Numerical investigation of casing shear deformation due to fracture/fault slip during hydraulic fracturing

Hu Meng1 | Hongkui Ge1 | Dengwei Fu2 | Xiaoqiong Wang1 | Yinghao Shen1 | Zhenxin Jiang2 | Jianbo Wang1

1 Unconventional Natural Gas Institute, China University of Petroleum, Beijing, China
2 PetroChina Xinjiang Oilfield Company, Karamay, China

Correspondence
Hongkui Ge, Unconventional Natural Gas Institute, China University of Petroleum, Beijing, 102249, China.
Email: gehongkui@163.com

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Abstract
The frequent occurrence of casing failure has significantly affected the development of shale gas in the Sichuan Basin. Based on engineering and geology analyses, natural fracture/fault slip leads to casing shear deformation during hydraulic fracturing. Hence, natural fracture/fault slip and casing-cement sheath-formation assembly finite element models were established to quantitatively examine the characteristics of natural fracture/fault slip and mechanisms of casing shear deformation. Many factors, such as formation elastic property, in situ stress, natural fracture/fault geometry property, fluid pressure, casing elastic property, cement sheath elastic property, and well trajectory, were considered. The simulated results were in good agreement with the field data. The results indicated that natural fracture/fault slip leads to a sharp increase in casing deformation and stress in the adjacent region. Furthermore, factor sensitivity analysis results showed that a higher fluid pressure, larger fracture length, larger fracture dip angle, higher in situ stress difference, lower formation Young’s modulus, and shorter distance from the wellbore to the center of the slip surface lead to severe casing stress and deformation. The countermeasures for preventing casing shear deformation involve decreasing the fracturing treatment pressure, reducing the crossing angle between the wellbore and natural fracture/fault, maintaining a safe distance from the wellbore to the large fracture/fault center, and adopting “balanced stress” fracturing operation. Hence, this study proposes a reasonable method to evaluate casing shear damage under hydraulic fracturing.

KEYWORDS
Casing shear deformation, hydraulic fracturing, natural fracture/fault, shale gas

1 INTRODUCTION

Casing deformation frequently occurs during the development of shale gas in the Sichuan Basin. This leads to the failure of downhole fracturing tools and thus they cannot operate normally, thereby seriously affecting the field fracturing operation. Furthermore, partial treatment stages with severe casing damage are abandoned. Based on statistics, casing deformation was observed in 38 wells out of 72 horizontal wells after hydraulic fracturing. Previous studies on casing deformation during fracturing considered cementing quality, high casing internal pressure, temperature load, and casing
The influence of in situ stress field redistribution and asymmetric treatment on casing deformation was calculated by estimating the spatial distribution of microseismic events as stimulated rock volume. Based on comprehensive analysis of field microseism, well logging, and lead model, the main casing damage mode corresponds to shear failure due to the formation slip that is reactivated in the process of fracturing fluid injection. As shown in Figure 1, Guo et al. noted that the casing failure rate near the natural fracture/fault was as high as 56.76%, which included 37 total natural fractures. Chen et al. conducted risk analysis on formation shear slip with 3D seismic data and a Mohr's circle. Liu et al. proposed a semi-analytical model to predict the slip distance of a partial open fault. However, there is no unified understanding of the casing failure mechanism during shale gas volume fracturing. It is important to draw attention to the fact that only some casings were damaged while others were intact near the natural fracture. The casing shear failure is closely related to the in situ stress, natural fracture property, formation property, injection fluid, and well trajectory wherein some of the factors act on the natural fracture/fault slip. Casing damage due to formation slip induced by water injection and reservoir compaction during oilfield production has been extensively studied. However, extant studies on hydraulic fracturing induced formation slip mainly focused on the mechanism of hydraulic fracturing induced microseism. A few studies examined the effect of different formation slip distances on casing deformation via qualitative methods. Chen et al. used focal mechanism theory to calculate the slip distance due to different microseismic magnitudes during hydraulic fracturing, and thereby ignoring the elastic deformation and slip orientation. Yin et al. studied the casing mechanical behavior due to formation slip by setting different slip distances. However, this method lacks a theoretical basis for determining the slip distance. Dong et al. evaluated the probability of natural fracture slip based on the Mohr-Coulomb criterion. However, they did not consider the mechanical behavior after formation slip.

Previous studies on casing damage due to natural fracture slip lack quantitative analysis. The studies perform postevent analysis characterized by qualitative analysis of field lead impressions, multi-arm caliper measurements, and microseismic data. Hence, generally there are three drawbacks as follows: (a) Based on the premise of equal deformation of natural fracture intersecting with the wellbore, the difference in formation deformation near the natural fracture was neglected without considering the elasticity of formation. (b) Qualitative analysis on casing damage due to formation slip was conducted by artificially setting the slip distance without quantitative calculation of the actual slip distance, and thus, the casing shear deformation was not assessed reasonably under actual conditions. (c) Factors, such as the change in the in situ stress after fracturing and the property of natural fracture, were not considered in assessing the slip distance. Hence, the effect of multiple factors on formation slip and casing stress was ignored. Thus, there is a need for deep understanding of the mechanism of casing failure due to formation slip.

Determining the slip distance of formation is key to calculating the casing stress and deformation. To ensure accurate calculation, a sequential coupled method was proposed. In this study, the mechanism and potential of formation slip were investigated. Secondly, natural fracture slip model and casing-cement sheath-formation assembly model were established to examine the interactions between formation slip and casing deformation.
casing shear damage. The slip distance of natural fracture was quantitatively predicted via natural fracture slip model. Subsequently, shear deformation and stress of casing were accurately calculated through casing-cement sheath-formation assembly model. The influence of formation slip on the casing shear deformation was analyzed via a combination of the aforementioned two models. Furthermore, the factors affecting the formation slip distance, casing stress, and deformation were systematically researched. The factors also included the formation elastic property, in situ stress, natural fracture geometry property, fluid pressure, well trajectory, casing elastic property, and cement sheath elastic property. Finally, the key factors affecting casing shear failure were identified and countermeasures were proposed.

2 | REASONS FOR NATURAL FRACTURE SLIP AND CASING FAILURE

The casing damage problem is significantly more prominent in China’s shale gas wells when compared to those of the United States. This is due to the development of natural fractures. Based on the interpretation of seismic data, natural fractures develop around the horizontal well while some horizontal wells even cross natural fractures. The casing deformation points highly coincide with natural fractures/faults, as shown in Figure 2.

As per statistics, the deformation position is at a certain distance from the nearest fracturing treatment stage. Therefore, a fluid flow channel exists between the casing damage point and fracturing fluid injection point or a stress disturbance occurs near the casing damage point. Hydraulic fractures propagate and connect with natural fractures to form a complex fracture network, which can be used as a flow channel for the fluid. Additionally, fractures along the borehole axis are expected to form in multistage volume fracturing, and a micro-annulus can be created at the second interface of the cement sheath in case of poor cement quality. The injected fracturing fluid enters the natural fractures along the aforementioned flow channel. This leads to an increase in the fracture surface pressure, a decrease in the normal stress, and a decrease in the friction strength. The natural fracture in equilibrium is activated and slides as soon as the shear stress exceeds the friction strength. The phenomenon of fracture slip induced by hydraulic fracturing was confirmed via microseismic monitoring. The Mohr-Coulomb (MC) criterion is often used to calculate the critical pressure of the formation slip along a natural fracture, as shown in Equation (1). The fracture slides when the pore pressure in the natural fracture exceeds \( P_i \). Coulomb’s law is generally used to describe the friction motion between two slip surfaces, as shown in Equation (2).

\[
P_i = \sigma_3 + (\sigma_1 - \sigma_3)(\cos^2 \theta - \frac{\sin \theta \cos \theta}{f})
\]

\[
\tau = (\sigma_1 - (\sigma_1 - \sigma_3)\cos^2 \theta - P_c)f
\]

\[
\tau > C + f_n(\sigma_n - p_p)
\]

where \( P_i \) denotes the critical slip pressure (MPa) (the minimum pore pressure in fracture/fault that induces the formation slip), \( P_c \) denotes the fluid pressure in the fracture (MPa), \( \tau \) denotes the friction stress (MPa), \( f \) denotes the friction coefficient of the fracture surface, \( \sigma_1 \) denotes the maximum horizontal stress (MPa), \( \sigma_3 \) denotes the minimum horizontal stress (MPa), and \( f_n \) denotes the friction coefficient of the fracture surface.

**Figure 2** Ant-tracking plot and casing deformation points (the black areas mark natural fractures and the red circles represent casing deformation points)
stress (MPa), and \( \theta \) denotes the dip angle between the fracture surface and minimum horizontal stress \( (\circ) \).

Based on the treatment parameters, \( P_c = 80 \text{ MPa}, \sigma_1 = 75 \text{ MPa}, \sigma_3 = 54 \text{ MPa}, \) and \( f = 0.6 \). The critical slip pressure is shown in Figure 3. The minimum critical slip pressure is 58.7 MPa with a dip angle of \( \theta = 55^\circ \). This indicates that when the dip angle exceeds 17.5\(^\circ\), the natural fracture slips with a fluid pressure \( P_c \) of 80 MPa. The high fluid pressure and in situ stress difference are the important driving factors of fracture slip in the Sichuan Basin.

If the casing’s minimum inner diameter after deformation is larger than the maximum outer diameter of the downhole tools, then the hydraulic fracturing operation can be implemented normally. Therefore, the effective inner diameter of the casing should be considered in the casing failure criterion. When the natural fracture slips, the amount of formation deformation is different near the natural fracture, and the relative positions of the wellbore and fracture result in different shear deformation values of the casing. Additionally, the slip distance and degree of casing shear deformation are affected by many influencing factors, as shown in Figure 4. Casing shear deformation is under the influence of a combination of these factors, and this leads to casing damage near partial natural fractures during hydraulic fracturing.

**FIGURE 3** Critical slip pressure of natural fracture

**FIGURE 4** Influence factors of casing shear deformation

**FIGURE 5** Model of natural fracture/fault slip and casing-cement sheath-formation assemble

(A) Model of natural fracture/fault slip  (B) Model of casing-cement sheath-formation assembly
3 | **CALCULATION MODEL**

3.1 | **Natural fracture/fault slip model**

The width of the natural fracture/fault is negligible when compared to its length. Hence, a thickness-free interface element was used to model the fault/natural fracture.\(^{35,36}\) The dynamic effect of a fracture/fault is ignored, and thus quasi-static analysis is adopted.\(^ {37}\) To simplify the calculation, a two-dimensional plane strain model for the shear slip of a natural fracture was established to stimulate formation slip, as shown in Figure 5A. To eliminate the influence of boundary on stress, the overall size of the model was set to 500 m × 500 m (it varies with different fracture lengths). The Coulomb friction was set between the two fracture surfaces. The outer boundaries of the model were restricted. In situ stress was applied via the predefined field method, and fluid pressure was added to the fracture surface.

3.2 | **Model of casing-cement sheath-formation assembly**

A three-dimensional model of the casing-cement sheath-formation assembly was established to simulate the casing shear deformation during formation slip, as shown in Figure 5B. The size of the model was set to 3 m × 3 m × 10 m, which was large enough to avoid the boundary effect of the wellbore. The model was separated into a fixed body and sliding body based on fracture. The friction contact was set between two fracture surfaces, and a displacement load was applied to the sliding body to move the formation along the fracture. A full displacement constraint was imposed on the outer boundaries of the fixed body, and a displacement load was applied on the outer boundaries of the sliding body along the sliding direction with a full displacement constraint in other directions. In situ stress was also applied via the predefined field method, and fluid pressure was added to the inner wall of the casing.

3.3 | **Parameter setting and calculation procedure**

The elastic constitutive model was applied for the formation/cement sheath and bilinear constitutive model for casing. The fluid friction in the fracture was ignored, and the fluid pressure in the fracture was set equal to the pressure in the casing. The aforementioned models were resolved in the finite element software, Abaqus. First, the displacement of the fracture was calculated via the slip model Figure 5A. Subsequently, the displacement load was transferred to the boundary of the assembly model Figure 5B to analyze the mechanical behavior of the casing. The slip model was meshed with CPE4R element by using the free mesh technique, and the local grid refinement was set around the fracture owing to the large deformation. The C3D8R element was selected to discretize the assembly model with the structured mesh technique, and thus the mesh seed was denser along the radial direction. The mesh quality was verified via a mesh check tool and by increasing the mesh number.

4 | **RESULTS AND ANALYSIS**

4.1 | **Calculation results**

We obtained the calculation parameters from the field data of a well. The formation was in a strike-slip faulting environment, where the maximum horizontal (\(\sigma_H\)), minimum horizontal (\(\sigma_h\)), and vertical stress were 82 MPa, 57 MPa, and 55 MPa, respectively. The internal pressure of the casing was 70 MPa. The length, dip angle, and friction coefficient of the natural fracture were 50 m, 45°, and 0.6, respectively. The axis of the wellbore traversed the natural fracture center. The material geometry and mechanical parameters are presented in Table 1. The total elements of the slip model and assembly model were 39,654 and 31,536, respectively.

The critical slip pressure of the fracture was 46 MPa, and the fracture was activated under an injection pressure of 70 MPa. Figure 6 shows the distribution of the y-direction displacement around the fracture. The positive and negative displacements denote the relative motion of the two fracture surfaces. The natural fracture did not slip before the fracturing fluid entered, and the maximum displacement was 1.2 mm owing to the elastic deformation of the formation. However, the maximum displacement of the natural fracture corresponded to 19.4 mm after the fracturing fluid entered. To investigate the deformation

| **Table 1** Geometry and mechanical parameters of casing/cement sheath/formation |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Material**    | **Inner diameter (mm)** | **Outer diameter (mm)** | **Young’s modulus (GPa)** | **Poisson’s ratio** | **Yield strength (MPa)** | **Tangent modulus (MPa)** |
| Formation       | 215.9            | –                | 22              | 0.23            | –              | –                |
| Cement sheath   | 139.7            | 215.9           | 10              | 0.17            | –              | –                |
| Casing          | 114.3            | 139.7           | 210             | 0.3             | 758            | 2000             |
at different positions, the displacement after slipping was extracted along the natural fracture and wellbore axis, respectively, as shown in Figure 7A,B. The slip distance at the center of the natural fracture was the highest and corresponded to 28.3 mm. The slip distance rapidly decreased outward along the center of the natural fracture surface. The transverse displacement and axial displacement at the intersection of the wellbore and natural fractures rose to 17.8 mm and 22.3 mm, respectively, and the displacement gradually decreased from the intersection. The casing was subjected to both shear and tension stresses, and the forces on the casing were complex.

The stress and deformation of the casing due to formation slip are shown in Figures 8 and 9. The Mises stress and transverse displacement of the casing along the wellbore were identical before slipping. However, after slipping, the stress and deformation of the casing near the fracture increased sharply because of formation squeezing. The casing maximum stress rose from 123 MPa to 822 MPa, and thus the casing yielded. The maximum transverse displacement sharply increased from 0.092 mm to 17.3 mm, and the maximum transverse displacement of the casing was almost equal to the transverse displacement of the formation at this point. This was due to the negligible cross section of the casing relative to the slip formation. Furthermore, the position of the casing maximum transverse displacement was at a certain distance from the slip surface. The casing deformation due to formation slip was concentrated near the fracture, and the transverse displacement and stress of the casing far from the fracture surface remained stable. The shape of the deformation casing was S-shaped (Figure 8).
and displayed the same characteristics as the field multi-arm caliper measurement (Figure 1).

4.2 | Factor sensitivity analysis

Many factors, such as the casing, cement sheath, formation, natural fracture, and fracturing operation exhibited significant impact on the casing shear deformation. Therefore, a sensitivity analysis of these factors was performed to clarify the crucial parameters, and the countermeasures were put forward. Other parameters remained unaltered throughout the sensitivity analysis and were identical to that in section 4.1.

4.2.1 | Formation

To investigate the influence of the formation properties on the mechanical behavior of the casing during formation slip, the Young's modulus was set to 5, 10, 20, 30, 40, and 50 GPa, besides, Poisson's ratio was set to 0.1, 0.2, and 0.3.

The effect of Young's modulus and Poisson's ratio on the slip distance of the fracture center is shown in Figure 10. The slip distance decreased exponentially from 130.3 mm to 13 mm due to the reduction in elastic deformation as Young's modulus varied from 5 GPa to 50 GPa. The casing maximum transverse displacement and Mises stress under different formation properties are shown in Figure 11. Increases
in Young's modulus substantially decreased the stress and displacement. The maximum transverse displacement decreased from 92.4 mm to 9.2 mm, and the maximum Mises stress decreased from 1083 MPa to 795 MPa. Poisson's ratio showed slight influence on the stress and displacement of the casing. The results of this study differed from those of previous studies. In previous studies, the stress and deformation of the casing increased with the addition of formation Young's modulus because the influence of formation properties on slip distance was not considered based on the assumption of equal slip distance. Therefore, it is important to focus on formation with low Young's modulus.

4.2.2 | In situ stress

The in situ stress field is redistributed during hydraulic fracturing because of induced stress. The change in the in situ stress is related to the reservoir property, natural fracture distribution, and fracturing operation parameter. In this study, we did not conduct research on this topic in detail. Hence, the minimum horizontal in situ stress was assumed as constant, and thus stress differences of 10, 15, 20, 25, 30, and 35 MPa were chosen to simulate the redistribution of in situ stress. The critical slip pressure, slip distance of the fracture center, casing maximum Mises stress, and transverse displacement under different stress difference values are shown in Figure 12.

Given a stress difference of 35 MPa, the natural fracture is activated at a fluid pressure of 43.3 MPa, and the slip distance of the fracture center easily reaches 33.4 mm. As the stress difference increases, the slip distance of the natural fracture center also increases. The casing maximum Mises stress exhibits the same trend as the maximum transverse displacement. With the increase in the stress difference, the maximum Mises stress increases gradually in the early stage and sharply in the later stage. Based on statistics, the horizontal stress difference of the Chaising-Weiyan shale gas reservoir (approximately 20 MPa) was remarkably higher than that of the American shale gas reservoir (approximately 2 MPa). Extremely high stress difference values can easily lead to casing shear failure and significant casing shrinkage. With respect to areas with high stress difference values, implementation of the balanced stress fracturing operation is recommended. This operation utilizes the induced stress generated during volume fracturing to reduce the stress difference by adjusting the engineering parameters to obtain a balanced stress field based on the reservoir property.

4.2.3 | Nature fracture/fault

The fracture length and dip angle exhibited an impact on the formation slip and casing stress. The length was set to 10, 30, 50, 70, and 100 m, and the dip angle was set to 30°, 45°, 60°, 75°, and 85°. Figures 13-15 show the slip distance of the fracture center, casing maximum Mises stress, and transverse displacement under different conditions.

Increases in the fracture length increase the slip distance of the fracture center, as shown in Figure 13. When the fracture length is 100 m, the maximum slip distance is 58.7 mm. This is due to the decrease in the slip boundary constraint at the center of the fracture with improvements in the length of the fracture. Additionally, when the dip angle varies from 30° to 85°, the slip distance increases in the early stage and then slightly varies after 45°. As shown in Figure 14, when the fracture length exceeds a specific value,
the casing is in the plastic deformation stage and the stress of the casing demonstrates a slight change after 45°. The casing maximum transverse displacement increases continuously with increases in fracture length and dig angle, as shown in Figure 15. Therefore, the trajectory of the horizontal well should not cross large scale and large dip angle fractures. Furthermore, the friction coefficients of fracture that were chosen to stimulate corresponded to 0.4, 0.5, and 0.6. The friction coefficients exhibited slight effect on the slip distance, casing maximum Mises stress, and transverse displacement.

4.2.4 Fluid pressure

The fluid pressure in the fracture was set to 50, 60, 70, 80, and 90 MPa. Figure 16 shows the slip distance along the slip surface. The slip distance increases as the fluid pressure increases from 50 MPa to 90 MPa. Figure 17 shows the casing maximum Mises stress and transverse displacement. The shear deformation of the casing increases significantly and casing transverse displacement increases from 3.7 mm at 50 MPa to 37.3 mm at 90 MPa. Additionally, as the casing exhibits plastic deformation after the initial elastic deformation, the casing maximum Mises stress increases from 301 MPa to 981 MPa. The formation slip is obviously affected by the injection fluid pressure because as the fluid pressure becomes significantly high in the fracture, the normal stress and friction on the fracture surface become low. Therefore, the casing deformation due to formation slip can be reduced by lowering the flow rate, increasing the fluid viscosity, and adopting multiple injection fracturing to decrease the fluid pressure.

4.2.5 Casing

The casing wall thickness and steel grade can be increased to prevent casing damage as per conventional means. The thickness of the casing was set to 10, 12, 14, 16, and 18 mm. The casing maximum Mises stress and transverse displacement under different casing wall thickness values are shown in Figure 18. An increase in the wall thickness value exhibited a lower variation in casing deformation, and the transverse displacement was maintained at 20 mm. The stress of the casing decreased slightly as the casing wall thickness varied from 10 mm to 18 mm. However, it remained in the plastic deformation stage. Increases in the wall thickness cannot resist the formation shear slip. The higher steel grade of the casing can be used to prevent the casing from premature plastic damage, and the lower wall thickness value can result in the passability of the downhole tools. However, both have slight
effect on casing damage due to formation slip. Field practice shows that increasing steel grade from P110 to TP125 and wall thickness from 12.7 mm to 15.2 mm are still not practical methods in solving casing shear deformation.10,12

4.2.6 | Cement sheath

Young’s modulus of the cement sheath is an important parameter that affects the integrity of the well. Young’s modulus was set to 0.1, 1, 5, 10, 15, 20, 30, 35, and 40 GPa. Figure 19 shows the effect of Young’s modulus on the casing maximum Mises stress and transverse displacement. The casing maximum Mises stress initially increases and then decreases as the modulus varies from 0.1 GPa to 40 GPa. The casing maximum Mises stress changes from 793 MPa to 843 MPa, and the casing maximum transverse displacement almost remains constant. Additionally, Poisson’s ratios of 0.1, 0.2, 0.3, and 0.4 were selected for simulation. The results indicated that Poisson’s ratio exhibits slight effect on the stress and deformation of the casing. Therefore, it is not useful to change the mechanical properties of the cement sheath for casing shear deformation. Hence, noncementing operation should be adopted in the vulnerable area of the casing due to formation slip.40

4.2.7 | Well trajectory

The case where the well trajectory crosses the fracture center was discussed in the previous section. The casing deformation at different distances from the fracture center is examined below. A 100-m long fracture was considered as an example while other parameters remained constant. The distribution of formation deformation around the fracture is shown in Figure 20. The transverse displacement of formation varies at different distances from the center of the slip surface, and the maximum transverse displacement is 38.8 mm. Overall, the casing deformation decreases as the distance from the wellbore to the fracture center increases. To ensure an effective inner diameter of the casing, a critical wellbore safe distance exists under the premise of allowing a certain amount of casing deformation. When the wellbore vertical distance from the center of the fracture is less than the critical wellbore safety distance, the casing failure occurs. The critical wellbore safety distance in this study is 43 m, which is based on the standard of 20-mm diameter reduction. Based on the discussions in section 4.2.3, as the fracture length and dip angle increase, the casing shear deformation at the same distance as that from the slip surface center becomes more severe. Hence, higher wellbore safety distance is required to ensure casing safety. The formation slip model established in this

FIGURE 14 | Effect of fracture dip angle and length on casing maximum Mises stress

FIGURE 15 | Effect of fracture dip angle and length on casing maximum transverse displacement

FIGURE 16 | Effect of fluid pressure on slip distance
study can be used to predict the slip distance of natural fractures based on the fracture parameters interpreted from the seismic data. Hence, reasonable safe distance and well trajectory are designed to prevent high casing shear deformation.

5 | CASE STUDY

During hydraulic fracturing in the W201-H well, the TP95S casing deformed at 2331.5. The bridge plug with Φ114 mm and Φ108 mm grinding shoe was blocked. However, the grinding shoe with Φ105 mm could pass normally. The inner diameter of the casing was 121.36 mm, and the transverse displacement of the casing was 13.36 mm and 16.36 mm. The well trajectory was along the direction of minimum horizontal principal stress. Microseismic data indicated that the angle between the extended direction of microseismic events and well trajectory direction was 45°. Additionally, the microseismic events were significantly strong. This indicated that the natural fracture/fault was activated and slipped, as shown in Figure 21. The length of the fracture was approximately 400 m, and the casing deformation point was 100 m from the center of the fracture. The maximum horizontal, minimum horizontal, and vertical stresses were 48 MPa, 29 MPa, and 35 MPa, respectively. Young's modulus and Poisson's ratio of formation were 22 GPa and 0.25, respectively. The fluid pressure in the fracture was 47 MPa. The maximum casing transverse displacement can be predicted by the method.
established in this study, which is 17.07 mm, as shown in Figure 22. The deviation between the calculated results and actual values was low, which proves the reliability of this method.

6 | CONCLUSIONS

To examine the casing shear deformation due to natural fracture/fault slip, a two-dimensional finite element slip model was established to quantitatively predict the slip distance of a natural fracture/fault. Based on this, the casing-cement sheath-formation assembly model was established to study the casing mechanics behavior. Factor sensitivity analysis was conducted to investigate the effect of various factors, such as formation elastic property, in situ stress, natural fracture geometry property, fluid pressure, well trajectory, casing elastic property, and cement sheath elastic property, on formation slip distance and casing shear damage. The main conclusions are as follows:

1. The formation slip is induced by the pore pressure elevation of the natural fracture/fault and the high in situ stress difference in the Sichuan Basin. Natural fracture/fault slip causes an increase in formation deformation, which leads to a sharp increase in the casing shear deformation and stress in the adjacent area.

2. The magnitude of the casing stress and deformation are positively related to the injection fluid pressure, fracture
FIGURE 22  Contour diagram of casing transverse displacement

length, fracture dip angle, and in situ stress difference while they are negatively related to the formation Young's modulus and distance from the wellbore to the center of fracture.

3. Optimal results for preventing casing shear deformation cannot be obtained by increasing the casing grade and wall thickness or reducing Young's modulus of the cement sheath. Hence, it is effective to prevent casing shear failure during hydraulic fracturing by lowering fracturing pressure, reducing the crossing angle between the wellbore and natural fracture/fault, keeping away from the center of large faults/nature fractures, and adopting “balanced stress” fracturing operation.

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CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

ORCID
Hu Meng https://orcid.org/0000-0002-0560-8408

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