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Study on catastrophe of coal and gas outburst in coal tunneling face

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ABSTRACT

According to the conservation of mass and momentum conservation principle of the breakdown section in coal-rock system, the cusp catastrophe models of coal and gas outburst are established by using mutation theory, in order to reveal the coal and gas outburst mechanism. The expressions of coal and gas outburst occurring necessary and sufficient conditions are educed, and the occurrence mechanism of coal and gas outburst is analyzed. When the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is ≥ 0.1897 MPa , it meets with the necessary conditions of the heading face mutation to extrude and dump coal and gas. When the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is ≥0.7589MPa, it meets with the necessary conditions of the heading face mutation to burst coal and gas outburst. This research results are useful for analyzing and forecasting coal and gas outburst at locale.

Keywords: coal and gas outburst; cusp catastrophe; gas pressure; flow model

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INTRODUCTION

Coal and gas outburst is one of the serious disasters in coal mine. In order to reveal the mechanism of coal and gas outburst, the mutation process of coal and gas outburst is researched by applying mutation theory which is an important branch of nonlinear science.

Coal and gas outburst is the phenomenon of dynamic instability which happens when the system of coal rocks containing gas is under the outer disturbances. The catastrophe theory is applied to research the coal and rock mutation model[1-3] by many academics, and some scholars used the catastrophe model to study the mechanism of coal and gas outburst[4-5]. From the process of gas outburst gestation to motivating until developing, the interactions between elements in inner system and the external system has not been completely ascertained on account of the complexity of the gas outburst mechanism. The cusp catastrophe models of coal and gas outburst are established in tunneling of the coal roadway, the expressions of coal and gas outburst occurring necessary and sufficient conditions are educed, and the gas outburst mechanism and occurred conditions has been studied from the point of view of one-dimensional flow model. The understanding of properties of outstanding mutation is deepened. This research results provide a new technical support for analysis and forecasting coal and gas outburst at locale.

1 The Analysis of Broken Surface of Raw Coal in Tunneling Face

During the processing of the coal lane tunneling, there are three kinds of stress zones change constantly and cyclically ahead of working face. The stress distribution ahead of working face is always from balance to imbalance state and then to state of balance, and the cycle continues. The advancing forward speed of three kinds of stress distribution is asymmetrical during coal tunneling at a uniform velocity. The advancing forward speed is intimately related with the uniformity of the coal structure and the balance state of the stress is an unstable state .The balance state will be destroyed and three kinds of stress is going to redistribute and will reach a new imbalance state or the coal and gas outburst takes place when it suffers work disturbance such like tunneling. The gas pressure goes round with the transformation of the stress balance state and the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is closely associated with such factors as coal seam gas content, the original coal gas pressure, gas radiation ability, gas permeability of coal seam and geologic structures. The dynamic changes of the frontage tunneling work appear three phenomena.

(1) **Phase Evolving Phenomenon.** The distressed zone, the stress concentrated zone and the original stress zone move forward with face advance as well as with the processing of the coal lane tunneling at a uniform velocity in homogeneous coal of no geological damage. Meanwhile, the moving speed of roof or floor is approximately equivalent .The gas gushes equably in coal and the gas pressure of the frontage tunneling work is low and takes fluctuation within a narrow range on. The working surface will be out of the mutation danger or threaten space under the circumstances.

(2) **Stress Stagnation Phenomenon.** The moving speed of coal mining floor slows down or even stops during the working face of the coal lane tunneling advanced when some kinds of geologic structures have been caused damage. That the stress concentration belt doesn't move forward is called stress stagnation phenomenon. The precursor information of the stress stagnation phenomenon is that the factor of stress concentration shows an increasing trend, the distressed zone， and that the stress concentrated zone increase not obvious when tunneling advanced; the gas permeability of coal seam will reduce and the gas emission is small at the condition of non tunneling work but the gas emission fluctuates more larger when tunneling .The power is going to gather not far away from the ahead of working face when it comes to stress stagnation phenomenon and it will cause coal and gas outburst easily .The gas pressure of stress concentrated zone is higher and the pressure gradient magnifies at the ahead of tunneling face at the moment.

(3) **Gas Pockets Phenomenon.** The gas pockets will exist at ahead of tunneling face when the coal changes from thin to thick or there exists soft coal which is highly wrinkled by the stress of structure at the ahead of tunneling face. The supporting coal pillars of the part of the stress concentration shorten gradually. The relationship between the concentrated stress and gas pressure is reduced gradually and the supporting coal pillars are on imbalance state. Coal fracture sometimes open and sometimes close while the gas emission of tunneling face shows a rising generally trend phenomenon which it sometimes becomes big and sometimes small up. The gas pressure of the part of the stress concentration ahead of the tunneling face becomes high as well as the pressure gradient is increasing at this moment. The stress state of coal changes sharply and it causes that the power release suddenly and then the coal and gas outburst takes place when supporting pillars shorten to a certain degree.

The gas pressure of the three kinds of stress zone which is in the front of the tunneling face in coal roadway is different and it is an index of analysis and prediction of coal and gas outburst.

That the pressure relief and damage comes form the porous media containing with gas is the core problem of outburst. The damage can be shown by sparse continuous wave named failure wave. According to the strong and weak of the damage, it has two kinds of models which are outburst and lamination crack, as shown in figure 1. That prominent broken array of coal face takes on layer stripping state is called lay-crack and the finite thickness of coal layer stripped can be called lay-crack debris [6].

The lay-crack debris spread to the coal with intermittent form and named lamination crack of raw coal. Outburst brings about great ruin and the damage will reach two phases. The lay-crack is that it reaches the destroy conditions but does not get to the conditions of outburst. The framework has been stretched and destroyed but it tends to static balance soon[7].

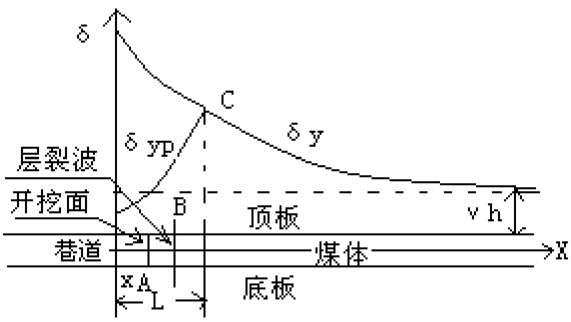

Figure 1 Model of Lamination Crack of Raw Coal

2 The Cusp Catastrophe Model of Coal and Gas Outburst

2.1 The Moving Equation of Lamination Crack of Raw Coal

The original coal seams are under the state that is pressured by ground stress before mining. Three kinds of stress phenomenon which turns up in front of the coal will redistribute because of excavation and forming the new free-surfaces. The gas seepage is going to aggravate in coal seams which will cause the gas pressure field to change. The coal structure may be in damage and pushed forward and then fling out under the action of gas pressure during the process of change.

As shown in figure 1, the development of layer crack wave named B is caused by excavation surface and it is closely related with the excavation face named A. In order to simplify the calculation, we assume that the development speed of layer crack wave B of the coal and rock and the propulsion speed in excavation face A are at the same speed. Actually, the tunneling of excavation face is rolling and we establish the one dimensional quality and momentum conservation equation[8、9] of layer crack wave of the coal and rock with constant speed in tunneling which is simplified by the most simple method.

$$\frac{\partial\varepsilon\rho}{\partial t}+\frac{\partial\varepsilon\rho u}{\partial x}+\frac{\partial(1-\varepsilon)q}{\partial t}=0 \qquad (1)$$

$$\frac{\partial\varepsilon\rho u}{\partial t}+\frac{\partial\varepsilon\rho u^2}{\partial x}+\varepsilon\frac{\partial p}{\partial x}=-f_i \qquad (2)$$

In these equations, they show that the time coordinate, x is for the space coordinates of direction of motion, p,ρand u are for the pressure, density and speed of free gas, εrepresents the porosity, q is for un-free gas quality adhered in one unit coal, f_i is for the effect of gas phase to solid phase, which is caused by speed difference in phases.

The solutions of equations (1) and (2) are only based on the solution of $x+\omega_c t$ because of constant speed simplified in tunneling. ωc stands for the development speed that the layer crack wave of the coal and rock tends to deep coal.

The new coordinate of this linear combination is generally used x expression and x is for the distance from the layer crack wave of the coal and rock to the rib. The partial differential equations of equations (1) and (2) can be transformed ordinary differentiable equations.

$$\varepsilon_0\omega_c\frac{d\rho}{dx}+\varepsilon_0\frac{d(\rho u)}{dx}+(1-\varepsilon_0)\omega_c\frac{dq}{dx}=0 \qquad (3)$$

$$\varepsilon_0\frac{dp}{dx}-\varepsilon_0(u+\omega_c)^2\frac{d\rho}{dx}-(1-\varepsilon_0)\omega_c(2u+\omega_c)\frac{dq}{dx}=-f_i \qquad (4)$$

In the above equations, ε_0 stands for the coal's porosity. We get the effect law between linear adsorption law and linear law in phases by taking isothermal gas relation.

$$p=C^2\rho;\quad q=Q\rho;\quad f_i=\frac{\varepsilon_0^2 u}{k_0}\mu \qquad (5)$$

Among the equations above, C is for isothermal sound speed of gas. Q is for the rate of change of gas quality with pressure adhered in one unit coal.μstands for the gas viscosity coefficient. k_0 is for the penetration of coal.

λis for the percentage that free gas takes in total gas and it is a dimensionless parameter.

$$\lambda=\frac{\varepsilon_0\rho}{\varepsilon_0\rho+(1-\varepsilon_0)q}=\frac{\varepsilon_0}{\varepsilon_0+(1-\varepsilon_0)C^2Q}\leq 1 \qquad (6)$$

And do it with dimensionless method as follows:

$$p=\frac{p}{p_{if}}\;;\quad U=\frac{u}{C}\;;\quad w=\frac{\omega_c}{C}\;;\quad X=\frac{\lambda\varepsilon_0\mu C^2 x}{k_0 p_{if}\omega_c} \qquad (7)$$

And p_{if} stands for the maximum of gas pressure of stress concentrated zone at the ahead of tunneling face.
Mass equation (3) and momentum equation (4) can been written to the form of dimensionless

$$\frac{\lambda U}{w}=\frac{1-P}{P} \qquad (8)$$

$$-\frac{dP}{dX}=\frac{\lambda U}{H-(1+\frac{\lambda U}{w})^2}=\frac{P(1-P)}{HP^2-1} \qquad (9)$$

And: $H=1-\lambda+(\frac{\lambda}{w})^2>0$ (10)

Integrating the equation (9) and getting as follows:

$$X=(H-1)\ln\left|\frac{\sqrt{H}(1-P)}{\sqrt{H}-1}\right|+\ln\left|\sqrt{H}P\right|+HP-\sqrt{H} \qquad (11)$$

Taking the first derivative of X of equation (9) and making it equal to zero means that $\frac{\partial X}{\partial P}=0$.We get the positions of maximum of X. It is easy to get P.

$$P=\frac{1}{\sqrt{H}} \qquad (12)$$

2.2 Development Speed of Lamination Crack Wave of Broken Surface

Take the first item of equation (7) and equation (10) to substitute in equation (12) and we can get as follow:

$$\frac{p}{p_{if}}=\frac{1}{\sqrt{1-\lambda+(\frac{\lambda}{w})^2}} \qquad (13)$$

Unfold equation (13) and get as follow: $F(w)=w^2+\frac{\lambda^2p^2}{(1-\lambda)p^2-p_{if}^2}$ (14)

According to equation (14), we can create the catastrophe potential function named V(w) which is described the development speed of lamination crack wave of broken surface by using the method of topology because the catastrophe type would not change at the condition of topological transformation. We assume that $F(w)$ and the second derivatives of potential function are topological equivalent, $\frac{\partial^2 V}{\partial w}\sim F(w)$.Also, assume that differential homeomorphism Φ: $\sqrt{3}w \to w$ (15)

$$a\to\frac{\lambda^2p^2}{(1-\lambda)p^2-p_{if}^2} \qquad (16)$$

So: $F(w)\sim 3w^2+a$ (17)

According to topological equivalent $\frac{\partial^2 V}{\partial w}\sim F(w)$,we get that $\frac{\partial^2 V}{\partial w^2}\sim 3w^2+a$ (18)

Integrate equation (18) and get that $\frac{\partial V}{\partial w}\sim w^3+aw+J$ (19)

Among the equation above, J represents the integration constant. J is another extension parameter which is separate from the parameter a according to catastrophe theory. Assume that topological equivalent of J is to the development resistance parameters b of lamination crack of raw coal, which shows J∽b. And we get the equilibrium surfaces equation (20) of catastrophe function.

$$\frac{\partial V}{\partial w}\sim w^3+aw+b \qquad (20)$$

Do the integral for equation (20) again and obtain the potential function of development speed of lamination crack of raw coal.

$$V(w,a,b)=\frac{1}{4}w^4+\frac{1}{2}aw^2+bw \qquad (21)$$

Among the equation, the integration constant is omitted because it does not influence the catastrophe properties.

The catastrophe of development speed of lamination crack of raw coal belongs to cusp catastrophe type from equation (20) and (21) and also it is gotten the equilibrium surfaces equation M.

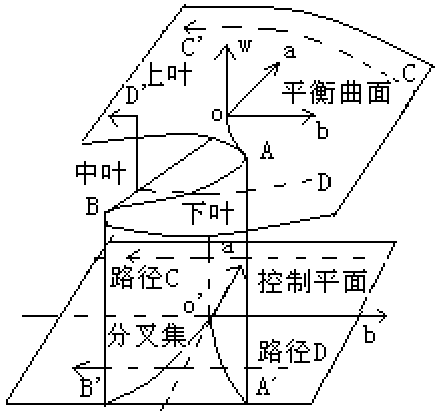

Figure2 Model of Cusp Catastrophe on Coal and Gas Outburst

$$\frac{\partial V}{\partial w} = w^3 + aw + b = 0 \quad (22)$$

The singularity set equation S is that $\frac{\partial^2 V}{\partial w^2} = 3w^2 + a = 0$ (23)

Associating equations (22) and (23) and we get rid of w, get bifurcation set K.

$$4a^3 + 27b^2 = 0 \quad (24)$$

2.3 The Necessary Conditions of Coal and Gas Catastrophe to Outburst

Coordinate of three-dimensional space control parameters consist of a and b and state variable w (w represents the development speed of coal layer crack wave) in figure 2. From the point C, with the continuous change of control parameters, the system status evolves to C' along path C, with state variable continuously changing, and does not occur catastrophe; but from the point of D along path DD' evolution, when it is close to the mid lobe, if control parameters have any small change, the system status will occur a mutation, from lower lobe change to the upper lobe. It illustrates that only when the system across bifurcation set, the system status can occur to mutate. Therefore the calculation (24) is the criterion of coal and gas outburst of necessary and sufficient.

While the equilibrium surfaces equation M is the manifolds of development speed of lamination crack wave of broken surface. a and b respectively represent the resistance and gas pressure of controlling the development speed of lamination crack wave of broken surface. The bifurcation set K is the mutation curve. It satisfies the equation (24) when a is obviously less than or equal to zero in the bifurcation set K. We can get the necessary conditions of causing the coal and gas outburst from the equation (16).

$$\frac{\lambda^2 p^2}{(1-\lambda)p^2 - p_{if}^2} \le 0 \quad (25)$$

Simplify the equation (25) and get as follow: $p_{if} \ge \sqrt{1-\lambda}\, p$ (26)

It is divided into three types according to the power source and those are coal and gas outburst, extruding and dumping[11] coal and gas. Now we calculate the necessary conditions which causing coal and gas outburst.

(1) The necessary conditions to extrude and dump coal and gas. The inter-space gas pressure P of the lamination crack wave of broken surface is greater than the atmosphere pressure P_0 of excavating surface in roadway. The short of P and P_0 is exceeding short ΔP and $\Delta P = p - p_0$. We found that fracture surface of coal will be cracked but not smashed when ΔP is at 0.05 to 0.1MPa according to the experiment from Fang Jianzhi[12]. The extrude phenomenon will be observed when coal has been smashed when ΔP is greater than 0.1MPa and so take $\Delta P = 0.1$MPa. Generally, the adsorption gas volume occupies 80%～90%, the free gas volume occupies 10%～20%[13] in coal. Letλwhich is for the percentage that free gas takes in total gas equals to 10%. The atmosphere pressure (Atm) P_0 of excavating surface in roadway is 0.1MPa.

Take λ=10%, $p = p_0 + \Delta p = 0.1 + 0.1 = 0.2$ MPa to substitute in equation (26) and get $p_{if} \ge \sqrt{1-\lambda}\, p$ equal 0.1897MPa.

The necessary conditions of extruding and dumping coal and gas is that when the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is ≥ 0.1897MPa. In other words, the heading face mutation will extrude and dump coal and gas when the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is > 0.1897MPa and which is not sure to happen. The literatures[11] indicate that the effect of coal and gas extruding and dumping is subordinate and the gas pressure is not high, which is more than about 2 Atm. The calculated consequences of the original gas pressure in this paper were matched with the literatures[11,14].

(2) The necessary conditions of coal and gas outburst. The main energy sources come form compression power for gas outburst which needs high gas pressure. It is going to take to extrude when the gas pressure gets seven to ten Atm[11]. Take $\Delta P = 0.7$ MPa and let λ which is for the percentage that free gas takes in total gas equals to 10%. The atmosphere pressure P_0 of excavating surface in roadway is 0.1MPa.

Take λ=10%, $p = p_0 + \Delta p = 0.1 + 0.7 = 0.8$ MPa to substitute in equation (26) and get $p_{if} \geq \sqrt{1-\lambda}p$ equal 0.7589MPa.

The necessary conditions of coal and gas outburst is that when the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is ≥ 0.7589MPa. In other words, the heading face mutation will happen coal and gas outburst when the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is > 0.1897MPa and which is not sure to happen. It meets with the gas pressure of 0.74MPa which is stated in The Rules of Prevention and Cure Coal and Gas Outburst (19 order of State Administration of Work Safety) and which shows that the mutation analysis which is on base of the conservation of mass and momentum conservation principle of coal and gas outburst is correct.

This research results provide a new technical support for analysis and forecasting coal and gas outburst at locale, which has some guiding significance.

CONCLUSION

(1) From the perspective of catastrophe theory, the inherent dynamic characteristics of the system of coal and rock containing gas which possesses outburst risk and the qualitative sudden change mechanism and conditions of the starting process of outburst is analyzed. This research results have further deepened the understanding the essential rules of coal and gas outburst.

(2) According to the conservation of mass and momentum conservation principle of the breakdown section in coal-rock system, the cusp catastrophe models of coal and gas outburst are established and the conclusion that when the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is ≥0.1897MPa, it meets with the necessary conditions of the heading face mutation to burst coal and gas outburst is drawn. This calculation results is closed to gas pressure about 2 atmosphere pressure which is provided in other literature [11、14]. That is proved that this analysis is correct.

(3) According to the research of coal and gas outburst, the conclusion is that when the gas pressure in concentrate stress section coal-rock from the frontage tunneling work is ≥0.7589MPa, it meets with the necessary conditions of the heading face mutation to burst coal and gas outburst is drawn. This calculation results is closed to the gas pressure of 0.74MPa which is stated in The Rules of Prevention and Cure Coal and Gas Outburst. This has some guiding significance for analysis and prediction of coal and gas.

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