case, i.e., $|\sigma_{xx} - \sigma_{yy}| > 0$, and the following relational equations can be obtained:

$$\begin{aligned}\sigma_m &= \frac{\sigma_{xx} + \sigma_{yy}}{2},\\ \varepsilon_m &= \frac{\varepsilon_{xx} + \varepsilon_{yy}}{2},\\ S_{xx} &= \sigma_{xx} - \sigma_m,\\ S_{yy} &= \sigma_{yy} - \sigma_m,\end{aligned} \tag{1}$$

where σ_m is the average stress in the system, ε_m is the average strain in the system, ε_{xx} is the lateral strain, ε_{yy} is the vertical strain, S_{xx} is the lateral stress bias, and S_{yy} is the vertical stress bias.

Before the coal and gas outburst, the surrounding rock of the fault has been in the deformation stage of deformation. In rock and soil mechanics, it is considered that the rock in this state is incompressible, that is, the strain of the model $\varepsilon_m = 0$. Therefore, the physical relationship between the stress deviation S_{ij} and the strain deviation e_{ij} can be obtained as

$$e_{xx} = \frac{\sigma_{xx} - \sigma_m}{2G}, \tag{2}$$

where G is shear modulus. According to the same reason we can obtain

$$e_{xx} = \frac{1}{2G} S_{yy}, \tag{3}$$

$$e_{xy} = \frac{1}{2G} S_{xy}. \tag{4}$$

From Equations (2)–(4), the relationship between total strain increment and total stress increment of fault surrounding rock is

$$e_{ij} = \frac{1}{2G} S_{ij}. \tag{5}$$

Because of the symmetry of the model in Figure 1, we take the left half of the faulted surrounding rock for research. Due to the softening property of the fault dielectric zone, the shear stress τ in the fault zone will gradually decrease as the displacement μ of the two plates of the fault increases. This constitutive relationship is assumed [36]:

$$\tau = g\gamma \exp\left[-\left(\frac{\gamma}{\gamma_0}\right)^m\right], \tag{6}$$

where g is the initial shear strength of the fault zone, γ is the maximum shear strain of the fault medium, γ_0 is the initial shear strain, and m is the curve family index, which is also referred to as the homogeneity parameter. τ gradually decreases as the fault slips.

In addition, the shear strain can be expressed as

$$\gamma = \frac{v}{b}. \tag{7}$$

Similarly, the rock mass strain γ' can be expressed as

$$\gamma' = \frac{v'}{B}, \tag{8}$$

where v' is displacement of surrounding rocks at both ends of fault media.

The relationship between shear stress and shear strain in faulted surrounding rock is

$$\tau = G\gamma'. \tag{9}$$

Equations (6)–(9) can be combined to obtain the relationship between the fault surrounding rock and the lateral movement of the fault and the shear stress [35].

$$Q_1 = \frac{GDL}{B} v', \tag{10}$$

$$Q_2 = \frac{gDL}{b} v \exp\left[-\left(\frac{v}{v_0}\right)^m\right], \tag{11}$$

where v_0 is the initial shear stress.

According to Equations (10) and (11), the relevant line chart is shown in Figure 2. As shown in Figure 2, the left half is the line graph of the relationship between the shear stress and the lateral displacement of the fault surrounding rock, and the right half is the line graph of the relationship between the shear stress of the fault and the lateral displacement. From Equations (11) and (12), GDL/B and gDL/b can be regarded as constant under normal conditions, that is, the

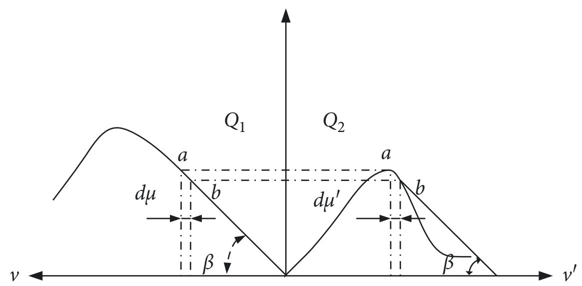

Figure 2: Line diagram of shear stress lateral displacement.

stiffness of the surrounding rock or fault medium, which is, respectively, set to K_1 and K_2. When $Q_1 = Q_2$, surrounding rock slowly changes, and the system is in equilibrium, that is, point a in Figure 2.

2.2. Impact of Dynamic Disturbance. In actual production, the tunnel excavation operations such as Shimen are always accompanied by certain dynamic disturbances. When the excavation of rock gates in prominent high-prone gas mines is performed to expose faults, the precipitating factors of gas outbursts are extremely complicated. The impacts of rock masses will all have a good or bad influence on the gestation during the roof falling, the mining power of coal mining machinery or shot blasting, etc. In this paper, it is assumed that the mining disturbance has a promoting effect on the gas outburst, then the perturbation equation is introduced into the lateral stress σ_{xx}, and the perturbation is assumed to be periodic, as follows:

$$Q_1 = N + f, \tag{12}$$

$$f = N \cos\phi \cos\phi \frac{\pi v'}{T}, \tag{13}$$

where N is the original lateral stress; f is the superimposed mining disturbance force, which is a periodic harmonic wave; T is the action time; and ϕ is the disturbance angular frequency. Equations (12) and (13) are available:

$$Q_1 = N + N \cos\phi \cos\phi\left(\frac{\pi v'}{T}\right). \tag{14}$$

It can be seen that the lateral displacements of surrounding rocks and fault media are affected by mining disturbances and have a superposition effect. The displacement increases, the shear stress of the fault changes more significantly, and the cohesion force decreases significantly. To simplify the operation of the symbol, Equation (14) can be further simplified as follows.

$$Q_1 = \lambda N. \tag{15}$$

For the same reason,

$$Q_2 = \lambda F, \tag{16}$$

where λ can be considered as the proportional coefficient of the lateral stress under nonperturbation state in the superposition state of mining disturbance, and its value is greater than 1; F is the lateral stress when the fault medium is disturbed by no mining.

2.3. Energy Analysis and Folding Mutation Model. In the mechanical model established in Figure 1, it can be seen from Figure 2 that the system instability mainly occurs in the softening stage of the fault medium. When the lateral displacement $d\mu$ occurs in the fault medium, the faulted medium must inevitably undergo cracking and the crack gradually expands. It is necessary to absorb energy U_1, that is, $dU_1 = Fd\mu$. At this point, the surrounding rock of the fault is also deformed and needs to absorb external energy U_2, that is, $dU_2 = Fd\mu'$. The energy conservation equation can be obtained as follows:

$$U_1 d\mu + U_2 d\mu' = W d\mu''. \tag{17}$$

Dividing the obtained equation by $d\mu$ on both sides,

$$U_1 + U_2 \frac{d\mu'}{d\mu} = W \frac{d\mu''}{d\mu}. \tag{18}$$

According to Figure 2, $Q_1 = Q_2$ at point (a) can be further reduced to

$$Q_1 + \frac{Q_2 \cdot Q_2'}{K_2} = J, \tag{19}$$

where J is the energy that needs to be absorbed from the outside when the lateral displacement $d\mu$ of the fault medium occurs.

In Figure 2, the inflection point of the softening phase of segment Q_2 is α, where the abscissa is $d\mu_\alpha$, and Equation (11) can be derived as follows:

$$\begin{aligned} Q_2'' &= \lambda K_2 \exp\left[-\left(\frac{\mu_\alpha}{\mu_0}\right)^m\right] \\ &\quad \cdot \left[-\frac{m+m^2}{\mu_0}\left(\frac{\mu_\alpha}{\mu_0}\right)^{m-1} + \frac{m^2}{\mu_0}\left(\frac{\mu_\alpha}{\mu_0}\right)^{2m-1}\right]. \end{aligned} \tag{20}$$

In this turning point, it is a polyline of a function, so $Q_2'' = 0$, which is brought into Equation (20) to obtain

$$\frac{\mu_\alpha}{\mu_0} = \left(\frac{m+1}{m}\right)^{1/m}. \tag{21}$$

It can be known from Equation (21) that since μ_α and μ_0 are the fault displacement and the tangential displacement of the fault at the initial time at any time, the variation λ caused by the mining disturbance after the division is correspondingly omitted. It can be seen that, with the deepening of the digging work, the stress field around the rock mass constantly changes and the rock mass undergoes elastic deformation and plastic deformation. Subsequently, under the effect of pressure, it is compacted, the hardness is increased, the deformation is reduced, and the displacement is reduced. Therefore, the curve becomes steeper.

Bring Equation (21) to Q_2'

$$Q_2 = -\lambda m K_2 \exp\left(\frac{m+1}{m}\right). \tag{22}$$

Then, expand Q_2' and Q_2 by Taylor expansion formula at μ_α and substitute it into Equation (19).

$$\begin{aligned}&\frac{\lambda\mu_0^2}{me(1-m)} + \frac{\lambda\mu_0}{me}(\mu_\alpha - \mu_0)\\ &\quad - \frac{J\mu_0}{mK_2} + \frac{\lambda^2\mu_0^2}{me^2} + \frac{\lambda^2\mu_0}{me^2}(1-m)(\mu_\alpha - \mu_0)\\ &\quad - \frac{\lambda^2\mu_0}{e^2(1-m)}(\mu_\alpha - \mu_0) + \frac{\lambda^2}{e^2}(\mu_\alpha - \mu_0)^2 = 0.\end{aligned} \tag{23}$$

Observing Equation (23), it can be seen that the form is similar to the equilibrium surface equation [36] of the simplest folding mutation, i.e., $\mu + 3x^2 = 0$. Equation (23) is transformed into the standard folding mutation equation as follows:

$$\begin{aligned}&\frac{\lambda\mu_0^2}{me(1-m)} + \frac{\lambda\mu_0}{me}(\mu_\alpha - \mu_0) - \frac{J\mu_0}{mK_2}\\ &\quad + \frac{\lambda^2\mu_0^2}{me^2} + \frac{\lambda^2\mu_0}{me^2}(1-m)(\mu_\alpha - \mu_0)\\ &\quad - \frac{\lambda^2\mu_0}{e^2(1-m)}(\mu_\alpha - \mu_0) = \mu,\end{aligned} \tag{24}$$

$$\frac{\lambda}{e\sqrt{3}}(\mu_\alpha - \mu_0) = x,$$

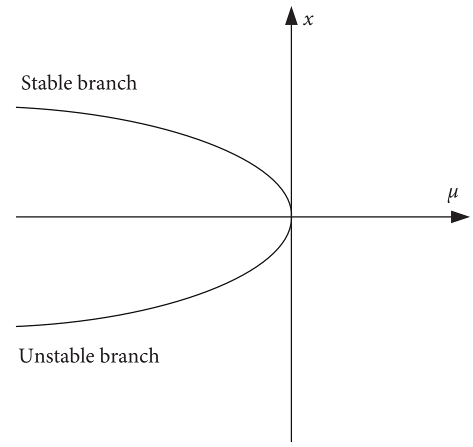

Figure 3: Schematic diagram of folding catastrophe model.

where μ is the control variable and x is the state variable. When $\mu > 0$, the system is empty; when $\mu = 0$, it is the critical state of the system; when $\mu < 0$, the image is shown in Figure 3. The upper part is the stable branch, and the lower part is the unstable branch.

3. Analysis of Influencing Factors

3.1. Systematic Instability Fault Width. Let $\mu = 0$ to find the critical state condition

$$K_2 = \frac{Je^2(1-m)}{\lambda[\mu_0 e + e(\mu_\alpha - \mu_0)(1-m) + \mu_0\lambda(1-m) + \lambda(1-m^2)(\mu_\alpha - \mu_0) - \lambda m(\mu_\alpha - \mu_0)]}. \tag{25}$$

It can be obtained from the analysis of Equation (25) that, when the displacement is determined and the mining disturbance is certain, the problem of homogeneity is ignored, and it can be seen that the relationship between K_2 and the external energy J is a first-order function. Assuming that

$$K = \frac{e^2(1-m)}{\lambda[\mu_0 e + e(\mu_\alpha - \mu_0)(1-m) + \mu_0\lambda(1-m) + \lambda(1-m^2)(\mu_\alpha - \mu_0) - \lambda m(\mu_\alpha - \mu_0)]}. \tag{26}$$

We can obtain

$$b = \frac{1}{J}\cdot\frac{gDL}{K}. \tag{27}$$

Equation (26) is transformed into a dimensionless form; other unrelated constants are treated as a unit, and then bring the fixed value into the relationship. Available curves are shown in Figure 4.

From Figure 4, we can see that the relationship between the width of the fault medium and the energy provided by the outside is an inverse function. The thinner the fault medium, the more the energy input from the external system needs to be destabilized. That is, the lithology is closer to the surrounding rock mass, and the more energy is needed to move, the more external input be. The greater the width of the fault, the less energy the system requires for external input. It can be understood that the width of the fault is infinite in the system, that is, the lithology in the system is close to the lithology of the fault, and the parameters such as compressive strength, tensile strength, and adhesion are low, and the system instability is easier. And then, the less external energy is needed.

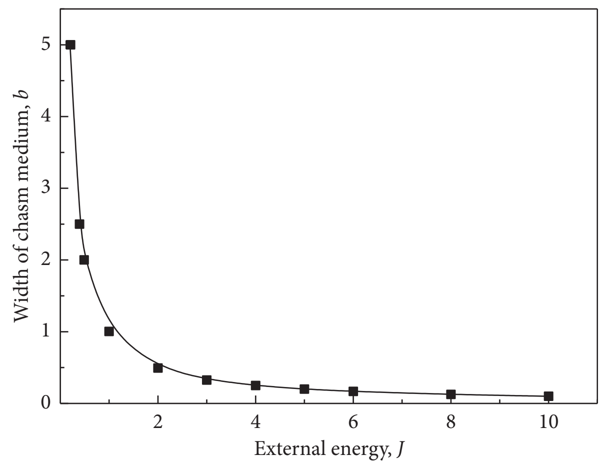

Figure 4: Width of fault medium-outside providing energy diagram.

3.2. Impact of Dynamic Disturbance on System Stability. Put Equation (19) into further transform to obtain the binary equation of λ. The positive value of λ can be used to obtain the influence of mining disturbance on the stability of the system, as shown:

$$\frac{gDL}{Jb} \cdot \frac{e(\mu_\alpha - \mu_0)(1-m)}{(1-m^2-m)(\mu_\alpha - \mu_0) + \mu_0(1-m)} = \lambda. \tag{28}$$

In the analysis of the equation, the unrelated parameter items are unified as a unitary process, and unknown parameters such as λ, J, and b are brought into the special-value drawing correlation curve for qualitative analysis, as shown in Figure 5.

From Figure 5, the relationship between λ, J, and b can be obtained through intuitive analysis. When the width of a fault is fixed, the stronger the mining disturbance is, the less energy the system requires for external input. On the contrary, the weaker the mining disturbances, the more energy the system requires for external input. Similarly, it can be analyzed that when the external input energy is constant, the smaller the width of the fault, the easier the system will lose stability.

3.3. System Instability Kinetic Energy Conservation. When the instability of the system occurs, the rock mass will fall from the initial stationary state to the last one and fall into the roadway as a stage. In this stage, the loss of other energy is ignored, and the energy conservation equation is used in combination with Equation (19) to obtain

$$\sum_{i=1}^{i=i+1} \frac{1}{2} m_i v_i = J = Q_1 \frac{d\mu_\alpha}{d\mu}, \tag{29}$$

where m_i is the weight of the rock that protrudes from the process and μ_i is the initial velocity of the rock that protrudes from the accident.

In this state, the rock blocks fly from the static state after reaching the initial velocity μ_i by absorbing energy, and the velocity is reduced to zero. According to the conservation of energy, it is assumed that the energy source of the kinetic energy of the rock mass in this process comes from the externally absorbed energy J. According to Equation (19), the stability of the system can be judged according to the symbol of J. In this paper, it is assumed that an outburst occurs, and if the system is unstable, then $J > 0$. Due to the large amount of energy input outside the system, the kinetic energy of the rock mass in the system is increased, so that it has a certain initial velocity based on instability. The difference in external energy input leads to prominent types such as dumping, extrusion, and protrusion.

At the same time, Equation (28) can be simplified as

$$\frac{d\mu_\alpha}{d\mu} \cdot \lambda GDL\mu \cdot \frac{1}{\sum_{i=1}^{i=i+1} (1/2) m_i v_i} = B. \tag{30}$$

At this time, if the rock mass is a whole and ignores other unnecessary influencing factors, when μ_i approaches the μ, the width of the fault surrounding rock at this time is considered as the critical value of the rock mass under critical conditions. From Equation (29), we can see that when the other influencing parameters are all constant, the influence of the dynamic disturbance parameter λ on the thickness B of the surrounding rock is a linear function, that is, the stronger the mining disturbance, the greater the critical value of the surrounding rock thickness. In addition, when the rock mass is converted into kinetic energy by absorbing external energy, the greater the initial velocity, the greater the width of the fault surrounding rock when the system is stable, that is, the critical point of coal and gas outburst.

4. Conclusions

In this paper, a fault-rock system based on catastrophe theory is established. The conditions of system instability and even outburst under the conditions of dynamic disturbance are analyzed. By establishing the model, we know that the sign of the external energy J can reflect the stability

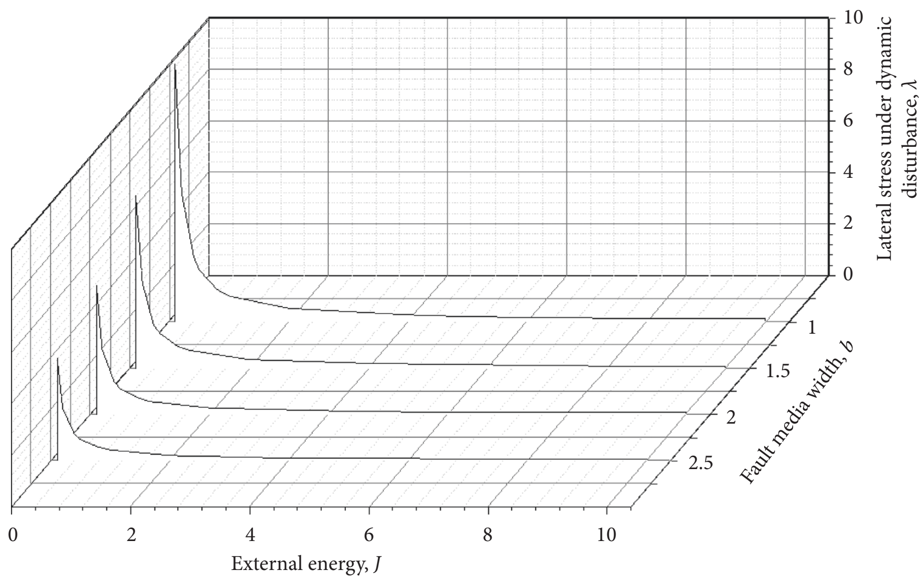

Figure 5: $\lambda - J - b$ relation diagram.

of the system, that is, when $J > 0$, the fault displacement needs to absorb energy from the outside. At the same time, the thinner the fault medium is, the more energy the external input is required for system instability. By combining catastrophe theory analysis, when the width of fault media is constant, the stronger the mining disturbance is, the less the external input energy is required for system instability. Conversely, the weaker the mining disturbances, the more energy the external input requires for system instability. When the external input energy is constant, the smaller the fault width is, the easier the system is to lose stability. The kinetic energy conservation equation is brought into the mutation equation, and it can be known that the stronger the mining disturbance, the greater the critical value of the surrounding rock thickness. When the external energy absorbed by the rock mass is converted into kinetic energy, the greater the initial velocity is, the greater the width of the fault surrounding rock is when maintaining the stability of the system, that is, the critical point of coal and gas outburst.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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