Influence of formation activation induced by fracturing fluid on casing deformation during hydraulic fracturing operation in shale gas wells

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Abstract: Sichuan Basin in China is rich in shale gas resources and has great exploration and development capacity. It is the main area of shale gas exploration and production in China. The proved shale gas reserves discovered by Sinopec in Weirong area exceed 100 billion m3, and they play an important role in the development of shale gas in China. In Sichuan Basin, the use of traditional shale gas production methods such as multi-stage hydraulic fracturing is hampered by serious casing deformation. By December 2019, Sinopec performed hydraulic fracturing operations in 20 wells in this area, where casing deformation was encountered in 10 wells, resulting in an increase of up to 5.69% in the proportion of invalid fracture sections. In order to explain the mechanism of casing deformation during hydraulic fracturing, the geological structures of a shale gas production site in Sichuan Basin with frequent casing deformation were examined, and the geological reasons for this deformation were revealed. In addition, a geological model was established to calculate the influence of formation activation induced by fracturing fluid on the casing load, and formation activation during hydraulic fracturing was studied. The results reported in this paper are of great significance for optimizing hydraulic fracturing parameters and reducing the influence of formation activities on the casing of horizontal wells.

1. Introduction

With the development of unconventional gas reservoirs worldwide, breakthrough progress has been made in shale gas development in China. Since the large-scale exploration and development began in 2013, some problems have been observed in some shale gas wells. These problems include poor sealing integrity of the cement sheath and casing deformation, which is observed especially during fracturing stimulation in horizontal shale gas wells.
Casing damage causes failure of the stimulation operation. In the Weirong block of Sinopec, casing damage occurred in some shale gas wells, gravely affecting the fracturing effect and single-well production of these wells. The shale gas reservoir in Weirong block is deep and has the characteristics of high fracture pressure and high closure pressure in fracturing operation. Ultra-high pressure fracturing is necessary to realize a good stimulation effect. An overview of the positions of casing damage in a horizontal section of the wells in the Weirong block (Figure 1) shows that the damage mainly occurs from the middle of the fractured section to the bottom of the well; subsequently, fracturing tools in some wells are blocked, and they cannot enter these wells smoothly, thereby affecting the later fracturing operation.

**Figure 1.** Positions of casing damage in the horizontal section of the wells drilled in Weirong block in China

2. Geological structure

Weirong block is located in the southern margin of Weiyuan structural belt in the north of Southwest Sichuan Depression, which is located in the secondary structural unit of Sichuan Basin. The Leshan–Longnusi giant paleo uplift that formed in the Caledonian period persisted as an ancient slope in Southwest Sichuan before the Permian. The exploration area is located along the axis of this paleo uplift. The superimposed ancient Caledonian and Indosinian uplifts were further strengthened and reformed in the Yanshan Himalayan period, forming the present Weiyuan large-dome anticline structure. During the tectonic formation and evolution, the deformation intensity of the central Sichuan area was weaker than that of the surrounding Sichuan Basin, and the overall structural pattern was a large uplift and large depression. Weirong block is located in the region of the paleo uplift slope and sag, which is a syncline
stress concentration area. The basement uplift is high, and the basement fault activity easily affects the Silurian system (Figure 2).

![Figure 2. Geological structure of Weirong block](Image)

Weirong block is located in a geologically active area. During fracturing, when the fracturing fluid meets the natural fracture, it will preferentially pass through the natural fracture. Even after the fracture is pinched out, it is continued to make fractures in the surrounding formation. Because of the formation of a large number of fractures and the invasion of the fracturing fluid and sand, the rock around the well show certain plasticity after fracturing. In a geologically active area where natural fractures are developed, the strata show slip and dislocation in the direction of natural fractures because of the release of stress, resulting in serious shear deformation of the casing.

3. Mechanism of sliding of strata

In the process of fracturing, when the fracturing fluid enters the original fault, the increased fluid pressure in the fault causes the fault to slide under the action of shear stress. Hydraulic fracturing induces two types of formation activity—the microseismic events commonly caused by fracture propagation during fracturing and the activation of the natural fault, resulting in a low probability of strong earthquake events. In this second type of formation activity, the high-pressure fluid enters the nearby fault, resulting in a sudden rise in pore pressure, thereby disturbing the surrounding stress field and inducing fault slip. The resulting energy release is far greater than that of the first type of formation activity. Zhang Huali et al. (2018) proposed the formation mechanism of a fluid channel and applied it to the study of casing failure. It is believed that the fracturing fluid enters a fault through the dominant channel and activates the fault, resulting in casing deformation. Using field casing deformation data, the formation conditions of a wellbore channel and shale bedding channel were analyzed by applying the geomechanics theory and method to establish the aforementioned formation mechanism of fluid channels. The French research center and Zurich Federal Institute of Technology jointly analyzed the structural geology of a fault zone in southern France and provided research experience regarding the fault evolution law; in addition, they jointly developed a solid fluid coupling simulation platform for fractured rock mass geology to effectively simulate crack propagation, joint deformation, fault slip, etc.

The Mohr–Coulomb model is commonly used as the criterion for judging the shear slip of strata, as shown in Formula (1).
\[ \tau = 0.5(\sigma_1 - \sigma_3)\sin 2\beta \]
\[ \sigma_n = 0.5(\sigma_1 + \sigma_3) + 0.5(\sigma_1 - \sigma_3)\cos 2\beta \]
\[ \tau > c + f(\sigma_n - p_f) \]

where \( \sigma_n \) is the critical slip pressure of formation; \( P_f \), the fluid pressure in the fracture; \( \tau \), the friction between fracture surfaces; \( f \), the friction coefficient of the fracture surface; \( \sigma_1 \), the maximum in situ stress; \( \sigma_2 \), the vertical stresses; \( \sigma_3 \), the minimum in situ stress; and \( \theta \), the angle between the fracture surface and the minimum in situ stress.

The key step in the study of the casing deformation caused by natural fracture dislocation is the determination of formation slip. In order to study the slip of a fracture zone during fracturing, a finite element model was established to study the characteristics and laws of natural fracture slip for various in situ stress differences, fracture lengths, fracture dip angles, fluid pressures in the fracture, and formation properties. The deformation of the natural fracture surface and surrounding strata was quantitatively predicted, and the influence of various factors on formation shear slip in a strong tectonic background was analyzed.

The width of a natural fracture or a fault can be neglected in comparison to its length. Hence, a fault or natural fracture is modeled by using interface elements without thickness. In order to simplify the calculation, a two-dimensional plane strain model of the shear slip of natural fractures, as shown in Figure 3, was established to analyze the factors affecting the natural fracture slip. Since the fault in the study area belongs is a strike-slip fault and a reverse fault, the model was established considering the strike slip fault as an example. The overall model dimensions were 500 × 500 m. The parameters considered in the model were as follows: fracture length \( l \), the angle between the fracture and the minimum horizontal geostress \( \theta \), the friction coefficient of the fracture surface \( f \), the minimum in situ stress \( \sigma_0 \), the maximum in situ stress \( \sigma_H \), and the fluid pressure on the fracture surface \( P_f \). The friction of the joint surface satisfied the Coulomb friction criterion. The fluid pressure in the fracture was 70 MPa, and the geostress difference was 20 MPa. The fracture dip angle is 45 degrees, and the fracture length is 50 m. The calculation results are shown in Figure 4, 5, and 6.

**Figure 3.** Finite element calculation model of the stratum slip
Figure 4. Deformation before and after strata sliding

Figure 4 shows that when the fracturing fluid does not enter a natural fracture or fault, the stratum does not slip; in this case, only elastic deformation is produced. The maximum deformation perpendicular to the wellbore was 1.2 mm, but after the fracturing fluid entered the fault, the displacement was large, and the lateral deformation reached 19.4 mm.

Figure 5. Distribution of strata slip along fractures

Figure 6. Horizontal and circumferential displacement along the wellbore
Figure 5 and 6 show that the maximum sliding occurs at the center of the natural fracture surface, where the outward slip decreases faster than it does elsewhere. The maximum slip along the crack surface was 28.3 mm. The lateral displacement and axial displacement at the intersection of the shaft and the natural fracture were 17.8 mm and 22.3 mm, respectively, and the displacement decreased with increasing distance from the fracture. The local part of the casing intersecting the crack was simultaneously subjected to a shear load and tensile stress load.

The shear slip of the shale fracture or fault is affected by many factors such as the fracture length, the Young’s modulus and Poisson’s ratio of the rock, fluid pressure in the fracture, and friction coefficient of the shear plane.

Figure 7 shows that while the Poisson’s ratio has no obvious effect on the shear slip of fractures, the elastic modulus has a great influence on the slip. As the elastic modulus increases, the slip decreases exponentially; the maximum slip decreases from 130.3 mm to 13 mm, mainly because of the increase in the elastic modulus and the reduction in the elastic deformation of the formation.

Figure 7. Influence of stratum properties on slip

Figure 8 shows that the crack length and slip amount are positively correlated. The longer the crack, the greater is the slip. This relation is attributed to the size effect of shear slip. The size effect is observed in the case of deformation dislocation of the joint surface. With an increase in crack length, the slip constraint of the crack boundary on the midpoint decreases. In addition, the slip increases rapidly initially with increase in the fracture dip angle; after the dip angle exceeds 45 degrees, and the slip remains almost unchanged.
Figure 8. Influence of fracture parameters on slip

Figure 9 shows that under a differential stress of 35 MPa, the midpoint displacement of the natural fracture reaches 33.4 mm. In contrast, in the case of 10 MPa ground stress difference, the natural fracture dislocation is only 21.8 mm. The slip value and maximum lateral displacement of the crack are larger under a high stress difference than under a low stress difference.

Figure 9. Influence of in situ stress difference on slip

4. Conclusion

1. Large differences in ground stress and high construction pressure are the main controlling factors resulting in natural fracture or fault slip in Sichuan Basin.
2. Natural fracture or fault slip leads to increased deformation of the surrounding formation, which in turn leads to a sharp increase in the casing shear deformation and stress in this area.
3. The slip amount is mainly controlled by the fracture length, fracture angle, formation elastic modulus, and in situ stress difference. It is positively correlated with injected fluid pressure, fracture length, fracture angle, and ground stress difference and negatively correlated with the formation elastic modulus. The maximum shear displacement is observed along the center of the fracture surface.

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