INTRODUCTION

Large-scale hydraulic fracturing is an essential technical method to achieve effective shale oil and gas development. The complex interaction mechanism between HF and NF needs to be considered in the hydraulic fracturing of shale reservoirs. However, there are a large number of NF, faults, and bedding planes developed in the shale, and the presence of these surfaces of discontinuity significantly affects the geometry of the HF. At the same time, the injection of high-pressure fluids and the propagation of HF may cause a shear slip in NF that are in a critical stress state. Therefore, the study of the relationship between hydraulic and natural fracture...
interaction is critical. Many theoretical studies have established guidelines for determining the interaction between HF and NF. However, these criteria assume that the stress state of NF is not affected by the propagation of HF. Some experiments on hydraulic fracturing under prefractured conditions in rock samples have been conducted to understand HF/NF interactions better. These experimental results demonstrated that in-situ stress, HF approach angle, and NF properties are the essential factors affecting HF propagation characteristics.

A system of research on the effect of NF on HF propagation has been developed. However, fewer studies consider the combined effects of high-pressure fluid injection and HF propagation on the mechanical characteristics of NF, especially in the aspect of shear slip occurring in NF during fracturing. Almakari et al. conducted a series of injection fluid-induced NF shear experiments under triaxial conditions and found that fluid injection could activate NF by shear slip, which in turn caused an increase in fracture permeability. Ye and Ghassemi conducted a number of injection-induced shear tests on shale fractures with various roughness and mineralogy composition to probe the coupled hydromechanical properties and permeability evolution during shear reservoir stimulation. Bijay et al. found that fracture plane roughness is an essential factor affecting shear fracture permeability through injection-induced shear experiments, and shear slip of rough fractures can permanently increase fracture permeability. Kim et al. conducted the hydroshearing characters of rough fracture surfaces by triaxial compression test pairs and compared the experimental results with the numerical simulations. Sheng et al. reported triaxial injection shear tests on cylindrical granite samples containing inclined and embedded fractures, and found that a slip evolution of injection-induced shearing includes three visible stages that are static friction, slip weakening, and slowly stick-slip friction. These experiments all investigate the shear-slip behavior of NF under the action of injected fluids, but all simplify the effect of HF propagation on natural fractures. Hu and Ghassemi first carried out a natural fracture shear-slip experiment under the simultaneous influence of injected fluid and HF, and studied the mechanical response mechanism of the natural fracture during hydraulic fracturing. They found that significant shear slip occurred in the natural fracture during the HF approach, and the degree of shear slip varied with the change of NF approach angle and friction angle. Although there were numerous works on the study of injection fluid-induced NF shear-slip mechanism, the root causes of the NF mechanical response mechanism and its influencing factors during HF approximation are not fully explained. The details of shear slip in NF during hydraulic fracturing need to be further investigated.

Therefore, experimental studies about the shear-slip characteristics of NF in shale were conducted in our work. This work presents a more realistic hydraulic fracturing experiment under triaxial conditions, focusing on the NF shear-slip characteristics under the combined effect of high-pressure fluid and HF propagation. A 20 mm depth injection hole was drilled in the upper end of the sample, and 7% KCl solution was injected into the injection holes to create a HF propagation in the direction of the deviator stress. In addition, the effects of in-situ stress and NF properties on the results are considered in the experiments. The injection pressure and sample deformation data were recorded to characterize the natural fracture mechanical response mechanism during the fracturing process. The hydraulic fracture approach angle was controlled by cutting the specimens at an angle to the axis, and the roughness of the fracture surface was varied by grinding with different grades of emery.

2 | EXPERIMENTAL METHOD

2.1 | Experimental principles and design

The injection of high-pressure fluids during the fracturing process induces the initiation and propagation of HF. And these HF will inevitably interact with the NF present in the shale reservoir during propagation. This will cause the injected fluid to enter the NF through the HF, resulting in a change in the stress state on the NF plane. With the further fluid injection, the pressure acting on the NF plane gradually increases, the effective normal stress on the NF plane gradually decreases. As shown in Figure 1, the reduction of the effective normal stress on a NF causes its molar stress circle to shift continuously to the left. The NF will shear failure when the molar stress circle intersects with the NF shear failure envelope.
Some unique treatments have been applied to the experimental samples to simulate the actual stress state and NF properties of the shale reservoir more realistically. As shown in Figure 2, a 20 mm deep water injection hole was drilled at the top end of the sample. A 7% KCl solution was injected into the pre-drilled hole to create a propagation of the HF along the direction of the deviator stress. The hydraulic fracture approach angle is controlled by changing the angle between the sawing direction and the core axis. The roughness of the fracture surface is changed by sanding the sawn surface with different grades of emery grinding plates.

### 2.2 Sample preparation

The experimental samples were taken from the shale outcrop of the Chang 7 section of the Yanchang Formation in the Ordos Basin (Figure 3A), and their underlying mechanical properties parameters are shown in Table 1. Firstly, the shale outcrop gained from the site was processed into a standard core of φ50 × 100 mm by a deep hole drilling machine and core cutter (Figure 3B,C). The cores were drilled parallel to the bedding to control the effect of the bedding on the experimental results. An 8 mm drill bit was used to drill a 20-mm deep water injection hole in one end face of the core, which provided a channel for fluid injection and reduced the difficulty of HF initiation (Figure 3D). The samples were cut in half by a cutting disk along the axes at 30°, 45°, 60°, and 75°, respectively, to form different hydraulic fracture approach angles (Figure 3E). The cut surface was polished by an emery polishing plate with grit sizes of # 40 grits (420 μm), # 80 grits (178 μm), and # 120 grits (124 μm), respectively, and then the roughness of the fracture surface was then measured by a TR-200 surface roughness tester manufactured by China Times Group Corporation (Figure 3F). Finally, the core’s two halves were glued together by epoxy glue (Figure 3G), and the injection pressure gasket was glued to the end face of the sample injection hole (Figure 3H). The samples need to be left to stand for more than 24 h after preparation to ensure bond strength.

### 2.3 Experimental equipment and programs

The axial stress, confining pressure, and injection pressure are provided by the servo system of the GCTS TRT-1000 Rock Triaxial Mechanical Test Machine. The equipment can provide maximum axial stress of 1000 kN, a maximum confining pressure of 140 MPa, and maximum pore pressure of 70 MPa, which can fulfill the requirements of stress loading and fluid injection. As shown in Figure 4, the average axial deformation of the sample during the experiment can be obtained by two Linear Variable Differential Transformers (LVDT) position sensors mounted on the sample axial. A radial ring LVDT sensor with an accuracy of 0.001 mm was used to record the transverse displacement of the sample.24

As Table 2 shows, this work included ten experimental samples, each with different experimental parameters for each group. Four influencing factors have been designed in this work: deviator stress, confining pressure, hydraulic fracture approach angle, and fracture surface roughness.

### 2.4 Experimental procedure

Before testing, check the equipment piping connection and calibrate the displacement sensor. The experimental sample is packed into latex film and a shrinkable heat tube to ensure that the sample is isolated from the pressure vessel oil; this also reduces the probability of jacket failure at large slip distances. A 7% KCl solution was used for the injection fluid to reduce the effect of clay minerals in the shale on the experimental results. The axial and radial LVDT were installed, and 7% KCl solution was injected into the injection hole at the top of the sample to exclude the effect of air in the injection hole on the experimental results. The injection device is then installed on the top of the sample and held in place with heat shrink tubing. Use the axial pressurized rod to provide a slight preload on the sample to keep the sample stable. Finally, adjust the axial and radial LVDT to the initial value to complete the sample.
installation. The axial pressure and the surrounding pressure are alternately applied step by step through the servo system of the device until the experimental setting value. When the axial stress and the confining pressure have been stabilized, the 7% KCl solution is injected into the injection hole through the injection system of the device, with the injection rate set at 0.2 ml/min. The pressure and displacement data are collected at a frequency of 10 Hz by a data acquisition system to obtain sufficient real-time data. When the injection pressure drops to around the confining pressure and remains stable, and the deviator stress and LVDT sensor readings do not change much, it means that the injected fluid has been mixed with the pressure vessel oil. At this point, the sample is destroyed, and subsequent monitoring is not meaningful.

2.5 Fracture deformation

As shown in Figure 5, the sample used for the experiment were diagonal shear fractures, so the data measured from the experiment needed to be converted to the direction of...
the fracture plane. The following equations can calculate the normal stress, shear stress, and shear slip on a natural fracture.

\[ \sigma = \sigma_3 + (\sigma_1 - \sigma_3) \sin^2 \theta \]  \hspace{1cm} (1)

\[ \tau = (\sigma_1 - \sigma_3) \sin \theta \cos \theta \]  \hspace{1cm} (2)

where, \( \sigma_1 \) and \( \sigma_3 \) in the above equation are the experimentally applied axial stress and confining pressure, MPa; \( \theta \) is the hydraulic fracture approach angle; \( \Delta x, \Delta y \) are the axial deformation and radial deformation of the sample, respectively.

\[ d_s = \Delta x \cos \theta + \Delta y \sin \theta \]  \hspace{1cm} (3)
respectively, mm; \(\sigma\) and \(\tau\) are the normal stress and shear stress on the fracture plane, MPa; \(d_s\) is the shear-slip distance along the natural fracture plane, mm.

3 | EXPERIMENTAL RESULTS

3.1 | Analysis of shear-slip characteristics of natural fractures

Under the action of the injected fluid, HF propagates along the axial stress direction during the experiment until it intersects with the NF. Therefore, injected fluid will enter NF through HF and generate fluid pressure on the natural fracture surface. The effective normal stress on the NF plane is the difference between normal stress on the NF plane and injection pressure. Therefore, the NF initiation in shale reservoirs can be classified into tensile initiation and shear initiation by comparing the magnitude of normal stress and injection pressure during the test. In the tensile initiation mode, the injection pressure will gradually increase until greater than injection pressure. In the shear initiation mode, the injection pressure is always less than the normal stress before damage occurs in the NF.

#2 (tensile initiation) and #5 (shear initiation) were used for comparison to reveal the NF shear-slip characteristics under different initiation modes. The injection pressure, deviator stress, shear-slip distance, and NF stress state curves during the experiments are plotted in Figures 6 and 7, respectively. Figures 6 and 7 indicate high instantaneous fracture slip velocities and short durations under tensile opening initiation.

In contrast, the instantaneous fracture slip velocity is relatively low and long under shear initiation. Moreover, the NF maximum slip distance under shear initiation is more significant, about 2–4 times larger than under tensile initiation, due to the higher elastic strain energy released when the rock undergoes tensile failure. Apart from these, we can find that the trend of the experimental parameters over time is consistent for each group, and the whole process of the experiment can be divided into three stages.

Stage I: As the fluid is injected, the pressure in the injection hole gradually rises until it reaches the maximum fluid pressure required for NF initiation. Small shear slips were observed in the NF in both sets of experiments, and the shear slips at this stage were 0.01 mm and 0.02 mm for #2 and #5, respectively. In addition, there was a slight decrease in deviator stress in both sets of experiments. The shear slip observed at this stage is caused by the compaction of the fracture under the action of the bias stress, not by the actual NF creating shear slip.

Stage II: A slight decrease in the injection pressure was observed after reaching 8.27 MPa and 7.06 MPa for #2 and #5 correspondingly, which was due to HF propagation. The deviator stress and NF shear slip did not change much during this process.

Stage III: The injection pressure of #2 increased to 11.17 MPa and then dropped abruptly until it finally stabilized near 7.57 MPa; the injection pressure of #5 advanced to 10 MPa and then remained stable until the end of the experiment. After the injection pressure of #2 and #5 increased to the maximum value, the natural fractures underwent significant shear slip, with shear-slip amounts reaching 0.06 mm and 0.22 mm, respectively. Figures 6B and 7B show that the sample deformation at this stage led to stress relaxation and an abrupt decrease in deviator, normal, and shear stress.

As shown in Figure 8, the two samples were destroyed at the end of the experiment, which shows the HF propagated along the bottom of the injection hole until
intersected with the NF. It was also found that the samples broke in half from the bonded NF under slight external forces, which may be caused by the strength reduction of the bonded NF, the details of which need to be proven by further experiments.

3.2 Analysis of factors influencing shear-slip characteristics of natural fractures

3.2.1 Deviator stress

Figure 9A,B show the curves of injected pressure and shear-slip distance versus time for different deviator stresses. Figure 9 shows that the NF are all tension initiating at deviator stresses of 3 MPa, 4 MPa, and 5 MPa. The NF initiation pressures corresponding to the three deviator stresses are 10.83 MPa, 11.17 MPa, and 11.42 MPa, respectively, and the corresponding maximum shear-slip distances are 0.04 mm, 0.06 mm, and 0.20 mm, respectively. This indicates that the NF initiation pressure and maximum shear-slip distance positively correlate with the deviator stress. According to Equation (1), an increase in deviator stress causes an improvement in the normal stress at the fracture plane, which in turn results in a higher injection pressure required for the fracture to undergo tensile initiation. Deviator stress simulates the stress difference in the formation. With larger stress differences in the formation, more energy is released by NF failure, so the maximum slip distance of NF increases with higher deviator stress. Furthermore, the injection pressure curve fluctuates at $\Delta \sigma = 5$ MPa due to the bedding encountered during HF propagation.

3.2.2 Confining pressure

The injection pressure and shear-slip distance versus time for different hydraulic fracturing approximation angles are shown in Figure 10A,B. Figure 10 shows that the initiation pressure is 8.90 MPa, 11.17 MPa, and 9.99 MPa at
a confining pressure is 5 MPa, 7 MPa, and 9 MPa, and the corresponding maximum shear-slip distances are 0.05 mm, 0.06 mm, and 0.22 mm. As the confining pressure increases, the maximum shear-slip distance grows, and the change of initiation pressure with confining pressure is not apparent. The NF are tensile initiation at confining pressure of 5 MPa and 7 MPa, and shear initiation at confining pressure of 9 MPa. This indicates a transition from tension to shear in the NF initiation mode as the confining pressure increases. The increase in confining pressure strengthens the ductile characteristics of the rock sample and limits the appearance of tensile fractures, which is consistent with what has been observed in some triaxial compression experiments.28–31

3.2.3 | Hydraulic fracture approach angle

Figure 11A,B show the relationship between injection pressure and shear-slip distance with time for different hydraulic fracture approximation angles (θ). Figure 11 shows that the initiation pressures for θ = 30°, θ = 45°, θ = 60°, and θ = 75° are 5.59 MPa, 8.13 MPa, 8.90 MPa, and 9.94 MPa, respectively. The initiation pressure increases with the hydraulic fracture approach angle, caused by a positive correlation between the normal stress on the fracture plane and the hydraulic fracture approximation angle. When θ = 45°, θ = 60°, θ = 75°, the natural fracture is tensile initiation and corresponds to a maximum shear-slip distance of 0.07 mm, 0.05 mm, and 0.04 mm. The reason for the different maximum shear-slip distances is that the forces on the fracture plane are different under the same conditions, with the NF at θ = 45° being subject to the highest shear stress and the lowest normal stress, and therefore, more likely to produce shear slip. Moreover, when θ = 30°, the shear stress applied to the fracture is slightly less than the case of θ = 45°, but the normal stress applied is only half of the case of θ = 45°. So the NF undergoes shear initiation, and the maximum shear-slip distance is 0.12 mm.

3.2.4 | Roughness of fracture surface

Tse and Cruden32 proposed a regression formula for calculating joint roughness coefficient (JRC) values based on the analysis of the geometric characteristics of standard joint profile. Currently, this method is widely applied to the characterization of fracture face morphology.33–36 The formula establishes an empirical relationship between JRC and root mean square (RMS) slope (correlation coefficient R = 0.986), and its expression is shown in Equations (4) and (5)

\[
JRC = 32.2 + 32.47 \lg Z_2
\]  

\[
Z_2 = \frac{1}{L} \int_{x=0}^{L} (\frac{dz}{dx})^2 \, dx = \left[ \frac{1}{M(\Delta x)^2} \sum_{i=1}^{M} (y_{i+1} - y_i)^2 \right]^{1/2}
\]  

FIGURE 9 (A) The curves of injected pressure versus time at different deviator stresses; (B) The curves of shear slip pressure versus time at different deviator stresses

FIGURE 10 (A) The curves of injected pressure versus time at different confining pressures; (B) The curves of shear slip versus time at different confining pressures
where, $L$ is the total length of the profile, mm; $JRC$ is the joint roughness coefficient; $Z_2$ is the RMS of slope; $\Delta x$ is the sampling spacing along the $x$-direction, mm; $y_{i+1}$ and $y_i$ are the elevations of two successive points over the length of the profile, respectively, mm; $M$ is the total number of sampling intervals.

We measured the morphology of the cut surface by a TR-200 surface roughness tester produced by China Times Group Corporation, which has a resolution of 0.001 μm and a vertical measurement range of 160 μm and has been used in previous studies to measure the morphology of the fracture surface.\textsuperscript{37,38} We then substituted the obtained fracture surface profile parameters into Equations (1) and (2), respectively, and finally averaged the obtained $JRC$ to obtain $JRC$ of 15.89, 11.22, and 9.76 after being sanded by # 40 grits (420 μm), # 80 grits (178 μm), and # 120 grits (124 μm) emery grinding plates, respectively.

Figure 12A,B plot the injection pressure and shear-slip distance for different $JRC$ curves with time. Figure 13 shows that the NF was in a tensile initiation mode when the $JRC$ was 15.89 and 11.22. At a $JRC$ of 9.76, the natural fracture is always subjected to normal...
stress larger than the injection pressure and is in shear initiation mode. The initiation pressures were 8.13 MPa, 7.88 MPa, and 5.53 MPa for JRC of 15.89, 11.22, and 9.76, respectively, and the corresponding maximum shear-slip distances were 0.05 mm, 0.08 mm, and 0.23 mm. As the JRC decreases, the initiation pressure gradually decreases while the maximum shear-slip distance increases. When the roughness of the fracture surface is larger, the higher the degree of non-closure of the fracture surface, the more glue can be filled in the fracture, which in turn causes the strength of the bonded natural fracture to be greater and less prone to shear slip under the same conditions. But we have only carried out limited research on this aspect, and further experiments are needed to prove the exact reasons.

4 | CONCLUSIONS

In this experimental study, hydraulic fracturing experiments were conducted on shale reservoir samples from the Chang 7 section of the Yanchang Formation in the Ordos Basin and focused on the shear-slip phenomenon of natural fractures when the hydraulic fracture approach. The main conclusions are as follows:

1. NF may be failed in the form of tension or shear during HF approximation, and shear slip (0.04–0.23 mm) will occur in NF in both forms of failure. Due to the higher elastic strain energy released by the rock when the tensile damage occurs, the fracture slip rate is high and the duration is short at the moment of tensional initiation. It is worth noting that the maximum slip distance under NF shear initiation is generally more significant, about 2–4 times larger than under tension initiation.

2. More considerable deviator stress benefits the generation of a larger shear-slip distance. As the confining pressure increases, the maximum shear-slip distance rises, and the NF failure mode transitions from tensile to shear.

3. The normal and shear stresses in the NF differ significantly for different hydraulic fracture approach angles, and thus their shear-slip degree varies. When \( \theta = 30^\circ \), the NF undergoes shear failure, and its shear-slip distance is the largest.

4. Fracture surface roughness affects fracture shear-slip characteristics by influencing NF bond strength, but we have only conducted limited research on this aspect, and further experiments are needed to demonstrate the detailed mechanism of action.

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