Short-term failure mechanism triggered by hydraulic fracturing

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Funding information
General Project of the National Key R & D Projects in the Thirteenth Five-Year Plan, Grant/Award Number: 2017YFC0805201; National Natural Science Foundation of China, Grant/Award Number: 51934004, 51974176 and 51674158; Major Program of Shandong Province Natural Science Foundation, Grant/Award Number: ZR2019QEE029 and ZR2018ZA0602

Abstract
Hydraulic fracturing may induce or trigger an earthquake while injecting fluid into strata to initiate a new fracture so as to promote oil and gas production. Previous studies have confirmed that the injection of fluids into the formation, especially hydraulic fracturing, is closely related to seismic activity. However, the mechanism through which fluid injection changes the stress field of rock mass and interacts with the in situ stress state is still poorly understood. This study focused on the short-term mechanism coupling shear stress and hydraulic fracturing in an experimental simulation. Preexisting tension fractures were initiated and propagated by loading shear force. The fracture propagation path of hydraulic fracturing was closely related to the preexisting fractures formed by the preshear stress. Short-term hydraulic fracturing promoted fracture propagation and acoustic emission events (or microearthquake signals), but it was less likely to cause rock mass instability or a large earthquake. The long-term fluid injection could saturate preexisting fractures and infiltrate rock mass to increase the pore pressure and change the in situ stress field in a large area to induce an earthquake.

KEYWORDS
fluid injection, shear stress, short-term, trigger earthquake

1 | INTRODUCTION

With the depletion of traditional fossil energy sources, the technique of hydraulic fracturing is commonly used for enhancing oil, gas, and geothermal reservoir productivity.1-6 The report on the World and China Energy Prospects 2050 (2017 Edition) points out that consumption of natural gas will be maintained at an average annual growth rate of 1.3% and oil will be increased by 0.3% a year until 2050. Meanwhile, it has been confirmed that the injection of fluids into the formation, especially hydraulic fracturing, is closely related to seismic activity.7-11 A total of about 11 000 locatable events were induced by injecting 21 600 m³ of water into the crystalline rocks at Fenton Hill in 1983.1 About 15 000 small earthquakes were recorded in the Zhaotong and Changning shale gas fields, which appeared to be associated with hydraulic fracturing activities.3 A series of 116 earthquakes and 16 earthquakes of magnitude ($M_L$) 2 or greater occurred...
More than 600 seismic activities connected with hydraulic fracturing were recorded in the northern Montney Play of British Columbia. Generally, the accepted view about induced earthquakes was the diffusion of pore pressure and its subsequent increase, effectively reducing the normal fault stress, releasing stored fault stress, and triggering an earthquake. Moreover, Dahm et al. roughly defined “induced seismicity” and “triggered seismicity” according to whether it was occurred with human activities. Tan et al. stated that “induced” events and “triggered” events according to “wet” events directly associated with rock deformation or to “dry” events that governed by the stress changes, respectively. Here, the correlation between the effect of fluid injection on formation and earthquakes was divided into long- and short-term effects. The long-term effect causes a stress change that is comparable in magnitude to the ambient shear stress acting on a fault to cause a slip, which can be defined as “induced” earthquake. The failure condition is usually expressed in terms of the effective stress $\tau_{\text{crit}} = \mu (\sigma_n - P) + \tau_0$, where $\tau_{\text{crit}}$ is the critical shear stress, $\mu$ is the coefficient of friction, and the effective normal stress given by the difference between the applied normal stress $\sigma_n$ and the pore pressure $P$. The mechanisms underlying the short-term effect, which can be defined as “triggered” earthquake, are as follows: (a) the injection pressure exceeds the so-called breakdown pressure, which is driven by the stress concentration around the borehole wall and the tensile strength of the rock, which is typically larger than the minimum principal stress $\sigma_3$. (b) The injection fluid penetrates into the preexisting fractures and promotes further propagation due to the water wedge and hydration effects; the stress change is only a small fraction of the ambient level.

The injection-induced earthquakes have, in particular, become a focus of discussion as the long-term effect lead to significant events. The first noted earthquake did not occur until 17 years after injection within the oilfields near Prague, Oklahoma. In 2016, the US Geological Survey produced a 1-year seismic hazard forecast map, which included contributions from both induced and natural earthquakes. However, related studies on triggered earthquakes (short-term effect) were scarce. It was even believed that no short-term correlation existed between fluid injection and earthquake. In 2012, the China National Development and Reform Commission and the Energy Administration approved the establishment of four shale gas demonstration zones (Figure 1). China’s shale gas industry entered a period of rapid development. Meanwhile, seismic activities ($M_L > 3$) increased significantly (Figure 2) in the last two decades (1998-2018). The first concentrated seismic activities occurred during the Wenchuan earthquake in 2008, and the second concentrated seismic activities occurred during the comprehensive development of shale gas, that is, 2012. Similarly, it also has been proved that hydraulic fracturing could induce instability in tight sandstone gas and coalbed methane exploitation. It was universally accepted that hydraulic fracturing promoted the initiation and propagation of new fractures.

Published studies mainly focused on purely statistical and numerical simulation. However, the relationship between hydraulic activity and short-term failure mechanism is still poorly understood. The risk of earthquakes triggered by hydraulic fractures is closely related to the stress state of rock strata and the development of fractures. It determines whether to initiate new tensile fractures or the propagation of preexisting fractures dominates the failure. Wang and Li et al. found that hydraulic fractures interacted with random microfractures will make the complex geometry. Li et al. investigated the hydraulic fracturing process of granite with different orientations of two precut flaws by analyzing the acoustic emissions data. In this study, hydraulic fracture experiments (at constant injection rate) were conducted under different shear stress using sandstone samples collected from Chongqing, China, to investigate the failure mechanism coupling the shear stress state with a hydraulic fracture. The goal was to identify the crack propagation paths of hydraulic fracturing under.
different stress states and offer the opportunity of predicting triggered seismicity.

2 | MATERIALS AND METHODS

2.1 | Material properties and sample preparation

Sandstone was selected as the object of the experiment, which was collected from the upper Triassic Xujiahe Formation at the Three Gorges region in Chongqing, China. It primarily comprised quartz, feldspar, chert, and muscovite with a grain size distribution of 0.1–0.5 mm. Young’s modulus was 11.89 GPa, Poisson ratio was 0.37, the porosity between 4% and 7%, and the permeability in the order of $10^{-18}$–$10^{-19} \text{ m}^2$, the uniaxial compressive strength was 55.97 MPa, and density was 2.33 g/cm$^3$.

Cores without obvious fractures were drilled from sandstone block and cut into cubes with a length of 100 mm. A borehole was drilled in the center of the specimen. The borehole diameter was 10 mm and the depth was 60 mm, and the open hole diameter was 8 mm and the length was 10 mm. The fluid injection pipe and borehole wall were sealed with epoxy resin (Figure 3).

2.2 | Experiments and procedures

A direct shear test apparatus for coupling the shear stress state with hydraulic fracturing was developed. A cubic sample of 100 mm length was used. Shear stress was loaded on the lower shear box in the horizontal direction with constant shear displacement velocity of 0.1 mm/min. The hydraulic pressure was monitored by liquid pressure gauge at the inlet, and the flow rate was obtained by a flowmeter at the outlet. The water was injected through the inlet, and it flowed out through the water outlet when fractures between the borehole and the outer surface of the specimen were initiated (Figure 3). The loading system was combined with the axial load, horizontal load, and fluid load. The axial and horizontal loads were applied to the specimen using a serve-controlled

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FIGURE 2 Seismicity activities in the period 1998–2018. (A) Fuling, (B) Yanchang, (C) Changning, and (D) Zhaotong. All data sets are available from the US Geological Survey$^{62}$
electric motor. Four and two LVDTs were employed to measure the normal and shear displacements, respectively. The principle of fluid load was similar to that of the needle tube, which could realize constant injection pressure or water injection rate by controlling the advancing pushing pressure. An acoustic emission monitoring system was used to monitor crack initiation and propagation, which could provide unique insights regarding the short-term failure process under fluid injection. The data acquisition frequency could reach 40 MHz, ensuring reliable stability. A threshold of 40 dB was applied to achieve a high signal/noise ratio.

2.3 | Three-dimensional fracture pattern measurement

The three-dimensional (3D) morphology of failure fracture patterns was scanned using an ATS system (Figure 4). This system facilitated an optical method based on a combination of white light fringe projection, triangulation, and phase shifting for fast and accurate calculation of high-dense 3D point clouds.

3 | RESULTS

3.1 | Shear behavior and AE events induced by hydraulic fracturing

Figure 5 shows laboratory direct shear test and geological evidence of shear-extensional fracture mechanism. An en echelon crack-array appeared under shear stress. To investigate the influence of stress state and fractures caused by stress on the seismicity induced by hydraulic fracturing, the initiation and propagation of cracks must be considered. Acoustic emission (AE) was used to monitor the increasing damage and estimate the failure process. Based on the cracking process under shear stress, this study focused on the preshear stress of 0, 0.2τp (where τp = 24.2 MPa is the peak shear strength with no injection pressure), 0.6τp, and 0.8τp, respectively, corresponding to the microcrack closing, microcrack initiation, and microcrack coalescence stages.

The experiment was divided into two stages (Figure 6): (a) preshear stress stage and (b) hydraulic fracturing stage. When preshear stress was not applied, AE activities corresponded to hydraulic pressure (Figure 6A). No
flow rate was detected until hydraulic pressure reached a peak. However, AE events occurred before peak hydraulic pressure, which indicating that microcracks initiating and propagating under hydraulic pressure was progressive, not macroscopic transient failure. This also explains the complexity of fracture propagation in hydraulic fracturing, see Figure 7. During the whole process, no obvious shear displacement was observed. As preshear stress increased (Figure 6B), AE events occurred smoothly. At stage II, the AE rate first increased rapidly before the hydraulic pressure reaches its peak. Meanwhile, the flow rate occurred when the hydraulic pressure peaked. However, after the peak of hydraulic pressure, it did not decrease rapidly and presented stage, which corresponding with the flow rate. Such significant changes indicated that hydraulic fracturing was limited by compression-shear stress, and the penetration of water into the existing cracks could promote the further expansion of the crack, especially the tension crack, due to tension cracks generated less AE events. It was worth noting that shear displacement increased by about 0.018 mm after peak hydraulic pressure.

When preshear stress was enough to initiate microcracks (Figure 6C,D), the flow rate increased immediately after injecting water. However, the first peak AE rate was generated before peak hydraulic pressure and the flow rate showed two stages in the trend of growth (Figure 6C). The shear displacement increased by about 0.032 mm after the second peak AE rate. When preshear stress reached 0.8τp (Figure 6D), the first peak AE rate was generated before injecting water. After increasing, there was a decrease in the flow rate at initial injection stage. It was speculated that it was caused by crack closure, the AE events remained high and indicating more cracks initiation. During the stage of injecting water, the flow rate increased obviously compared with the hydraulic pressure, and the AE rate was maintained at a high level. Different from other conditions, the shear displacement increased smoothly in the whole hydraulic fracturing stage. No significant AE activities occurred, and the increment was about 0.044 mm.

### 3.2 Failure mode of coupled shear stress and hydraulic fracturing

To identify the failure mode of coupled shear stress and hydraulic fracturing, 3D morphology was obtained using a 3D scanner (see the “Materials and Methods” section for further details). Figure 7 shows the obvious evolution trend of failure mode, which strongly depended on the preshear stress. The failure mode presented a typical tensile fracture along the borehole when the preshear stress was low (Figure 7A,B). In contrast, under high preshear stress, the failure mode presented approximately shear failure due to the compressive shear stress (Figure 7D). When the preshear stress was 0.6τp, the failure mode was more complex and combined the aforementioned two modes.

### 4 DISCUSSION

Generally, the occurrence of induced earthquakes is considered a Poisson process.\(^{37,54,55}\) Fluid diffusion occurs along a permeable fault zone, reducing the normal stress and friction and releasing regional tectonic shear stresses.\(^{16,56}\) The water injection experiment at the Nojima fault zone, Japan, showed an increase in the earthquake activity 4 or 5 days after the beginning of each water injection. The hypocenters of the induced earthquakes migrated at a speed of 2-40 m/h.\(^{57}\) The first earthquake occurred ~24 hours after hydraulic fracturing.
at the well in South-Central Oklahoma, and this delay was owing to the diffusion of pore pressure in the subsurface over a distance of ~2 km. However, fluid and pore pressure migration were greatly influenced by permeability. It was inferred that the fracture dominated the process of fluid infusion due to the slow change rate in the stress field.

Compared with the well-understood natural fluid injection triggering earthquakes along a fault zone, the instability of intact rocks caused by injecting fluid needs further analysis. Laboratory experiments conducted in this study indicated that the short-term failure triggered by hydraulic fracturing strongly depended on the stress state (Figure 2). Also, the shear displacement caused by hydraulic fracturing increased with the increase in preshear stress (Figure 8). This suggested that shear displacement occurred when the fluid was injected into the intact rock even if it was not in the fault zone. However, the peak hydraulic pressure and cumulative AE count decreased when the preshear stress reached 0.8 $\tau_p$ (Figure 8). Further, the fracture path induced by fluid injection was closely related to its preshear stress and could be divided into three situations (Figure 9). (a) When the preshear stress was small, no primary macrocracks were initiated and propagated; only longitudinal fractures were initiated and propagated perpendicular to the minimum principal

**FIGURE 6** Shear behavior and AE events induced over time by hydraulic fracturing. (A) No preshear stress, (B) preshear stress equal to 0.2$\tau_p$ (peak shear strength), (C) preshear stress equal to 0.6$\tau_p$, and (D) preshear stress equal to 0.8$\tau_p$. Temporal evolution of shear stress (black), shear strain (red), hydraulic pressure (green), flow rate (blue), AE rate (magenta), and cumulative AE count (orange) of induced events during hydraulic fracturing. Stage I is the shear stress loading stage (gray area), and stage II is the hydraulic fracturing stage (orange area).
stress along the borehole. (b) When the preshear stress was big, obvious tension transverse fractures were initiated due to preshear stress, the fluid penetrated into primary transverse fractures, and the wedge effect promoted its further propagation. It is worth noting that even the preshear stress was close to the shear failure for intact rocks; the short-term fluid injection did not induce rupture and only promoted little propagation at the tip of the crack. This was due to the transverse fracture aperture created by the interaction of shear stress and fluid injection, which was big enough to allow fluid flow and avoid the continuous rise in injection pressure, thereby not triggering failure. (c) More commonly, complex fractures were generated, including transverse fractures caused by preshear stress and longitudinal fractures caused by hydraulic pressure. Under constant force, the stress increased with the decrease in the forced area, especially at the tip of the crack, which required greater injection pressure to promote primary transverse fractures. In contrast, the stress
WANG et al. did not vary much with the increase in the primary transverse fracture propagation on the plane perpendicular to the minimum principal stress. The hydrofracturing crack propagated perpendicular to the minimum principal stress plane, and not along the direction of the shear stress, which in agreement with Wang et al.\textsuperscript{38} It avoided the continuous propagation of shear crack along shear stress and prevented shear failure. Therefore, near-wellbore complex fractures initiated with injection pressure increased, which was in agreement with the variation in cumulative AE count shown in Figure 4.

5 | CONCLUSION

The aforementioned analysis was based on the experimental results. The size of the sample was small, and the purpose of this study was to study the mechanism of short-term fluid injection. The study showed that with a short-term fluid injection, such as hydraulic fracturing, microearthquake events mainly occurred during the hydraulic fracturing stage, caused by propagation of preexisting fractures or initiation of new fractures; no large fractures were triggered. It was also showed that in the process of hydraulic fracturing, the more complex the in situ stress state is, the more complex the change in acoustic emission event and flow rate is, but it cannot be used as the direct basis for judging instability. This was for engineering rock masses, as the fluid was continuously injected for the long term. The fluid infiltrated the rock mass through the fracture surface, increasing the pore pressure and changing the stress field of near-wellbore fractures. In addition, when the stress field of rock mass was close to failure, the fluid flowed through preexisting fractures in the early stage of fluid injection. The failure modes combined compression-shear stress and hydraulic pressure can be divided three modes: (a) a typical tensile fracture along the borehole when the preshear stress was low; (b) shear failure due to the compressive shear stress under high preshear stress; and (c) a combined mode including transverse fracture and longitudinal fracture. However, for long-term continuous fluid injection, the preexisting fractures were saturated and provided a hydrostatic pressure on the fracture surface, promoting preexisting fracture propagation and triggering failures.

ACKNOWLEDGMENTS

We thank the General Project of the National Key R & D Projects in the Thirteenth Five-Year Plan (2017YFC0805201), the National Natural Science Foundation of China (51934004, 51974176, and 51674158) and the Major Program of Shandong Province Natural Science Foundation (ZR2019QEE029 and ZR2018ZA0602) for their financial support.

CONFLICT OF INTEREST

The authors declare no competing financial interests.

AUTHOR CONTRIBUTIONS

YL and JX conceived the idea and designed the experiments. YL carried out the experiments and analyzed the data. YL and GW co wrote the manuscript, while GW supervised the whole project. All authors discussed the results and checked the manuscript.

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**How to cite this article:** Wang G, Liu Y, Xu J. Short-term failure mechanism triggered by hydraulic fracturing. *Energy Sci Eng*. 2020;8:592-601. [https://doi.org/10.1002/ese3.535](https://doi.org/10.1002/ese3.535)