Casing Deformation Caused by Hydraulic Fracturing-Induced Fault Slip in Sichuan Basin and Optimization of Treatment Parameters

Rui Huang\textsuperscript{1,2}, Zhaowei Chen\textsuperscript{2*}, Bo Zeng\textsuperscript{3}, Yi Song\textsuperscript{3}, Xiaojin Zhou\textsuperscript{3}

\textsuperscript{1} China University of Petroleum (Beijing), Beijing, China
\textsuperscript{2} CNPC Engineering Technology R&D Company Limited, Beijing, China
\textsuperscript{3} PetroChina Southwest Oil & Gas Field Shale Gas Research Institute, Chengdu, China

*Corresponding author: chenzwdri@cnpc.com.cn

Abstract. Casing deformation is a key issue that restricts the efficient development of shale gas in the Sichuan Basin. In this study, the H pad of shale gas wells in this area is used to determine correlations among the casing deformation and ant-tracking faults, microseismic events, and treatment pressure. The results show that the deformation might have been caused by fault slip induced by hydraulic fracturing. Moreover, three-dimensional seismic and well log data are used to establish fracture and in situ stress models based on discrete fracture network and finite element methods, respectively. The relationship between treatment parameters and fault activation is established by hydraulic fracturing simulation, from which the parameter sensitivity is evaluated. The results show that when the fluid volume is reduced by 20\%, the length of the activated fault and the number of activated fractures decrease by 9\% and 23\%, respectively. In contrast, when the pumping rate is reduced by 20\%, these parameters decrease by 25\% and 38\%, respectively. These results indicate that reducing the pumping rate is more effective than reducing the fluid volume for mitigating fault activation. In summary, arranging the fracture stages adjacent to the fracture zones should reduce the pumping rate to some extent. This method can be used to mitigate fault activation during hydraulic fracturing, which in turn can prevent casing deformation.

1. Introduction
Located in the Sichuan Basin, the Changning–Weiyuan shale gas block is a Chinese
state-level shale gas demonstration area. Since 2009, horizontal well and hydraulic fracturing techniques used to develop shale gas in this block have caused casing deformation in more than 30% of these wells. This decreases the number of viable fracturing stages and reduces the overall life cycle of the well, which in turn severely restricts the efficient development of shale gas.

By evaluating substantial amounts of available field data, many researchers have concluded that casing deformation is primarily caused by fault activation induced by hydraulic fracturing\(^3-^3\). Zhang et al.\(^4\) used the discrete element method to simulate fault slip induced by hydraulic fracturing. Their simulation results demonstrated that a lower pumping rate and viscosity can effectively decrease the fault slip distance and help to mitigate casing deformation. Liu et al.\(^5\) put forward a semianalytical model to calculate the fault slip distance. Their results showed that a lower friction coefficient will increase the length of an activated fault and that the maximum fault slip distance occurs with a fault dip angle of 45°. Xi et al.\(^6\) established the relationships among microseism moment magnitude, slip distance, and reduction in casing inner diameter. Their results showed that the distance of a fault slip can be decreased by maintaining the distance between the designed horizontal segment of the well trajectory and the area of fracture development or by ensuring that the horizontal segment is parallel to the natural fracture. Although such research has provided many useful suggestions for mitigating casing deformation, it lacks sufficient field data analysis. Thus, it cannot be used to directly guide field practice.

To reasonably optimize the treatment parameters, we focus on the H pad of a shale gas development block to analyze the correlation between casing deformation and ant-tracking faults, microseismic events, and treatment pressure to conclude that the deformation might cause fault slip induced by hydraulic fracturing. Then, we establish a hydraulic fracturing numerical model of fault slip on the basis of geological data, and we verify the results against field fracturing data. Next, the model is used to analyze the fault activation sensitivity with different treatment parameters. Finally, on the basis of the analysis results, specific measures are suggested for mitigating the casing deformation.

2. Causal analysis of casing deformation in H pad wells

2.1. Casing deformation of H pad wells

Severe casing deformation has occurred during fracturing in three wells of the H pad in the shale gas development block of Sichuan Basin. The statistics of this deformation are shown in Table 1. Figure 1 shows a schematic diagram of the fracture stages, with the positions of casing deformation indicated by red circles. Of the 77 total fracture stages designed for the three wells of the platform, 19 were abandoned owing to casing deformation.

**Table 1. Statistics of casing deformation in H pad wells**

| Number | Well number | Resistance depth (m) | Resistance stage |
|--------|-------------|----------------------|------------------|
| 1      | H-1         | 4331                 | 5                |
| 2      | H-1         | 3839.7               | 12               |
| 3      | H-1         | 3772                 | 13               |
| 4      | H-1         | 3610                 | 16               |
5   H-1   3303   20
6   H-2   3667   14
7   H-2   3497.5  18
8   H-2   2925   30
9   H-3   3352   18
10  H-3   3195.1 22
11  H-3   3094   23
12  H-3   2615   32

Figure 1. Schematic diagram of the fracture stages

2.2. Correlation of casing deformation and ant-tracking faults
To explain the relationship between casing deformation and faults, the deformation is compared with ant-tracking faults. The faults interpreted by ant tracking are shown in Figure 2. The local geological conditions indicate the development of faults mainly with high dip angles and ENE strikes \(^7\). The faults interpreted by ant tracking are essentially consistent with these conditions. As shown in the figure, 12 casing deformation points are present, seven of which occur near the ant-tracking faults. Therefore, the casing deformation in most of these cases is related to faults.
2.3. Correlation of the casing deformation and microseismic events

To further explore the relationship between casing deformation and faults, the casing deformation was compared with microseismic events plotted in Figure 3. The sizes of the points representing these events reflect their magnitude. As shown in the figure, most of the microseismic events are large in magnitude, which indicates that the fracture size is also relatively large. Moreover, these events are distributed in an obviously linear pattern, which conforms to the characteristics of fault shear\cite{8}. Therefore, different small faults can be interpreted by microseismic events. The interpreted faults are represented by different colors in the figure. The faults interpreted by microseismic events are also essentially consistent with the local geological conditions\cite{7}. In addition, most of casing deformation has occurred near the intersections of small faults and the wellbore. Of the total 12 casing deformation points present in the H pad, nine occur near sliding faults; thus, most of the casing deformation in this case is related to fault slip.

Figure 2. Fault interpretation by ant tracking
2.4. *Correlation of casing deformation and treatment pressure*

Figure 4 shows the statistics of the treatment pressure of the H pad wells, where the fracture stages indicated by red circles represent the condition prior to encountering an obstacle during pumping. These stages likely activated the faults and caused casing deformation. As shown in the figure, the treatment pressure near the fracture stages causing casing deformation was relatively low, which indicates that fracture zones such as faults are activated by these stages\(^8\). Hence, the treatment pressure also reveals the mechanism of the casing deformation, with abnormally low pressure indicative of fault activation.

2.5. *Cause of casing deformation*
The correlation of casing deformation and ant-tracking faults, microseismic events, and treatment pressure shows that the deformation is likely caused by hydraulic fracturing-induced fault slip. In particular, the geological and engineering factors that cause casing deformation are faulting and fracturing, respectively.

3. Establishment and verification of hydraulic fracturing numerical model for fault slip

3.1. Fracture model

Three-dimensional seismic and well logs that included data on the orientation, size, and intensity of the fractures were used to establish the fracture model based on the discrete fracture network algorithm. The orientation of the faults was determined by ant tracking and microseismic events, whereas that of the natural fractures was determined by imaging logs. The fracture intensity was also determined by examining the imaging logs. Fracture trace analysis was performed to obtain the trace length slope for determining the size distribution of the fractures\(^9\). The fracture size range was constrained by the magnitude of microseismic events according to the focal mechanism theory\(^10\). The overall fracture model was composed of a fault model and a natural fracture model, as shown in Figures 5 and 6.

![Figure 5. Fault model](image1)

![Figure 6. Natural fracture model](image2)

3.2. In situ stress model

After establishing the discrete fracture model, the influence of discrete fractures on the geological grid properties must be determined\(^11\). Hence, the geomechanical properties of the grid need to be upscaled. The upscaling method is based on the crack tensor analysis reported by Oda\(^12\). By defining the stiffness of the discrete fractures, the mechanical properties of discontinuity are coupled to the continuous intact rock to obtain the mechanical properties of rock mass. Figure 7 shows that the elastic modulus of the rock mass of the H pad corresponding to the location with high fracture intensity (near faults) was relatively low. By considering the rock mass elastic modulus and the in situ stress along the wells as initial stress within the grid, the in situ stress field can be established by using the finite element method. According to the stress field model (Figure 8), the minimum and maximum horizontal stresses were approximately 50–62 MPa and 75–92 MPa, respectively, and the vertical stress was approximately 57–68 MPa. The stress field showed a strike-slip faulting stress regime. The azimuth of the maximum horizontal stress was approximately 109° N.
3.3. Hydraulic fracturing simulation and verification

The hydraulic fracturing simulated in the present study is based on Mohr–Coulomb criteria (Figure 9). The values of maximum and minimum horizontal stress in addition to the fracture orientation, fracture strength parameters, and pore pressure change were used to determine the mechanical state of the fracture. During the simulation, the fluid volume balance was always maintained, and the pumped fluid volume equated to the expanded volume of the natural fractures and the developed hydraulic fractures.

Figure 7. Elastic modulus of rock mass

Figure 8. Stress field model

Field fracturing data were used for the fracturing simulation. The fluid volume was approximately 1800 m³, and the pumping rate was approximately 13 m³/min for each stage. Figure 10 shows the activated faults after hydraulic fracturing of the H pad; most of the faults occurring near the casing deformation were activated during the fracturing.

Figure 9. Mechanical mechanism of hydraulic fracturing simulation
Figure 10. Faults activated after hydraulic fracturing

The simulation results were compared with the field data, which was used to adjust the model parameters and to verify the accuracy of the hydraulic fracturing simulation\textsuperscript{[13-14]}. Figure 11 shows a comparison of the simulated and field microseismic events of the 27th fracturing stage of Well H-2, where the green and red dots represent simulated results and field data, respectively, and the size of the dots represents the magnitude. Figure 12 compares the simulated and field treatment pressures of the 27th fracturing stage of Well H-2, where the blue and red lines represent the simulated results and field data, respectively.

Figure 11. Comparison of microseismic events
4. Sensitivity analysis of treatment parameters

4.1. Simulation with fluid volume changes
After the fracturing model was verified by field data, sensitivity analysis of the treatment parameters was conducted. Figure 13 shows the fault activation of the 27th fracturing stage of Well H-2, where the green and blue colors represent hydraulic fractures and activated faults, respectively. The pumping rate was unchanged, and the fluid volume was reduced. Specifically, a 5% reduction in fluid volume corresponded to activated fault lengths of 280, 278, 273, 265, and 255 m with 353, 337, 323, 295, and 270 activated fractures, respectively. These results indicate about a 24% decrease in activated fractures; the activated fault length decreased to a lesser extent, about 8%.

4.2. Simulation with pumping rate changes
Figure 14 also shows the fault activation of the 27th fracturing stage of Well H-2. The fluid volume was unchanged, and the pumping rate was reduced. Specifically, a 5% reduction in the pumping rate corresponded to activated fault lengths of 280, 275, 262, 245, and 209 m with 353, 346, 290, 250, and 217 activated fractures, respectively. These results indicate decreases in both the activated fault length and the number of activated fractures, at about 25% and 38%, respectively.

Figure 12. Surface treatment pressure over time

Figure 13. Fault activation according to fluid volume reduction
Figure 14. Fault activation according to pumping rate reduction

4.3. Simulation with pumping rate changes
The treatment parameter sensitivity for fault activation is shown in Figures 15 and 16, where the red and black lines represent the pumping rate and fluid volume, respectively. Reducing the pumping rate was more effective than reducing the fluid volume for decreases both the activated fault length and the number of activated fractures. Hence, we conclude that reducing the pumping rate is more useful than reducing the fluid volume to limit fault activation for mitigating casing deformation.

Figure 15. Sensitivity of the length of activated faults
Figure 16. Sensitivity of the number of activated fractures

4.4. Discussion
A reduction in the pumping rate corresponded to a decrease in the fluid pressure in fractures. The pressure in the fractures could not satisfy the activation conditions, which resulted in decreases in the lengths of activated faults and the number of activated fractures. Therefore, the pumping rate controlled the longest extension distance of activated fracturing to some extent.

The reduction in fluid volume corresponds to a decrease in the total volume of fracturing fluid pumping into the fracture. Because the pumping rate was unchanged, the pressure in the fracture still satisfied the activation conditions; thus, the length of the activated faulting remained essentially unchanged. The number of activated fractures decreased because insufficient fracturing fluid was available to expand the fractures. Thus, the fluid volume controlled the overall area of activated fracturing to some extent.

In summary, to prevent casing deformation, field engineers should take measures to reduce the pumping rate to mitigate the activation of faulting during hydraulic fracturing. This method is effective for preventing casing deformation. However, this research considers only whether the faulting activated by hydraulic fracturing intersects the wellbore. Therefore, further study is required, and the results need to be verified in the field.

5. Conclusion
(1) The correlation of casing deformation and ant-tracking faults, microseismic events, treating pressure show that hydraulic fracturing-induced fault slip can cause casing deformation. Faulting is the geological factor, and fracturing is the engineering factor.
(2) The simulation results show that when the fluid volume is reduced by 20%, the length of the activated fault and the number of activated fractures are decreased by 8% and 24%, respectively. In contrast, when the pumping rate is reduced by 20%, the length of the activated faulting and the number of activated fractures is decreased by 25% and 38%, respectively. Reducing the pumping rate is more effective than reducing the fluid volume for mitigating fault activation.
(3) It is suggested that arranging the fracturing stages to be adjacent to the fracture zones should reduce the pumping rate to mitigate fault activation. This method is also effective for preventing casing deformation.

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