Research on Horizontal Fracturing Crack Direction Change Mechanism of Shallow Layer Reservoir

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ABSTRACT: Yanchang Oil Field C6 Reservoir is a shallow-buried reservoir (500-600m) with natural fractures. During hydraulic fracturing, horizontal fractures are easy to form and direction turns frequently occur among hydraulic fractures. Thus, development of this shallow-buried reservoir is under great restriction. According to damage-fracture mechanics theory and based on continuous damage mechanics method, this thesis applied ABAQUS software cohesive unit to establish simulation model for the horizontal fracture propagation of C6 Reservoir. It simulated the propagation form of C6 Reservoir horizontal fracture and analyzed the induced stress field and mechanics diversion of horizontal fracture propagation. The findings of this numerical simulation include: when vertical stress was greater than the minimum horizontal principal stress. “T”-profile fractures will appear; otherwise, the fractures will mainly be horizontal fractures. The greatest induced stress was from the hydraulic fractures in the middle of the reservoir. With the increase in hydraulic fracture distance, induced stress would firstly increase and then decrease. The influence caused by the induced stress from fractures was within 10m.

Keywords: shallow-buried reservoir; horizontal fracture; diversion; induced stress

1 INTRODUCTION

As the C6 Reservoir in the east of Yanchang Oil Field is a three-low reservoir with low porosity, low permeation, and low pressure, it is in a gentle structure (dip angle is less than 1℃) and the rock strength is equal to or higher than medium level. The buried depth of the reservoir is 500–600 meters. Crustal stress locates in strike-slip and reserve fault pattern, leading to a complex hydraulic fracturing form of the reservoir. Hydraulic fracturing module of Abaqus was applied to simulate the propagation pattern of C6 Reservoir hydraulic fractures, so as to figure out the propagation mechanism and its geometrical morphology of the reservoir hydraulic fracturing.

Many commercial rock and soil mechanics computation software have been applied to simulate the propagation problem of hydraulic fracturing fractures. PFC Software takes loose rock particles as the objects of study. It is mainly used to simulate the fracturing and propagation problems of rock mass with joints, natural fractures, or anisotropy. U3DEC Software is mainly used to simulate rock mechanics problem of jointing stratum. When Nagel et. al (2012) applied UDEC discrete element model so simulate shale fracturing, shear failure occurred due to the fracturing network. [1]. HYFRANC3D can deal with interaction problems among complex fracturing shapes, continuity equation, nonlinear coupling of fluid equation inside fractures, structural deformation, hydraulic fractures, and other types of fractures (e.g. multiple fractures, natural fractures, etc.). Chun’an Tang et. al (2002) from Northeastern University of China compiled RFPA2D/3D which is an analysis software to study rock hydraulic fracturing process based on fluid, stress, and damage coupling model (FSD-Model). The software is also used to conduct simulation calculation.
on anisotropic hydraulic fracturing propagation problem [2]. The hydraulic fracturing module of Abaqus Software is based on damage fracturing mechanics theory and takes the damage model of cohesive unit to simulate the fracture initiation and propagation of hydraulic fracture. It can also simulate the flow and leak-off situation of fracturing fluid inside hydraulic fractures, dealing with the interaction problem between two hydraulic fractures in a better way. Chen et. al (2009) used cohesive pore pressure unit to simulate the fracture initiation and propagation problems of two-dimensional radial fractures. The simulation result was completely consistent with K-vertex analytical solution [3]. Yao et. al (2010) applied cohesive pore pressure unit to conduct numerical simulation on the hydraulic fracturing problem of plastic formation and found that results for plastic formation obtained from Abaqus were closer to analytic solution compared with those from P3D model or PKN model [4]. Guangming Zhang et. al (2010), Fangjun Biao et. al (2011) considered the influence of casing, cement sheath, micro-annulus, and perforation tunnel and applied three-dimensional cohesive pore pressure unit to study the hydraulic fracturing propagation mechanism of horizontal well and the influential factors of hydraulic fractures [5,6]. Suling Wang, Jun Zhu et. al (2011) applied three-dimensional cohesive unit to conduct numerical simulation study on hydraulic fracturing of open vertical well and sensitivity analysis on related influential factors [7,8]. Haiyan Zhu et. al (2013) applied cohesive unit to study the propagation process of micro-annulus during hydraulic fracturing [9]. Chengyong Peng et. al (2014) applied three-dimensional unit to conduct numerical simulation on the fracturing form of inclined shaft hydraulic fracture [10].

This thesis mainly used viscoelastic damage cohesive pore pressure unit of Abaqus Software to simulate the propagation problem during hydraulic fracturing process. It also studied geometric form and propagation mechanism of hydraulic fracture.

2 NUMERICAL SIMULATION RESEARCH ON HORIZONTAL FRACTURE PROPAGATION OF C6 RESERVOIR

2.1 Numerical model of horizontal fracture propagation

2.1.1 Model establishment

According to the layer-built characteristics of C6 Reservoir, establish two-dimensional plane strain finite element model shown as Figure 1. The model is 50m long and 16m tall. Mudstones in depth of 4m are on the top and on the bottom. The basement and the middle parts are sandstone formation. Shaft is in the middle part of the model. Place a perforation pore in the central spot of the shaft as the injection point for fracturing fluid. Apply vertical stress on y direction and stress the minimum horizontal principal stress on x direction. It can be known from the field outcrop of C6 Reservoir that natural fractures propagate in vertical direction in the sandstone reservoir. Density of natural fracture is 1-2m/strip and there is a distinct interface characteristic on the boundary of sandstone and mudstone. Therefore, place one horizontal natural fracture every 2m in sandstone reservoir. Place one interface fracture on the interface of sandstone and mudstone.
2.1.2 Constitutive model

Using the secondary stress crack criterion as the judgment of whether the hydraulic fracture crack initiate or not [11,12]:

\[
\left(\frac{t_n}{t_n^0}\right)^2 + \left(\frac{t_s}{t_s^0}\right)^2 + \left(\frac{t_t}{t_t^0}\right)^2 = 1
\]  

(1)

- \(t_n^0\): Tensile strength of cohesive elements;
- \(t_s^0, t_t^0\): The shear strength of two tangential directions;

Damage evolution model of cohesive elements:

\[
t_s = \begin{cases} (1-D)t_s, & T_s \geq 0 \\ \frac{T_s}{(1-D)}, & \text{when the stress on cohesive elements} > 0 \\ \end{cases}
\]

(2)

\(\bar{t}_n, \bar{t}_s, \bar{t}_t\): Stresses on the cohesive element in three dimensions, which is calculated in the stage of undamaged and the line elastic deformation.

In this paper, power law flow is used to express the flow in the cohesive elements:

\[
\tau = K'\dot{\gamma}^n'
\]

(3)

- \(\tau\): Tangential stress;
- \(\dot{\gamma}^n\): Tangential strain ratio;
- \(K'\): Consistency index;
- \(n'\): Power law exponent.

The leak-off through the upper and lower surfaces of the cohesive elements:

\[
\begin{align*}
q_t &= c_t(p_i - p_t) \\
q_b &= c_b(p_i - p_b)
\end{align*}
\]

(4)

- \(q_t, q_b\): The volume flow rate on the upper and lower surfaces;
- \(c_t, c_b\): The filtration coefficient on the upper and lower surfaces;
- \(p_i\): The fluid pressure inside the cohesive elements.

2.2 Fracture geometrical morphology during horizontal fracture propagation of C6 Reservoir

2.2.1 The difference between vertical principal stress and minimum horizontal principal stress is 3MPa

Although vertical stress was still greater than the minimum horizontal principal stress, vertical fractures occurred while vertical fractures occurred and propagated, forming a “T” fracture. See Figure 2, Figure 3, and Figure 4 for the fracture propagation state after applying fracturing treatment for 15 minutes. It can be seen from the model figures that all natural fractures started fracturing and propagating. As natural fractures on upper side had less crustal stress, natural fractures on upper side had the longest length. The length of natural fractures in the middle was the second longest. That of the natural fractures on the bottom was the shortest. Due to the influence of simultaneous propagation of multiple horizontal fractures, the width of fractures in the middle was the biggest while that of fractures on both sides was smaller. There were abnormal high spots among the intersection points of fractures due to horizontal fracturing and propagation of natural fractures.

Figure 2. Propagation tracks of hydraulic fractures and natural fractures.

Figure 3. Natural fracture propagation form.
2.2.2 The difference between vertical principal stress and the minimum horizontal principal stress is -6MPa.

As there was minor vertical stress, it was easy to have horizontal fractures. Within a short simulation time, hydraulic fractures didn’t propagate along a higher direction. They were mainly horizontal fractures. No vertical fracture was propagated which showed the same result with the simulation result of single horizontal natural fracture. After applying fracturing treatment for 15 minutes, the propagation state of natural fracture is shown in Figure 5, Figure 6 and Figure 7. It can be seen from the figures that natural fractures in the middle and on the upper side started fracturing and propagating. After injecting fracturing fluid, natural fractures in the middle had tensional fracturing and fracture width changed with length.

3 RESEARCH ON INDUCED STRESS AND MECHANICS DIVERSION MECHANISM OF HORIZONTAL FRACTURE PROPAGATION

Hydraulic fractures formed during fracturing transformation can change the distribution of original crustal stress field. Under different conditions, the influence can be in different degrees. Some fractures can...
cause 90° reversion in direction of the maximum/minimum horizontal principal stress.

Pitch points in different routes and on different locations were taken in interlayer. Stress analysis was conducted and we can see Figure 8 for the change law of induced stress with interlayer location. Selection of routes was divided into two directions: paralleling to fractures and vertical to fractures. When the route was paralleled to fracture, took pitch points from upside down. The interval was the vertical distance between the routes to the fracture. When the route was vertical to fracture, took pitch points from left to right which was from the fracture to the model boundary. The interval was the vertical distance between the route and the bottom of interlayer. Selection of routes for Interlayer 2 was done in the same manner.

Figure 9 shows the changes of induced stress along vertical distance on spots in different distances to the hydraulic fracture. In the middle of the reservoir, the induced stress could reach its maximum value (vertical distance: 4m) when width of hydraulic fracture was in the maximum level. When being close to the fracture tip, induced stress gradually decreased and became negative eventually due to the control of net pressure change inside the fracture.

Figure 10 shows the change of induced stress along horizontal distance on spots in different intervals parallel to the hydraulic fracture in Interlayer 2. As Interlayer 2 was above the fracture and had minor influence from deformation of fracture width direction. Frame stress decreased due to the control from pore pressure change, thus induced stress became negative. Moreover, the induced stress increased first and decreased later with along vertical distance. When vertical distance was longer than 3m, interval change had little influence on induced stress.

Figure 11 shows the change of induced stress along vertical distance on spots in different intervals parallel to hydraulic fracture in Interlayer 2. As Interlayer 2 was above the fracture and had minor influence from deformation of fracture width direction. Frame stress decreased due to the control from pore pressure change, thus induced stress became negative. Moreover, the induced stress increased first and decreased later with along vertical distance. When vertical distance was longer than 3m, interval change had little influence on induced stress.

Figure 12 shows the changes of induced stress along horizontal distance in different intervals of Interlayer 2. It can be seen that with increase in horizontal distance, induced stress in different intervals increased first and decreased later. When horizontal distance was shorter than 5m, the induced stress decreased with distance increase. When horizontal distance was longer than 5m, interval change had little influence on induced stress.
Figure 12. Changes of induced stress with horizontal distance variation and in different intervals on the horizontal direction of Interlayer 2.

4 CONCLUSIONS

(1) When vertical stress was greater than the minimum horizontal principal stress, horizontal fractures started fracturing while vertical ones had fracturing and propagating, forming fractures in “T” profile. Due to the influence from simultaneous propagation of multiple horizontal fractures, width of fractures in the middle was the biggest. When vertical stress was minor, hydraulic fractures were mainly horizontal fractures. Natural fractures in the middle and on the upper side started fracturing and propagating. Width of fractures in the middle changed with fracture length.

(2) In the middle of the reservoir, the induced stress could reach its maximum value when width of hydraulic fracture was in the maximum level. When being close to the fracture tip, induced stress gradually decreased and became negative eventually. The influence caused by the induced stress from fractures was within 10m. On direction paralleling to hydraulic fracture, induced stress increased first and decreased later with vertical distance. On direction vertical to hydraulic fracture, reduced stress increased first and decreased with increase in horizontal distance.

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