Study on the method of step-up hydraulic fracturing infiltration for soft coal seam

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Abstract. In view of the dilemma of the current hydraulic fracturing effect of soft coal seams, based on the existing hydraulic fracturing technology, a model corresponding to the jump pressure and the length of fracture propagation during the stepwise hydraulic fracturing process was constructed, the influence of the elastic modulus of coal and rock mass and the step-up pressure on the crack extension length during crack propagation was analyzed, and a step-up hydraulic fracturing infiltration method suitable for soft coal seam was formed. The research results show that the coal seam has strong stress sensitivity, and in the step-by-step step-up fracturing process, the coal seam cracks expand as the energy potential increases step by step, and they always extend along the direction of the maximum principal stress. The effect of infiltration is very obvious. In the process of fracture propagation, the elastic modulus of coal and rock mass, and the pressure difference of gradual jump have a great influence on the length of fracture propagation, and the initial crack width and crack height have a certain effect on the effect of fracture expansion and infiltration of the gradual jump hydraulic fracturing. The newly proposed step-up hydraulic fracturing and infiltration method can effectively extend the soft coal seam rock mass gradually when the cracks are fully developed, and has a good application prospect.

1. Introduction
95% of coal mining in China is underground operations, the geological conditions of coal seams are complex, and accidents are serious. In recent years, hydraulic fracturing technology has been widely used in the prevention and control of coal and gas outburst, gas drainage, coal body water injection, etc., and has achieved good results [1-3]. Most of the existing hydraulic fracturing technology uses high-pressure pulse or low-pressure hydraulic to fracturing the coal around the borehole. This method can achieve good results in high-strength hard coal seams [4-5]. However, in the soft coal seam, high-pressure high-flow water is entering the fissure, which largely destroys the coal and rock mass around the borehole, causing the soft coal seam to be damaged by high stress without fully developing the secondary fissure, then It cannot be fully expanded and extended further. As a result, the effect of hydraulic fracturing is insignificant, and even causes the danger of coal extrusion or outburst. If low-pressure hydraulic fracturing is adopted for soft coal seams, on the one hand, the influence range is small,
it is not easy to form a pressure difference, dynamic balance cannot be achieved, and it is not easy to
damage the coal body to expand cracks. On the other hand, the fracturing construction time is longer,
the water consumption is larger, and there are difficulties in drainage, which increases the cost and
difficulty of gas treatment. Therefore, for soft coal seams, how to effectively extend the coal and rock
mass gradually when the cracks are fully developed has become a technical bottleneck for the field
application of existing hydraulic fracturing methods [7-10].

2. Crack propagation model of hydraulic fracturing step by step

2.1. Model construction
This model builds a crack propagation model that only considers the single-stage lifting hydraulic
fracturing energy potential. The basic assumptions of the model are as follows:

(1) Suppose the cross section of the crack is a long rectangle with a length l and a width h; the top
view is a long ellipse model with a long axis l and a short axis w (as shown in Figure 1). Hydraulic
fracturing relies on high-pressure water to provide energy, which causes tensile stress damage to coal
and rock masses. When the water pressure is greater than the fatigue strength of coal and rock masses,
the coal rock mass is unstable and fractured and its original cracks are expanded and extended. Assuming
that the x-direction is the direction of the maximum principal stress and the y-direction is the minimum
principal stress direction, the original fractures of the coal rock body will be higher in the y-direction
due to high-pressure water, extend in the x-direction, and widen in the z-direction.

(2) Coal and rock masses are isotropic, and the fracturing fluid is an incompressible single-phase
Newtonian fluid, the fracturing fluid is laminar in the fracture, the influence of gas in the coal and rock
mass is ignored, h is the fracture height; w is the fracture Half width; l is the diffusion distance of
fracturing fluid (l extends with time l=l(t)).

(3) Does not consider the fluid loss of fracturing fluid during the fracturing process.

(4) Ignoring the influence of gravity in the channel, the fracturing fluid is affected by the reverse
shear force of the coal and rock mass, and the friction resistance coefficient λ=64/Re (Re is the Reynolds
coefficient, which takes the value of 0.6125).

Based on the above basic assumptions, the elliptical equation of fracturing fluid fracture plan view
from above can be obtained:

\[ \frac{x^2}{l^2} + \frac{y^2}{w^2} = 1 \]  

According to the literature [11], the fracture width of the initial fracture of hydraulic fracturing can
be expressed by the fracture toughness and elastic modulus of coal and rock mass:

\[ w_0 = \frac{4}{E} K \sqrt{\frac{l}{\pi}} \]  

In the formula, K is the fracture toughness of coal rock mass, E is the elastic modulus of coal rock
mass.
This time is to calculate the fracture extension length during hydraulic fracturing, so the fluid loss of fracturing fluid during fracturing is not considered. The volume of fracturing fluid is the fracture volume of the fracture. The following relationship can be derived integrally:

\[ Q = q t \approx 2h \int_{0}^{l} w' dx \]  

In the formula, \( Q \) is the flow rate of fracturing fluid, \( t \) is the fracturing time. So the time formula of the sewing speed \( u \) can be obtained:

\[ u = \frac{3wKqE}{\eta d} \]

2.2. Numerical simulation research

Based on the above analysis, PFC numerical simulation software is used to perform the numerical simulation of step-up hydraulic fracturing. The process of coal seam crack expansion and infiltration is shown in Figure 2 ~3.

![Figure 2. The fracture propagation in initial hydraulic fracturing](image)

![Figure 3. The fracture propagation in step-by-step jump hydraulic fracturing](image)

Due to the development of natural cleavage cracks in coal seams, numerical simulation analysis shows that coal seams have strong stress sensitivity. In the process of step-by-step step-up fracturing, coal seam cracks gradually expand with the stepwise increase of energy potential, and they always extend along the direction of the maximum principal stress, the effect of infiltration is very obvious.

3. Analysis and solution of crack propagation model

Ignoring the influence of gravity in the channel, the fracturing fluid flows under the reverse shearing force of the coal and rock mass, and the friction resistance coefficient \( \lambda = \frac{64}{Re} \) (\( Re \) is the Reynolds coefficient, which takes the value of 0.6125). The pressure at both ends of the fluid micro-element segment is \( p, p + dp \), and the pressure difference at the segment is \( dp \), then the fracturing fluid motion equation can be expressed [12-13]:

\[ \tau = z\lambda \frac{dp}{dx} = \tau_s + \mu \gamma \]  

\[ \frac{du}{dz} = \frac{1}{\mu} \left( z\lambda \frac{dp}{dx} - \tau_s \right) \]
In the formula, $\mu$ is the plastic viscosity, $\tau$ is the shear yield strength of the fluid, $\gamma$ is the shear rate, $\gamma = \frac{du}{dy}$. Then, the fracture cross-section is integrated along the $z$ direction, and formulas 5 and 6 are substituted into formula 4 to calculate the average velocity of the fracture, that is, the average flow rate of the fracturing fluid. During the fracturing process, the average velocity of the fracture tip and the fracture extension speed are always equal, then the hydraulic pressure function of each step during the step-by-step jump pressure process can be obtained $f(p) = (E, K, \mu, \tau, \gamma)$.

When the tensile stress generated by the high-pressure hydraulic fracturing pump at the fracture tip is equal to the vertical ground stress at the fracture tip, the fracturing fluid stops flowing, that is, the fracture expands to the maximum value $L_{\text{max}}$.

$$L_{\text{max}} = \left(\frac{(64E^2q^2\gamma^2 - \frac{1}{12\pi^2}w^3k\lambda^2_\tau(w^2 - 4z_0^2)(\pi^2\Delta pk\lambda^3(8z_0^3 - w^3) + 8E\mu_\lambda^3)}{\pi^2w^4k\lambda^2_\tau(w^2 - 4z_0^2))} + 8E\mu_\lambda^3 / (36\pi^2k^2\lambda^4 w^2(w^2 - 4z_0^2)^2)\right)^{\frac{1}{2}}$$

(7)

The pressure $P$ and the fracture extension length $L_{\text{max}}$ provided by each stage of hydraulic fracturing during the step-by-step jump process are solved by Matlab software programming. The calculation parameters are shown in Table 1, and the calculation results are shown in Figure 4–6.

**Table 1.** The calculating parameter table of crack propagation model

| Parameter                          | Unit   | Value  |
|------------------------------------|--------|--------|
| Fracturing fluid flow $Q$          | m$^3$/s| 200    |
| Mass elastic modulus $E$           | MPa    | 3500   |
| Fluid plastic viscosity $u$        | MPa.s  | 0.69   |
| Fracture toughness $k$             | MPa$^{0.5}$ | 13.8   |
| Shear yield strength $\tau$        | MPa    | 0.96   |
| Drilling radius $a$                | m      | 0.047  |
| Width $z$                          | m      | 0.2    |
| Pressure difference $p$            | MPa    | 20, 15, 10, 5 |

**Figure 4.** The elastic modulus of coal and rock mass
4. The method of step-up hydraulic fracturing infiltration

Based on the above analysis, a step-up hydraulic fracturing infiltration method is proposed, aiming to overcome the deficiencies of the existing hydraulic fracturing technology. The methods are as follows:

(1) First, classify the strength of the coal body from near to far according to the on-site measured geological structure distribution of coal and rock bodies, coal body joints and pore fissure development.

(2) The first zone of strength is a small area around the borehole, using a lower level of water pressure fracturing, and maintaining a certain small pressure difference, to prevent the direct high-pressure water action to crush the coal body and cause the crack to close.

(3) With the gradual expansion of the fracturing range, due to the resistance along the way during the flow of fracturing water in the fracture, the potential energy of the hydraulic pressure at the tip of the fracture is gradually lost, and it enters the second zone of strength to increase the pressure of the fracturing water and become a new pressure. The split zone provides energy. At the same time, except for the crack tip, the coal body in other positions is close to the three-way force state by the previous hydraulic pressure, and it is not easy to be killed by the increased hydraulic pressure and cause the crack to close.

(4) The coal body is subjected to increasing water pressure, the water content of the coal body is increasing, the strength is further reduced, and the crack network is further developed;
5. Conclusion

(1) The model of pressure and fracture extension length of each step during the hydraulic fracturing step by step is obtained. The coal seam has strong stress sensitivity. During the stepwise pressure cracking process, the coal seam cracks expand with the increase of the energy potential, and they always extend along the direction of the maximum principal stress. The effect of infiltration is very obvious.

(2) The elastic modulus of coal and rock mass and the pressure difference of gradual jump during fracture propagation have a great influence on the length of fracture propagation, and the initial crack width and crack height have certain effects on the expansion and permeability of the hydraulic fracture impact.

(3) A step-up hydraulic fracturing and fracturing infiltration method is proposed. The defect of small fracture range greatly improves the hydraulic fracturing effect and application range.

Acknowledgments

The study was supported by the State Key Research Development Program of China (Grant No. 2016YFC0801404), Chongqing Technological Innovation Leading Talent Support Program (CSTCKJXCLJRC14).

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