Study of influences of rock hardness on crack evolution rule under hydraulic fracturing

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Abstract. In order to study the crack evolution rules of hydraulic fracturing rock with different hardness, a numerical model of hydraulic fracturing rock was established. It explored the expansion length, expansion width, propagation rate of crack and initiation pressure of hydraulic fracturing different hardness rocks. The results show that the expansion length, the propagation rate along length and the initiation pressure of crack were positively correlated with the rock hardness, and the expansion width and propagation rate along width were negatively correlated with the rock hardness. In addition, considering the effect of in-situ stress difference, it took granite as an example, and studied the effect of in-situ stress difference on crack propagation. It is found that as the in-situ stress difference increases, the initiation pressure of the crack decreases, and the crack expansion length and the propagation rate along length shows a linear increase, but it has little effect on the crack expansion width. The results can provide theoretical references for improving the application of hydraulic fracturing technology in hard rock excavation, such as the coal roadway excavation, the tunnel excavation and so on.

1. Introduction

In the excavation of the coal roadway and tunnel, the heading machine is generally used to break the hard rock, but the hard rock will cause great damage to the cutting tools, so they need to be replaced frequently, which greatly affects the construction schedule and cost. Although breaking rocks by blasting can greatly improve the excavation efficiency, blasting may bring greater safety risks, which is infeasible in many cases. While it can use hydraulic fracturing technology to break the hard rock in advance, thus the rock integrity and hardness will be reduced evidently, the tool life will be extended, and then the construction efficiency can be improved greatly.

In recent years, scholars have carried out lots of researches on hydraulic fracturing rock technology. Li et al. [1] conducted the fully-coupled simulation of the hydraulic crack in a heterogeneous rock formation, considering the interaction between the pore pressure and solid. Zhang et al. [2] investigated the crack networks in the compact sandstone with different dip angles by a bonded-particle coupled
hydrodynamics model. Hou et al. [3] simulated hydraulic fracturing process of different lithologic rocks in the horizontal well utilizing the true physical model experiment on the large rock specimens. Hashish et al. [4] studied the effects of temperature on crack expansion under hydraulic fracturing. Luo et al. [5] developed the simulation of pressure fluctuations and acoustic emissions during hydraulic fracturing. Ji et al. [8] studied the effects of pressure changes on the pore size of the fissure during hydraulic testing. Lyu et al. [9] conducted field experiments and studied natural cracks in soft coal seams and their effect on hydraulic crack propagation. Huang et al. [10] established a variety of perforation models to study the hydraulic crack initiation and near-wellbore propagation. Wang et al. [11] researched the difference between consecutive and alternate hydraulic fracturing in horizontal wells by the extended finite element method. Bohloli et al. [12] carried out an experimental study on hydraulic fracturing of unconsolidated rocks, which focused on the mechanisms of crack initiation and propagation under different injection fluids and various confining stresses. And Taleghani et al. [13] utilized the cohesive zone model to numerically simulate the propagation of hydraulic cracks in natural cracks.

The above-mentioned researches have made great achievements in the theories and methods of hydraulic fracturing. While the formation conditions are complex and changeable, and rocks with different hardness have large differences, which may greatly affects the hydraulic fracturing efficiency and economy. Therefore, it is of great significance to fully explore the crack propagation rules under different rock hardness. So, the paper carried out a series of numerical simulations under different rock hardness, and discussed the relationship between crack propagation and rock hardness. The research results can provide the theoretical basis for hydraulic fracturing rock with different hardness, and help to further improve the application of this technology in the coal roadway excavation, the tunnel excavation and so on.

2. Numerical simulation

2.1. Model building

As shown in Figure 1, the model was a circular formation area with a radius of 50 m. Five Cohesive units with a size of 5 m were prefabricated as prefabricated cracks, and one Cohesive unit with a size of 10 m was used as a natural crack. One of the prefabricated cracks intersected the natural crack, the preset crack propagation direction was parallel to the maximum horizontal principal stress direction, and fracturing time was the same. The mechanical parameters of rocks with different hardness are shown in Table 1 [14].

| Rock material parameters. | Elastic modulus/GPa | Poisson ratio | Fluid proportion /N | Porosity ratio | Permeability |
|--------------------------|--------------------|--------------|---------------------|---------------|-------------|
| Granite                  | 60                 | 0.36         | 9800                | 0.1           | 1×10^{-7}   |
| Marble                   | 20                 | 0.27         | 9800                | 0.1           | 1×10^{-7}   |
| Shale                    | 12                 | 0.35         | 9800                | 0.1           | 1×10^{-7}   |
| Marl                     | 4                  | 0.40         | 9800                | 0.1           | 1×10^{-7}   |

| Crack element material parameters. | Elastic modulus/GPa | $t_n^0$/MPa | $t_s^0$/MPa | $t_r^0$/MPa | Viscous | Filtration coefficient |
|------------------------------------|--------------------|-------------|-------------|-------------|---------|-----------------------|
| Prefabricated crack                | 15                 | 6           | 20          | 20          | 1×10^{-14} | 0.0001                |
| Natural crack                      | 15                 | 2           | 10          | 10          | 1×10^{-14} | 0.0001                |
2.2. Control equation
The balance equation of solid rock [15]:
\[ \int_V (\bar{\sigma} - Pw) : \delta\epsilon \, dV = \int_S \hat{T} : \delta u \, dS + \int_V f^o \delta u \, dV \]  \hspace{1cm} (1)
The continuity equation of seepage liquid:
\[ \frac{d}{dt} \left( \int_V n \, dV \right) = - \int_S n \nu \, dS \]  \hspace{1cm} (2)
The critical stress criterion for damage:
\[ \max \left\{ \frac{\sigma_n}{\sigma_n^0} , \frac{\sigma_t}{\sigma_t^0} \right\} = 1 \]  \hspace{1cm} (3)
The linear degradation criterion of elastic modulus:
\[ E = \left( 1 - D \right) E_0 \]  \hspace{1cm} (4)
\[ D = \frac{\delta_m^f (\sigma_m^{max} - \sigma_m^0)}{\delta_m^{max} (\sigma_m^{max} - \sigma_m^0)} \]  \hspace{1cm} (5)

Where, \( \delta\epsilon \) is the virtual strain, \( \bar{\sigma} \) is the effective stress, \( \hat{T} \) is the surface force, \( f^o \) and \( \delta u \) are the unit volume force and displacement except gravity. \( \nu \) is the seepage velocity of the fluid in the solid. \( n^o \) is the unit vector of the surface \( S \) in the normal direction, \( n \) is the porosity. \( \sigma_n \) is the normal stress, \( \sigma_t \) is the tangential stress (\( \sigma_1 \) does not exist in two dimensions), \( \sigma_n^0 \) is the threshold stress of normal damage, \( \sigma_t^0 \)'s and \( \sigma_t^0 \) are the threshold stress of tangential damage. \( E_0 \) is the Young's modulus of the damage-free element, \( E \) is the Young's modulus of the damage element, \( D \) is the damage factor, \( \delta_m^{max} \) is the maximum displacement of the loading process, \( \delta_m^0 \) is the opening displacement when the damage is reached.

3. Comparative analysis
3.1. Effect of rock hardness on crack propagation and initiation pressure of crack
By the numerical simulations of hydraulic fracturing rock with different hardness (Figure 2), the rules of crack propagation with time were obtained. Due to the different positions and the mutual influence of the cracks, it can be seen that there were large differences in the crack extension length, direction, and velocity during hydraulic fracturing. Through detailed analysis of crack propagations, we can find that for the extremely hard rock (granite), the crack I extended along the positive direction of X-axis, which then connected to the natural crack and continued to expand until it reached the boundary of the rock formation. The crack II and the crack IV extended along the positive direction of X-axis, while the crack III and the crack V extended along the negative direction of X-axis. And for the hard rock (marble)
and the second hard rock (shale) under hydraulic fracturing, the expansion rules of the five cracks were basically consistent with that of the granite. While the five cracks in medium-hard rock (marl) showed different crack growth results, which propagated symmetrically in the positive and negative directions of X-axis.

Furthermore, we made a comparison of rocks with different hardness. As shown in Figure 3 and Figure 4, from the medium hard rock to the extremely hard rock, the fracture initiation pressure, the propagation rate along length and the propagation rate along width all had remarkable changes. The fracture initiation pressure increased from 10 MPa to 46 MPa, the crack length increased from 7.87 m to 35.0 m, the propagation rate along length increased from 0.0067 m/s to 0.02 m/s, and the crack width decreased from 1.20 mm to 0.40 mm, the propagation rate along width decreased from 0.48 mm/s to 0.026 mm/s. It can be concluded that the expansion length and the propagation rate along length were positively correlated with the rock hardness, while the expansion width and the propagation rate along width were negatively correlated with the rock hardness. As the rock hardness increased, the initiation pressure of the crack increased significantly. This is because that as the rock hardness increases, the brittleness of rock increases and the plasticity decreases, thereby the rock is difficult to occur deformation, causing the crack difficult to spread along the width direction. In contrast, as the rock hardness decreases, the plasticity increases, the rock is easy to take place deformation, which makes the preformed crack easier to spread along the width direction. Moreover, in the simultaneous propagation process of several cracks, due to the stress interference between the cracks, there were an interference zone between these cracks, causing the different crack propagations.

![Figure 2. Crack propagations in rock with different rock hardness.](image)

![Figure 3. Relationship between initiation pressure as well as crack dimension and rock hardness.](image)
3.2. Effect of in-situ stress difference on crack propagation and initiation pressure of crack

The in-situ stress difference plays a decisive role in the hydraulic crack extension [16]. Taking hydraulic fracturing granite as an example, the effect of horizontal in-situ stress difference on propagation and initiation pressure of crack was discussed of 0 MPa, 2 MPa, 4 MPa and 6 MPa as shown in Figure 5. By the detailed statistical analysis of the numerical simulation results in Figure 6 and Figure 7, it is found that under the difficult in-situ stress differences, the average propagation lengths of the crack were 35.0 m, 37.5 m, 42.2 m and 44.2 m in turn, the propagation rate along length increased from 0.48 mm/s to 0.63 mm/s, and the crack initiation pressure decreased from 42.0 MPa to 35.7 MPa. And the average propagation width of the crack and the propagation rate along width only had a slight variation.

It is obvious that the increase of in-situ stress difference can bring the linear increase of expansion length and propagation rate along length, but has little effect on expansion width and propagation rate along width. And the initiation pressure of the crack decreased as the in-situ stress difference increased. This is because the in-situ stress difference can guide the crack propagation under hydraulic fracturing, and its directivity increases with the increase of in-situ stress difference. So with the increase of the in-situ stress difference, it requires less energy for the crack initiation and propagation, leading to longer cracks.

Figure 4. Relationship between the propagation rate of crack and rock hardness.

Figure 5. Crack propagations under different in-situ stress differences.
Figure 6. Relationship between initiation pressure of crack as well as crack dimension and in-situ stress differences.

Figure 7. Relationship between the propagation rate of crack and in-situ stress differences.

4. Conclusion
(1) By the comparative analysis of the influences of rock hardness on crack evolution, it is found that the expansion length and propagation rate along length were positively correlated with the rock hardness, while the expansion width and propagation rate along width were negatively correlated with the rock hardness. And as the rock hardness increases, the initiation pressure of the crack increases significantly.

(2) In the simultaneous propagation process of several cracks, due to the stress interference between the cracks, there is an interference zone between these cracks, causing the different crack length, direction, and velocity.

(3) Based on the analysis of the effect of in-situ stress difference on crack propagation, it is obtained that the increase of in-situ stress difference can bring the linear increase of expansion length and propagation rate along length, but has little effect on expansion width and propagation rate along width. And the initiation pressure of the crack decreased as the in-situ stress difference increased.
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