Study of Horizontal Fracture Network Formation Mechanism of Shallow Layer Reservoir

Hongsheng Tao & Jingfu Mu
Research Institute of Shanxi Yanchang Petroleum (Group) Co., Ltd., Xi’an, Shanxi, China

Hui Xiao*
Chongqing Key Laboratory of Complex Oil & Gas Fields Exploration and Development, Chongqing University of Science and Technology, Chongqing, China

ABSTRACT: Yanchang Oil Field C6 oil layer has shallow burial depth (500-600m), compact reservoir, and natural fracture development with high rock brittleness, containing the condition of forming complex horizontal fracture network. However, as the formation mechanism of horizontal fracture network is unclear, the oil field development has experienced serious restriction. Based on continuous damage mechanics method, this thesis applied secondary development on user subroutine of AQAQUS, established numerical simulation model for simultaneous propagation of hydraulic fracture and natural fracture, simulated and analyzed the horizontal fracture network form and its formation condition of C6 Reservoir. Through numerical simulation, it is found that the main conditions of forming the fracture network includes: less stress difference, high-density natural fracture, high-angle natural fracture, cluster interval of around 30m, large discharge capacity (>12m³/min), and low-viscosity slick hydraulic fracturing fluid. The study conducted in this thesis can provide guidance on horizontal fracturing network of similar shallow layer reservoir.

Keywords: data mining; load analysis; electric power data; visualization; big data

1 INTRODUCTION

The distribution of sand bodies in the target block C6 Reservoir has inter-bedding of tight sandstones and shale. Hydraulic fracturing is required for remolding and forming fracture network, so as to link up the reservoir as much as possible. According to numerical simulation and decades of experience on small-scale fractured intervals and multiple fracturing in Yanchang Oil Field, the artificial fractures generated by oil formation improvement are mainly horizontal fractures. The natural fractures of C6 Reservoir mainly include high-angle fractures and vertical fractures. The existence of natural fractures makes the fracture system after artificial modification more complicated, thus providing great advantage to formation of volume fractures and fracture network. The minimum horizontal major stress and vertical stress of C6 Reservoir are similar to each other with a stress ratio within 1.3.

Based on numerical simulation, we have found that the disturbance of induced stress is very serious. The fractures have the potential stress condition to form complex fracture network. Therefore, it is necessary to study the propagation mechanism of natural fractures before hydraulic fracture propagation route exists by conducting numerical simulation. The mechanical mechanism problem of hydraulic fracture propagation involves fluid percolation, non-linear deformation, natural fracture damage slippage, and rock fracture damage theories [1-3] which are all focuses and difficult topics in research. Fracture network pressure breaks are commonly seen in shale gas. Current research mainly focuses on vertical fracture network [4-6]. There’s very few research on horizontal fracture network pressure breaks of shallow layer reservoir. Nevertheless, a large number of scholars have conducted studies of the influence that natural fracture has on formation mechanism of complex fracture network [7-10]. These studies have laid foundation for the research of this thesis. This thesis regarded
natural cement micro-fracture as weak plane with low intensity and applied continuous damage mechanics method to introduce the molding damage fluid seepage coupling of natural fracture into Mohr-Coulomb Criterion. It took natural fracture tensile stress damage and permeability damage evolution into consideration and took permeability as the proof of whether representation fracture network had formed, so as to conduct the study of horizontal fracture network development mechanism and formation condition of C6 Reservoir horizontal well.

2 CONCRETE DAMAGE PLASTICITY
CONSTITUTIVE MODEL OF NATURAL FRACTURE

During hydraulic fracturing, natural fracture contains two kinds of damage: one is shearing stress damage; and the other is tensile stress damage. Damage of natural fracture can cause abrupt increase in its permeability. Thus, additional stress generated by seepage will also increase and connect adjacent natural fractures. In this way, the goal of remolding volume through fracture network can be reached.

2.1 Modified Mohr-Coulomb yield criterion

Effective shearing strength indexes of rock $c^*$ and $\phi^*$ are functions of damage status. With combine action of damage and pore pressure, the Mohr-Coulomb Criterion of rock damage can be expressed by effective stress, pore pressure, and effective shearing strength as follows:

$$\tau_n = c^* + \frac{\sigma_n + DP_w}{1 - D} \tan \phi^* \quad (1)$$

In which, $\sigma_n$, $\tau_n$ respectively refer to the normal stress and the tangential stress of damage plane. $p_w$ refers to pore pressure.

Set uniaxial compressive strength of rock as $\sigma_c$, then the uniaxial strength of rock after damage shall be $\sigma_c^* = (1 - D)\sigma_c$. According to Mohr-Coulomb Criterion, the relation of $c^*$, $\phi^*$ and uniaxial compressive strength can be expressed as follows:

$$\sigma_c^* = (1 - D)\sigma_c = \frac{2c^* \cos \phi^*}{1 - \sin \phi^*} \quad (2)$$

From which, it can get to know that the effective shearing strength indexes of damaged rock $c^*$, $\phi^*$ can be expressed as the functions of the normal stress and the tangential stress on damage plane, and of the uniaxial compressive strength and the damage variant of rock.

2.2 Evolution equation of natural fracture damage

2.2.1 Tensile stress damage of natural fracture

In this thesis, the pressure stress (strain) is negative while the tensile stress (tension strain) is positive. The damage evolution equation with uniaxial tensile stress can be expressed as follows:

$$D = \begin{cases} 0 & 0 < \varepsilon \leq \varepsilon_{t0} \\ 1 - \frac{\lambda S_t}{\bar{E}E_0} & \varepsilon_{t0} < \varepsilon \leq \varepsilon_{tu} \\ 1 & \varepsilon_{tu} < \varepsilon \end{cases} \quad (3)$$

Among which, $\lambda$ refers to residual strength coefficient, $E_0$ refers to elasticity modulus before natural fracture is damaged, $\varepsilon_{t0}$ refers to tensile stress corresponding to elastic limit; and $\varepsilon_{tu}$ refers to ultimate tensile strain of natural fracture. Thus, $\bar{E}$ can be expressed as:

$$\bar{E} = \sqrt{E_{p1}^2 + E_{p2}^2 + E_{p3}^2} \quad (4)$$

2.2.2 Shearing strength damage of natural fracture

When natural fracture generates plastic deformation after exceeding its ultimate strength under the coupling action of stress and pore pressure, the equivalent plastic strain shall be:

$$\varepsilon_p = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_{p1} - \varepsilon_{p2})^2 + (\varepsilon_{p2} - \varepsilon_{p3})^2 + (\varepsilon_{p3} - \varepsilon_{p1})^2} \quad (5)$$

In which, $\varepsilon_{p1}$, $\varepsilon_{p2}$ and $\varepsilon_{p3}$ respectively refer to the three main plastic strains.

Damage factor and equivalent plastic strain can meet the first-order exponential decay. Normalize the equivalent plastic strain, that is:

$$D = A_0 e^{-\bar{E}_{pu}/a} + B_0 \quad (6)$$

In which, $\bar{E}_{pu}$ refers to equivalent plastic strain of normalization and $a$ refers to material parameter. According to experiment, it can be assured that:

$$A_0 = \frac{1}{e^{-1/a} - 1}; \ B_0 = -\frac{1}{e^{-1/a} - 1}.$$
2.3 Natural fracture permeability evolution equation

2.3.1 Permeability evolution equation of natural fracture without damage

The relation between permeability coefficient and volumetric strain is as shown below:

\[ k = \frac{2k_0\left[\varepsilon_v - \frac{\varepsilon_v^2}{1 + \varepsilon_v}(1 - n_0)\right]^3}{n_0^3(1 - \varepsilon_v)} \quad (7) \]

In which: \( k_0 \) refers to initial permeability coefficient; \( n_0 \) refers to initial porosity; \( \mu \) refers to coefficient of fluid kinetic viscosity, and \( d \) refers to diameter of solid particle.

2.3.2 Permeability evolution equation of natural fracture with damage

Part of the damaged natural fracture can still bear shearing load and pore pressure. According to seepage cube law, the damage permeability coefficient of rock can be evolved as follows:

\[ k = (1 - D)k_0 + Dk_f(1 + \varepsilon_{VP}^P)^3 \quad (8) \]

In which, \( k_0 \) and \( k_f \) respectively refer to the permeability coefficients of rock without and with damage. \( \varepsilon_{VP}^P \) refers to plastic volumetric strain of damaged phase.

3 FINITE ELEMENT MODEL OF ELASTOPLASTIC DAMAGE OF C6 RESERVOIR FRACTURE NETWORK PROPAGATION

While synthesizing the situation that there were multiple low-angle natural fractures existing in C6 sand shale reservoir, Abaqus software was applied to do secondary development of user subprogram and establish the numerical simulation model of simultaneous extension of hydraulic fractures and natural fractures as shown in Figure 1. The overall dimension of the model was 50m×100m while that of the sand shale reservoir was 8m×50m. The 8m in the middle was sand shale layer section with mudstone formation up and down. The injection spot of fracturing fluid was in the middle part of the model. Due to the symmetry of the model, only half of the x direction was required for calculation. See Figure 1 (right) for the distribution of natural fractures in the reservoir. There were two groups of natural fractures criss crossing. Interval between fractures on y direction was \( d_1 \) while that on x direction was \( d_2 \). Viscoelastic damage Cohesive pore pressure unit was applied to simulate the extension process of hydraulic fracture. Before hydraulic fracturing occurred, the top, bottom and right side boundaries of the model were restrained. Initial pore pressure of stratum was applied on these boundaries. Before calculation, initial crustal stress equilibration was firstly conducted to assign the maximum principal horizontal stress, the minimum principal horizontal stress, and pore pressure of the stratum on each node inside the model, so as to simulate the initial strained condition of rock in stratum. Then, fracturing fluid with certain flow and viscosity was injected inside.
through the node at the borehole of the horizontal well.

When the permeability coefficient of natural fracture reached 2e-6m/s, that is 1mD, it shall be considered that the remolding for this natural fracture succeeded. Then, study shall be conducted on the fracturing state at 20min.

According to the fracturing design of Z804-4 Well C6 Reservoir, the depth of C6-3 section was 612m while the friction loss in slick water pipeline was 5.4MPa. See Figure2 for the simulated pressure at well bottom obtained from calculation and the pressure from actual measurement. While using the same displacement, the fracturing pressure predicted by the model of this thesis was basically the same with the calculated results from on-site measurement. The maximum difference was within 2MPa while that of fracture extension pressure was less than 3.1MPa. It shows that the model established in this thesis is basically feasible for solving the hydraulic fracturing problem of C6 Reservoir. In the meantime, the reason for the difference may be due to the distribution problem of natural fractures. When the intervals among natural fractures are too big, they cannot represent the distribution of natural fractures in stratum. Further optimized natural fracture distribution can be used to improve the accuracy of the model.

4 FORM AND FORMATION CONDITION OF HORIZONTAL FRACTURE NETWORK OF C6 RESERVOIR HORIZONTAL WELL

4.1 Influence of crustal stress on fracturing extension of hydraulic fracture

With the decrease in horizontal stress difference, more and more fractures appeared, and thus formed more complex fractures. Meanwhile, when fractures near the shaft became more complex, the influence of horizontal stress difference on the surrounding stress field of natural fracturing stratum fractures became greater. After reducing crustal stress difference, natural shearing fractures turned their direction to the maximum principal stress direction and finite fractures appeared on the normal surface of fractures. It shows that if crustal stress difference is reduced, microseism effect will extend. Thus, crustal stress difference will increase and both hydraulic fracture length and width will increase, showing that greater crustal stress difference can help extend hydraulic fractures more. The influence that horizontal crustal stress difference has on the hydraulic fracturing of C6 Reservoir with natural fractures is far more than that on uniform formation hydraulic fractures. Increase in crustal stress difference will accelerate the uniform formation fractures turn their directions to the maximum horizontal principal stress direction, and thus can make the fracture surface smoother.

![Figure 2. Finite element model validation of hydraulic fracture of Z804-4 Well C6 reservoir.](image)

(a) $\Delta \sigma = 2\text{MPa}$
more complex, anisotropism will become stronger. In order to have the same remolding area, the required construction displacement shall be more. Large-scale hydraulic fracturing must be conducted for C6 Reservoir to have fractures in net form.

4.3 Influence of displacement on fracturing extension of hydraulic fracture

It can be known that more displacement can bring more thorough fracture remolding and bigger fracture network volume. From Figure 5, we can know that smaller displacement will lead to longer hydraulic fracture length and slightly smaller fracture width. When distribution of natural stratum fractures reaches certain degree, more construction displacement will be required for obtaining more remolding area. If we want to accomplish fractures in net form from C6 Reservoir, we must conduct large-scale hydraulic fracturing.

4.4 Influence of fracturing fluid viscosity on fracturing extension of hydraulic fracture

It can be known that lower viscosity can bring more thorough fracture remolding. From Figure 6, we can know that higher viscosity will lead to longer hydraulic fracture length and slightly bigger fracture width. When distribution of natural stratum fractures reaches certain degree, lower viscosity will be required for obtaining more remolding area. If we want to accomplish fractures in net form from C6 Reservoir, we must make viscosity of fracturing fluid lower and apply slick water fracturing.

4.5 Influence of natural fracturing inclination on fracturing extension of hydraulic fracture

According to the features of C6 Reservoir, natural fractures are mainly high-angle fractures and vertical fractures. Establish a multi-fracture fracturing extension model to consider natural fracturing inclination. The red parts shown in Figure 7 represent fractures and interfaces, including hydraulic fractures, natural...
fractures, and sand shale interface. The model is 32 meters long and 16 meter tall. 4m on the top and on the bottom are mudstone layers. 8m in the middle is sandstone section. The injection spot for fracturing fluid locates on the middle part of the model.

When all displacements were 12m³, stress difference was $\Delta \sigma = 2\text{MPa}$ and fracturing fluid viscosity was 0.01 Pa·s, the high-angle fractures shown in Figure 8 (b) didn’t crack. It can be seen that in the crustal stress model with C6 reverse fault and strike-slip fault crossing, the horizontal well will do staged fracturing. If complex fractures need to form, the main part of the natural fractures in the reservoir shall be high angle ones.
4.6 Influence of cluster interval stress disturbance on fracturing extension of hydraulic fracture

In order to simulate the disturbance between multiple fractures created by perforation cluster and the influence on hydraulic fracturing extension. A finite element model with fracturing extension of 30m, 40m and 50m cluster intervals was established. Large-displacement of 12m³/min and low-viscosity slick water of 0.01 Pa·s were applied to do dynamic multiple-fracture extension simulation. See Figure 9 for the stress disturbance results.
It can be seen from Figure 9 that: when interval between perforation clusters was 30m, fracturing disturbance was serious and stress reversal occurred. When interval between perforation clusters was 40m, fracturing disturbance was also serious and the maximum principal stress had stress reversal which is very beneficial for creating partial remolding volume around the principal fractures. Compared with 40m interval, 30m interval had stronger stress field disturbance. When interval between perforation clusters was 50m, fracturing disturbance was weaker compared to that of 30m and that of 40m. The stress disturbance was not obvious. Thus, smaller interval leads to more serious disturbance. Although it is good for creating complex fractures, it will also greatly limit the extension of middle fractures, leaving a counteraction. On the contrary, bigger interval leads to fewer disturbances. Each fracture will not leave any influence on each other which is not good for forming complex fractures. Therefore, cluster perforation shall be applied and the interval between perforation clusters shall be around 30m.

5 CONCLUSIONS

(1) Smaller crustal stress difference can make it easier for natural shearing fractures to turn their directions and form a complex horizontal fracturing network.

(2) Low-angle natural fractures are hard to crack. The existence of high-angle natural fractures and high-density fractures are more beneficial to form a complex horizontal fracturing network.

(3) Application of large-scale (higher than 12m³/min) and low-viscosity slick water fracturing fluid to conduct hydraulic fracturing construction is one of the keys to form a horizontal fracturing network for C6 Reservoir.

(4) Bigger cluster interval will lead to lower fracturing disturbance which goes against the mutual disturbance of fractures. Smaller cluster interval will lead to more serious disturbance. However, it may restrain the extension of fractures in the middle. Through simulation, we have reached a conclusion that cluster interval shall be around 30m to do horizontal fracture network fracturing for C6 Reservoir.

ACKNOWLEDGEMENT

This paper is sponsored by Scientific and Technological Research Program of Chongqing Municipal Education Commission (GN: KJ1501320).

REFERENCES


