Numerical Analysis on Shale Crack Model under Explosive Loading

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Abstract: High Energy Gas Fracturing (HEGF) technology can produce self-supporting crack network in rocks of oil and gas reservoirs under a large number of high temperature and high pressure explosive shock wave caused by explosive detonation. It is expected that the reservoir conductivity will be improved by generating the new crack channels for oil and gas flow, so as to achieve the goal of increasing oil and gas production. However, the numerical study on the crack initiation, extension and propagation of rock under blast loading is still insufficient, which plays a vital role in better understanding the mechanical performance of rocks in the HEGF process. In the present study, taking the typical shale gas demonstration area in Sichuan province as an example, the shale crack model is established, the mechanical properties of shale rock with cracks under explosive loading are studied, the evolution laws of crack propagation are analyzed, and the damage characteristics of crack tip are considered.

1. Introduction

With the rapidly increased demand and the serious insufficiency of oil and gas reserves in current industrial development, the technological development of Chinese onshore oil and gas fields has been faced with many difficulties and problems on how to explore the rich low permeability, ultra-low permeability and deep ultra-low permeability oil and gas reserves. Obviously, it is urgent to effectively develop and utilize low permeability oil and gas fields. Among various strategies to reconstruct the oil and gas reservoirs, High Energy Gas Fracturing (HEGF) technology can produce self-supporting crack network in rocks of oil and gas reservoirs under a large number of high temperature and high pressure explosive shock wave caused by explosive detonation. It is expected that the reservoir conductivity will be improved by generating the new crack channels for oil and gas flow, so as to achieve the goal of increasing oil and gas production. It has been proved that the HEGF technology is particularly effective in improving crude oil production, especially for the low permeability oil and gas reservoirs.

With the regards to the complex HEGF process, including the initiation and propagation of cracks under high temperature, high pressure and extremely rapid impact, researchers have begun to do experimental and theoretical research. Both David W. Yang [2] and Chen Dechun [3] paid attention on producing new testing devices to study the dynamic fracturing mechanism of rock by pressure pulse. A range of theoretical and computational models were proposed to perform the mechanic behaviors of rock in the HEGF process, including the energy balance theory model [4-6], shock stress wave based model [7,8], linear elastic fracture mechanics based model [9], coupled model [10] and so on. However, the numerical study on the crack initiation, extension and propagation of shale rock under blast loading is still insufficient, which plays a vital role in better understanding the mechanical performance of rocks in the HEGF process. In this study, taking the typical shale gas demonstration...
area in Sichuan province as an example, the shale crack numerical model is established, the mechanical properties of shale with cracks under explosive load are studied, the evolution laws of crack propagation are analyzed, and the damage characteristics of crack tip are considered.

2. Shale crack model

2.1 Geometric model

In order to simplify the numerical model and reduce the calculation workload, the geometric dimension of the calculation model is considered as 200 mm x 100 mm x 100 mm of shale rock. A micro crack with a width of 1 mm and a length of 14 mm is set on the bottom center of the shale, as shown in figure 1(a). The position of the explosive is assumed to be ‘H’ distance from the midpoint of the bottom crack. Except for the free surface on the bottom surface, the rest of the shale rock is set as non-reflective boundary. The 1 mm element size is employed within the area of 20 mm from the bottom crack, and the 2 mm element size are adopted in the other areas, as displayed in figure 1(b).

![Geometric dimension](image1.jpg) ![Mesh generation](image2.jpg)

Figure 1 Shale crack model

2.2 Material model

In the present study, the plastic damage model (MAT_CONCRETE_DAMAGE_REL3) is simulated for shale material, which is well known as K&C model. This material model is designed primarily for concrete developed by Karagozian&Case Company in the United States. The most prominent feature of this model is that the parameters needed input are very simple. The user only needs to provide the uniaxial compressive strength of concrete. Therefore, in the absence of static and dynamic parameters of materials, K&C model is a good choice to simulate the brittle material similar to concrete or rock. In addition, the previous studies have shown that K&C model can successfully simulate various static and dynamic tests of concrete, and the dynamic responses of concrete under explosive load can also be calculated with satisfactory results. In this model, the stress tensor is decomposed into the stress sphere tensor and the stress deviation tensor. The stress sphere tensor changes the volume of the material and the stress deviation tensor changes the shape of the material. The state equation between hydrostatic pressure and volume strain is as follows:

\[ p = C(\varepsilon_v) + \gamma T(\varepsilon_v) E \]

Where \( \varepsilon_v \) is volumetric strain, \( \gamma \) is specific heat coefficient, \( E \) is initial internal energy per unit volume.

In this study, the K&C material model is used to simulate the mechanical properties of shale under explosive loading, according to the fact that shale and concrete are both typical brittle materials. Based on the experimental data, the shale density is 2600 kg/m\(^3\), Poisson's ratio is 0.26, and the uniaxial compressive strength is 125 MPa.
2.3 Blast load
In the calculation software, the keyword *LOAD_BLAST provides a simple method to produce explosive shock wave. The weight, location and detonation time of explosive can be directly determined by parameters. The calculation efficiency of this calculation method is much higher than other calculation methods considering explosive load, such as fluid-solid coupling method. In the present study, the explosive loads on cracks are considered by the keyword *LOAD_BLAST. The total calculation time is 1 ms.

3. Computing results

3.1 Effect of charge weight
Assuming the distance of explosive from the crack ‘H’ is 200 mm, the mechanical properties of shale single-crack model are calculated as the charge weight of 100 g, 200 g, 300 g, 500 g, 800 g and 1000 g. It is also analyzed on the evolution law of crack propagation and the damage characteristics of crack tip.

3.1.1 Crack Propagation
When the charge weight is 500 g, the calculation results of the single-crack model are displayed in figure 2. The damage and failure of materials are represented by the equivalent plastic strain contours. At 50 us, the stress at the crack tip is concentrated and the plastic strain is maximum. The new crack will propagate and initiate from the crack tip. At 60 us, it is observed that the direction of crack propagation is about 15 degrees from the vertical symmetry surface of shale rock. At 100 us, the initiation of new cracks stops, and the opening displacement of cracks eventually tends to constant values after its oscillation (as shown in figure 3).

![Figure 2 Damage of crack tip (500 g explosive charge)](image)

![Figure 3 Changes of crack opening displacement (500 g explosive charge)](image)

3.1.2 Effect of charge weight
Figure 4 is the calculation results of different charge weights (100 g, 200 g, 300 g, 500 g, 800 g and 1000 g). The damage and failure of shale material are characterized by equivalent plastic strain contour. As seen in figure 4, with the increase of charge weight, the initiation and propagation of the
crack become more and more serious at the crack tip. This positive trend is also obviously observed in figure 5 and figure 6.

![Crack opening displacement](image1.png)

![Crack propagation range](image2.png)

**Figure 4** Damage and failure with different charge weights

**Figure 5** Changes of crack opening displacement

**Figure 6** Changes of crack propagation

### 3.2 Effect of crack dip angle

Assuming that the distance of explosive from the crack ‘H’ is 200 mm and the explosive weights are 100 g, 200 g and 300 g, the initiation and propagation of shale single-crack model are calculated with the different crack dip angles of 0°, 30° and 60°. The evolution laws of crack propagation and the damage characteristics of crack tip are also studied. The calculation model is shown in figure 7.
From figure 8 to figure 12, the damage and failure of the shale material are represented by the equivalent plastic strain contour. From the damage contour of the crack tip in figure 8, 9 and 10, it can be known that the damage of the crack tip become more serious with the increase of crack dip angle, and the damage with 60° crack dip angle is the most obvious. As can be seen from figure 11 and 12, with the increase of charge weight, the crack opening displacement with dip angles of 0° and 30° are very small (less than 0.2 mm). The results of 60° dip angle are 3.34 mm, 4.54 mm and 6.02 mm, respectively. The most obvious change of crack propagation range area is also presented in the calculation result of 60° dip angle with the different charge weight.
3.3 Effect of crack spacing

The shale double-crack model is established as displayed in figure 13. It is assumed that the explosive load is applied only to the left crack. The initiation and propagation of cracks is calculated with different crack spacing of 10 mm, 30 mm and 50 mm. The evolution laws of crack propagation are analyzed and the damage characteristics at the crack tip are also studied. When the distance of explosive from the left crack ‘H’ is 200 mm and the charge weight is 300 g, the different crack spacing of 10 mm, 30 mm and 50 mm are considered in the calculation model.

The damage and failure of the shale rock are characterized by the equivalent plastic strain contour in figure 14. The damage extent of crack tip is lighter with the increase of crack spacing under the 300 g charge weight. When the crack spacing is 10 mm, both the two crack tips have serious damage and there are a connected crack between the two crack tips. The opening displacement of the left crack is 0.84 mm due to the direct action of explosive load, while the right crack completely closes. When the crack spacing is 30 mm and 50 mm, no connected crack occurs, the opening displacement of the left crack is smaller (less than 0.005 mm), and the closing displacement of the right crack is also smaller (less than 0.001 mm). The crack tip has minor plastic strain with the crack spacing of 30 mm and 50 mm.

4. Conclusion

In this study, a new shale crack model is adopted in a three-dimensional numerical model to investigate the mechanical properties of shale rock with cracks under explosive loading. The evolution laws of crack propagation and the damage characteristics of crack tip are considered with different
charge weights, crack dip angle and crack spacing. The presented shale crack model can qualitatively and quantitatively perform and predict the mechanical behaviors of shale rock under explosive loading.

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