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Research Article

Cyclic Injection to Enhance Hydraulic Fracturing Efficiency: Insights from Laboratory Experiments

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In hydraulic fracturing applications, there is substantial interest to reduce the formation breakdown pressure. Previous research results show that the cyclic injection method can be used to reduce that pressure. In this study, we conducted laboratory hydraulic fracturing experiments to apply cyclic injection to reduce the breakdown pressures of very tight and strong sandstones. Experimental results show that using cyclic injection the average breakdown pressure was reduced by 18.9% in very tight sandstones and by 7.18% in normal sandstones. This indicates that the effect of cyclic injection is more significant for stronger and tighter rocks. The experiments also reveal that the rock tensile strength plays a more important role in the formation breakdown pressure with a rock strength factor of 2.85. This suggests that the breakdown pressure is higher than expected. In addition, we empirically related the breakdown pressure reduction and the injection pressure amplitude to the number of injection cycles. The curve fitting results imply that the effect of cyclic injection is more important if the number of cycles or the injection pressure amplitude is increased. Based on the results of this research, the *in-situ* formation breakdown pressure can be reduced by applying the cyclic injection method, and the breakdown pressure reduction is more significant as the number of cycles increases.

1. Introduction

Hydraulic fracturing has become increasingly important for hydrocarbon extraction in sedimentary rocks and enhanced geothermal systems in crystalline rocks [1–3]. However, in some field conditions, the rock is tight and strong, or the tectonic stresses are very high. As a result, the rock cannot be hydraulically fractured easily. Therefore, there is substantial interest in reducing the hydraulic fracturing breakdown pressure.

To reduce the hydraulic fracturing formation breakdown pressure, one commonly used method is cyclic injection. Several research groups have experimentally investigated the effect of cyclic loading on breakdown pressure reduction: Patel et al. [4] and Goyal et al. [5] conducted cyclic injection on sandstone; Zhuang et al. [6] and Zang et al. [7] conducted cyclic injection on granite; and Tariq et al. [8] conducted

cyclic injection on concrete. They reported that at laboratory scale, compared to conventional injection in which the injection pressure increases monotonically, the cyclic injection can reduce the breakdown pressure of sandstone [4, 5], granite [6, 7], and concrete [8]. For example, Zhuang et al. [6] conducted cyclic injection tests on 34 Pucheon granite specimens, and they reported that cyclic injection can reduce the breakdown pressure for granitic rocks by at least 10%. Patel et al. [4] conducted cyclic injection tests on both dry and saturated Tennessee sandstones; they stated that for dry sandstone, cyclic injection can reduce the breakdown pressure by 15%. Tariq et al. [8] conducted cyclic injection tests on concrete specimens with three different strengths. They observed that the effect of cyclic injection is more important on stronger concrete samples, and for strong concrete samples, cyclic injection can reduce the breakdown pressure by 20%. The effect of cyclic injection is dependent

on several experimental parameters: the number of cycles, injection pressure amplitude (this will be defined later), confining pressure, injection frequency, rock type, etc.

However, it appears that for sandstones, all previous experimental work was conducted on relatively porous specimens. For example, the porosity for the Tennessee sandstone tested by Patel et al. [4] and Goyal et al. [5] is approximately 8.5%. In other words, it appears that no experimental work has been conducted to systematically study the effect of cyclic injection on the breakdown pressure in very tight sandstones. It is very difficult for tight sandstone to be efficiently fractured [9] because of its high breakdown pressure; therefore, the effect of cyclic injection on very tight sandstone is worthwhile to explore.

So far, the effect of cyclic injection on the breakdown pressure has been studied by only a few research groups. In contrast, the effect of cyclic loading, with a similar mechanism to cyclic injection, on the rock strength under dry conditions has been extensively investigated experimentally. Numerous experiments have been conducted to explore the effect of the number of cycles, loading stress amplitude (this will also be defined later), confining pressure, injection frequency, rock type, etc [10]. Based on the results of cyclic loading experiments, Schijve [11] proposed an empirical curve which relates the rock strength reduction to the number of required cycles (S-N curve). Although the data of the S-N curve shows significant scattering, the S-N curve still provides a reference for strength reduction prediction. However, for cyclic injection tests, such an empirical curve has not been proposed yet. If such a relation is present, it could provide a good method to predict the breakdown pressure reduction to guide hydraulic fracturing operations.

The main objectives of this paper are as follows: (1) to systematically investigate the effect of cyclic injection on very tight sandstones and compare the results with normal sandstones and (2) to empirically relate the breakdown pressure reduction to the number of required cycles to provide breakdown pressure prediction. To achieve the two objectives, we first conducted systematic cyclic injection tests on very tight and normal sandstones. The breakdown pressure reduction for two different groups of sandstones was compared. Then, we proposed empirical relationships for cyclic injection from different experiments including the data obtained from publications. The experimental and curve-fitting results will eventually provide a reference for future laboratory-scale experiments under more complicated cyclic loading patterns or field hydraulic fracturing.

2. Laboratory Testing Methodology

In this research, the Xujiahe sandstone was used for cyclic injection tests. The experimental methodology and results are explained in detail in Kang et al. [12]. Therefore, in this paper, we briefly recapitulate the experimental methodology and the results.

2.1. Rock Specimens. The experimental large rock blocks were obtained from the outcrops of the Xujiahe sandstones, as

FIGURE 1: The outcrop of the Triassic Xujiahe sandstones in the Sichuan Province of China.

shown in Figure 1. The Xujiahe group comprises a sequence of sandstone sediments deposited in the area of the present Sichuan Basin, China, between the lower Triassic and upper Jurassic. The Xujiahe sandstone gas reservoirs underlie the Sichuan Basin at a depth of approximately 3000 to 5000 meters, and the outcrops from which we took the rock specimens are located in 31.43325°N, 104.00831°E. Two batches of sandstone intact specimens were cored from the outcrop. The first batch of sandstone is very tight and strong, with an average permeability of 0.054 mD and a porosity of 1.05%. The second batch of sandstone is not so tight, with an average permeability of 0.32 mD and a porosity of 13.24%.

2.2. Experimental Methodology. For each batch of experiments, cylindrical sandstone specimens were cored from neighboring locations from the same outcrop. After coring, one vertical borehole was drilled along the centerline of each cylindrical specimen for fracturing fluid injection. Figure 2 shows the schematic of the cylindrical specimen with a vertically drilled borehole and the picture of one of the rock specimens.

Each specimen was hydraulically fractured in a triaxial cell system, as shown in Figure 3. In the experiments, 2% KCl solution was used as the injection and fracturing fluid. During each test, the axial and confining pressures in the triaxial apparatus were applied first. The axial and confining pressures were fixed at 13 MPa and 8 MPa, respectively. After the axial and confining pressures reached these magnitudes, the fracturing fluids were injected and the injection pressure was increased and varied in different experimental scenarios. Two types of experiments were conducted: cyclic injection tests and conventional injection tests.

For cyclic injection tests, two methods were used: stepped pressure injection and constant pressure injection. Figures 4 and 5 explain the methodology for stepped pressure injection and constant pressure injection, respectively. Both methods have two stages: cyclic injection stage and rock breaking stage. In the cyclic injection stage, the pressurization rate
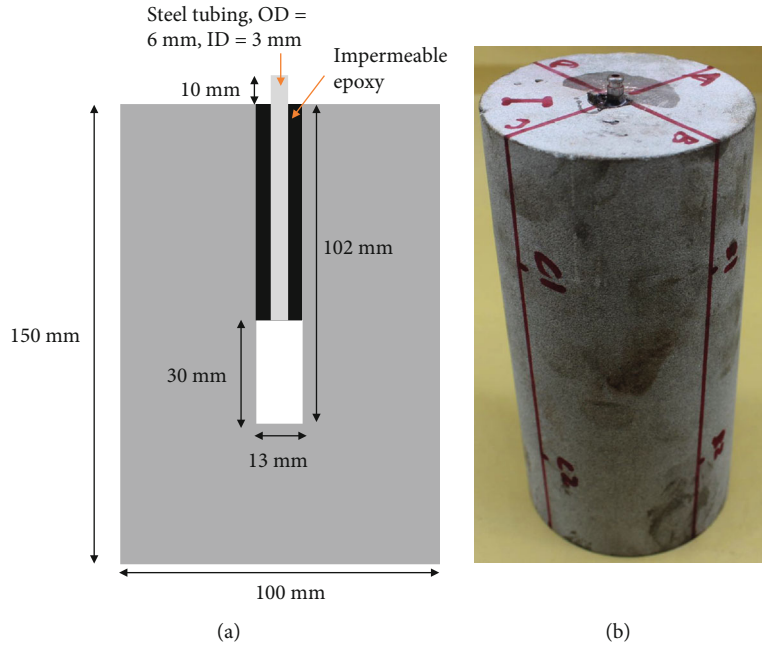
(a)

(b)

FIGURE 2: (a) Schematic of the vertical borehole drilled in each rock specimen for the first batch of sandstone. (b) Picture of one specimen from the second batch of sandstone (diameter: 100 mm; height: 190 mm).
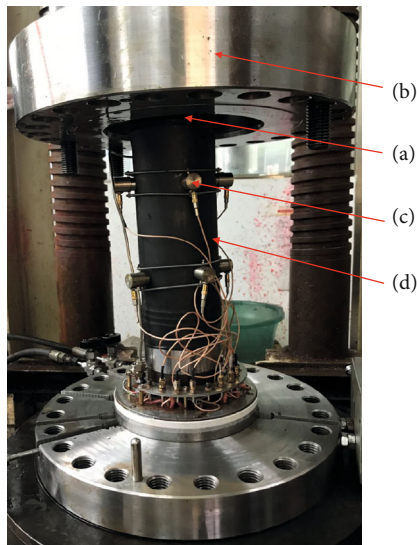

FIGURE 3: Triaxial testing system: (a) top cap for applying axial stress (not visible); (b) confining chamber for applying confining stress; (c) acoustic sensors attached to the sealing tubing; (d) sealing tubing (two layers of heat-shrink tubing).

was fixed at 0.167 MPa/s, the holding time for the reduction was fixed at 30 sec, the holding time for increment was fixed at 90 sec, and the reduced pressure was fixed at 1.5 MPa. In the rock breaking stage, the injection flow rate was fixed at 2.4 mL/min.

For conventional injection tests, the injection pressure was increased monotonically and the injection flow rate was fixed at 2.4 mL/min. The created fracture after the rock breakdown in each specimen was the vertical fracture, as

predicted. That is, the hydraulic fracture plane created by injection is along the borehole axial direction, as shown in Figure 6.

For each specimen, after the hydraulic fracturing test, one small cylindrical specimen (diameter: 25.4 mm; length: 50.8 mm) was cored for a uniaxial compression test, and another small cylindrical specimen (diameter: 25.4 mm; length: 12.7 mm) was cored for a Brazilian test. Both cylindrical specimens were cored from the unbroken part of the original specimen.

3. Laboratory Experimental Results

3.1. Experimental Results of Breakdown Pressures. Tables 1 and 2 summarize the hydraulic fracturing results for the first batch of sandstone, and Tables 3 and 4 summarize the results for the second batch of sandstone. In the first batch (very tight sandstones), the average breakdown pressure for conventional injection is 43.03 MPa and for cyclic injection is 34.90 MPa. This suggests that by using cyclic injection, the breakdown pressure was reduced by 18.9%. In the second batch (normal strength sandstones), the average breakdown pressure for conventional injection is 27.15 MPa and for cyclic injection is 25.20 MPa. This suggests that the breakdown pressure was reduced by 7.18%. Figure 7 compares the average breakdown pressures (both conventional and cyclic injections) for the first and second batches.

The results suggest that cyclic loading can reduce the breakdown pressure for sandstones. In addition, the effect of cyclic loading is more significant for reducing the breakdown pressure for stronger and tighter rocks.
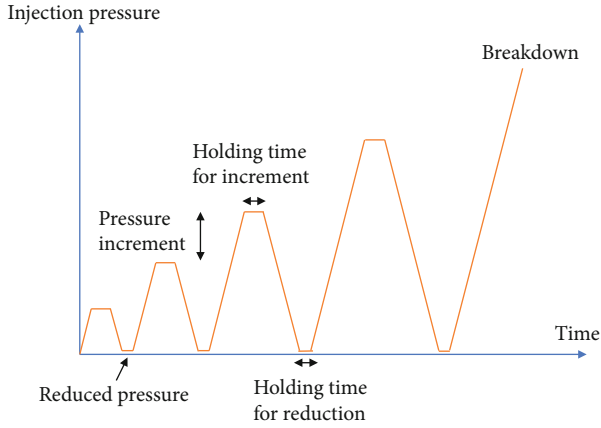
FIGURE 4: Schematic of the stepped pressure injection method in the cyclic injection tests.
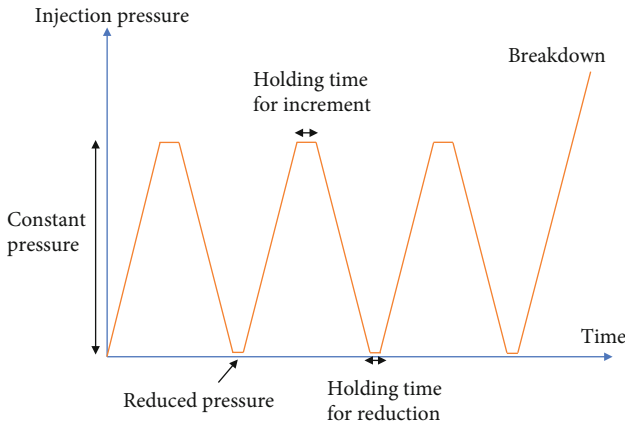

FIGURE 5: Schematic of the constant pressure injection method in the cyclic injection tests.

3.2. Correlations between Rock Strength and Formation Breakdown Pressure for Conventional Injection Tests. The results in Tables 1 and 3 suggest that for conventional injection tests, the formation breakdown pressure increases as the tensile strength of the rock matrix increases. This trend agrees well with the theoretical equation proposed by Zhang et al. [13] and Zhang [14]:

$$p_b = 3\sigma_h - \sigma_H - p_p + kT, \tag{1}$$

where p_b is the formation breakdown pressure, σ_H is the maximum horizontal stress, σ_h is the minimum horizontal stress, p_p is the pore pressure, T is the tensile strength, and k is the rock strength factor. Compared with the Haimson and Fairhurst equation [15] which calculates the fracture initiation pressure, Equation (1) predicts the formation breakdown pressure. Here, the k value can be determined for the Xujiahe sandstone. In all conventional injection tests, $\sigma_H = \sigma_h = \text{confining pressure} = 8\,\text{MPa}$ and $p_p = 0$. Therefore, by substituting σ_H, σ_h, and p_p into Equation (1), Equation (1)

FIGURE 6: The vertical fracture created along the axial direction in a specimen for the first batch.

becomes $p_b = (16 + kT)\,\text{MPa}$ and has only one variable. Using the linear curve fitting, the breakdown pressure can be expressed as

$$p_b = 16 + 2.8538T. \tag{2}$$

Figure 8 plots the data points and the fitted line. Equation (2) indicates that the rock tensile strength plays a much more important role in the formation breakdown pressure than expected (i.e., the rock strength factor $k = 1$). This suggests that for tight rocks, the breakdown pressure is expected to be higher, compared with normal rocks.

4. Empirical Curve Fitting for Breakdown Pressure Reduction in Cyclic Injection Tests

4.1. Breakdown Pressure Reduction versus the Number of Cycles. As discussed before, in hydraulic fracturing, cyclic injection can reduce the breakdown pressure [4, 5, 12, 16]. One method to quantify the effect of cyclic injection tests is to plot the normalized breakdown pressure (breakdown pressure in cyclic injection/breakdown pressure in conventional injection) versus the number of cycles. Table 5 summarizes the sources of data we used from this experiment and public literature. It appears that cyclic injection tests have been conducted mainly on granite, sandstone, and concrete.

Figure 9 summarizes the data we used for the curve fitting. The red line corresponds to the fitted line based on the cyclic injection test data from Table 5. Here, we compare this cyclic injection fitting curve to the results obtained from the cyclic loading tests, i.e., the dashed line corresponding to the empirical line published by Schijve [11]. Schijve's line plots the normalized cyclic loading strength (strength under cyclic loading/strength under monotonic loading) versus the number of cycles, under dry conditions.

The data points presented in Figure 9 are indeed scattered (r^2 of the fitted line is 0.11), but the trend is still clear. The breakdown pressure decreases with an increasing

TABLE 1: Result summary for the first batch of sandstone.

Specimen no.	Injection method	Injection flowrate or injection pressure	Breakdown pressure (MPa)	Tensile strength (MPa)	Compressive strength (MPa)
1	Conventional	2.4 mL/min	43.09	9.282	172.85
2	Conventional	2.4 mL/min	38.42	8.455	150.84
3	Conventional	2.4 mL/min	47.59	11.611	152.73
4	Stepped pressure	4-8-12-16-20-24 MPa	29.03	10.010	171.02
5	Constant pressure	20 MPa	31.53	9.148	157.51
6	Constant pressure	25 MPa	42.75	10.498	164.90
7	Constant pressure	25 MPa	36.28	8.690	153.56

TABLE 2: Some average results for the first batch of sandstone.

Parameter	Conventional injection	Cyclic injection
Averaged breakdown pressure (MPa)	43.03	34.90
Standard deviation of the breakdown pressure (MPa)	3.74	5.23
Averaged uniaxial compressive strength (MPa) (all 7 specimens)	160.49	
Averaged Brazilian tensile strength (MPa) (all 7 specimens)	9.67	

TABLE 3: Results summary for the second batch of sandstone.

Specimen no.	Injection method	Injection flowrate or injection pressure	Breakdown pressure (MPa)	Tensile strength (MPa)	Compressive strength (MPa)
1	Conventional	2.4 mL/min	18.35	2.819	47.64
2	Conventional	2.4 mL/min	26.70	2.362	48.93
5	Conventional	2.4 mL/min	36.40	2.557	46.92
3	Stepped pressure	2-4-6-8-11-13-15-17 MPa	25.36	1.785	48.76
4	Stepped pressure	2-4-6-8-11-13-15-17 MPa	26.10	1.614	44.07
6	Constant pressure	16 MPa	24.13	2.245	54.28

TABLE 4: Some average results for the second batch of sandstone.

Parameter	Conventional injection	Cyclic injection
Averaged breakdown pressure (MPa)	27.15	25.20
Standard deviation of the breakdown pressure (MPa)	7.38	0.81
Averaged uniaxial compressive strength (MPa) (all 6 specimens)	48.43	
Averaged Brazilian tensile strength (MPa) (all 6 specimens)	2.23	

number of cycles. The normalized breakdown pressure can be related to the number of cycles as

$$\frac{P_{cyc}}{P_{con}} = -0.009878 \ln N + 0.9097, \tag{3}$$

where N is the number of cycles, P_{cyc} is the breakdown pressure in cyclic injection, and P_{con} is the breakdown pressure in conventional injection. It is worth noting that the red line is below the dashed line, which indicates that compared with dry cyclic loading, cyclic injection (by fluid pressure) has a stronger effect on the strength reduction. In addition, most sandstone data points and all concrete data points are below Schijve's line, while some granite data points are above Schijve's line. This indicates that the effect of cyclic injection may be dependent on the rock type.
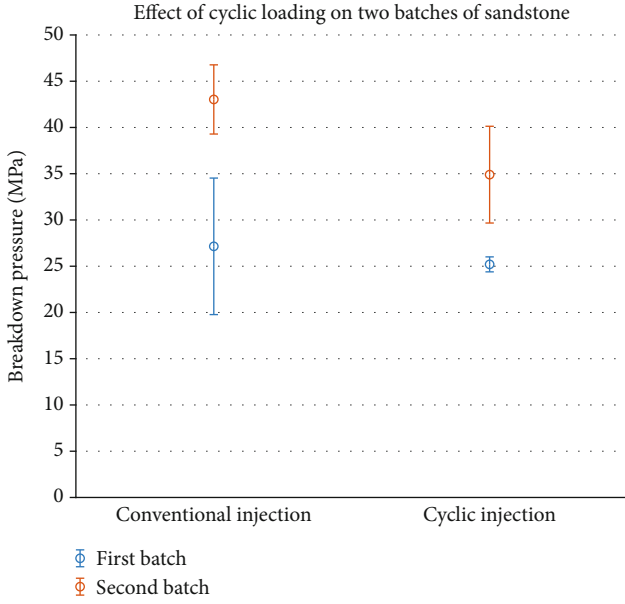
FIGURE 7: Average breakdown pressures for the first and second batches of sandstone. The error bars represent the standard deviation of each category.
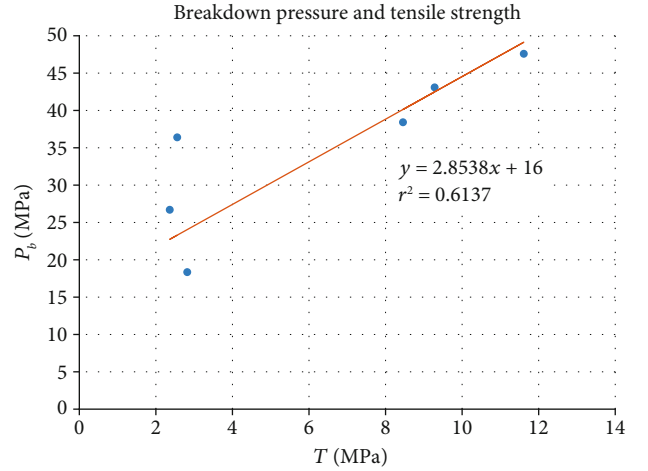

FIGURE 8: Correlation between breakdown pressure and tensile strength for conventional injection tests. The equation is calibrated based on Equation (1).

For concrete and sandstone, the amount of available data is very limited, and the number of cycles N falls into a very narrow range (between 5 and 12). Therefore, we also tried to plot the data only for granite, and Figure 10 summarizes the results for granite. The red line corresponds to the fitted line based on the cyclic injection data from Table 5 (granite only), and the dashed line corresponds to Schijve's line [11].

Similar to those in Figure 9, the data points shown in Figure 10 are scattered (r^2 of the fitted line is 0.15), but they have a visible trend. The breakdown pressure decreases with an increasing number of cycles. The normalized breakdown pressure of granite can be related to the number of cycles as

$$\frac{P_{\mathrm{cyc}}}{P_{\mathrm{con}}} = -0.01246 \ln N + 0.9255. \tag{4}$$

Equation (4) is obtained from the results of granite only, while Equation (3) is obtained from the results of granite, sandstone, and concrete. For granite, compared with dry cyclic loading, cyclic injection (by fluid pressure) has a stronger effect on the breakdown pressure (strength) reduction.

The amount of cyclic injection data is limited. As a result, between different data points in Figures 9 and 10, the injection pressure, injection frequency, and the confining pressure are different. In reality, the effect of cyclic injection can be strongly dependent on the above-mentioned experimental parameters, even for the same rock type. Therefore, if more data are available in the future, more reliable curves under each experimental condition could be fitted.

4.2. Injection Pressure Amplitude at each Cycle versus the Number of Cycles.
In fatigue analysis of metals, loading stress amplitude applied during cyclic loading is often related to the required number of cycles to failure. Figure 11 illustrates the

TABLE 5: Sources of data for the cyclic injection curve fitting (cyclic breakdown pressure/conventional breakdown pressure vs. number of cycles).

Authors	Rock type
Kang et al. [12]	Tight Xujiahe sandstone
Kang et al. [12]	Normal Xujiahe sandstone
Patel et al. [4]	Tennessee sandstone
Goyal et al. [5]	Tennessee sandstone
Zhuang et al. [16, 17]	Pocheon granite
Diaz et al. [18, 19]	Pocheon granite
Stephansson et al. [20]	Pocheon granite
Liang et al. [21]	Concrete
Tariq et al. [8]	Concrete

stress parameters for a cylindrical specimen under the time-varying axial stress $\sigma(t)$.

As shown in Figure 11, the stress parameters:

$$\begin{aligned} \Delta\sigma &= \sigma_{\max} - \sigma_{\min}, \\ \sigma_a &= \frac{\Delta\sigma}{2}, \\ \sigma_m &= 0.5(\sigma_{\max} + \sigma_{\min}), \end{aligned} \tag{5}$$

are defined as the stress range, the loading stress amplitude, and the mean stress, respectively.

For metals, if the stress amplitude σ_a is less than the yield strength σ_y, the fatigue process is defined as high-cycle fatigue. Basquin [22] observed that the σ_a versus N_f (the number of cycles required for fatigue failure) data can be effectively linearized on the log-log axis. The empirical equation is defined as
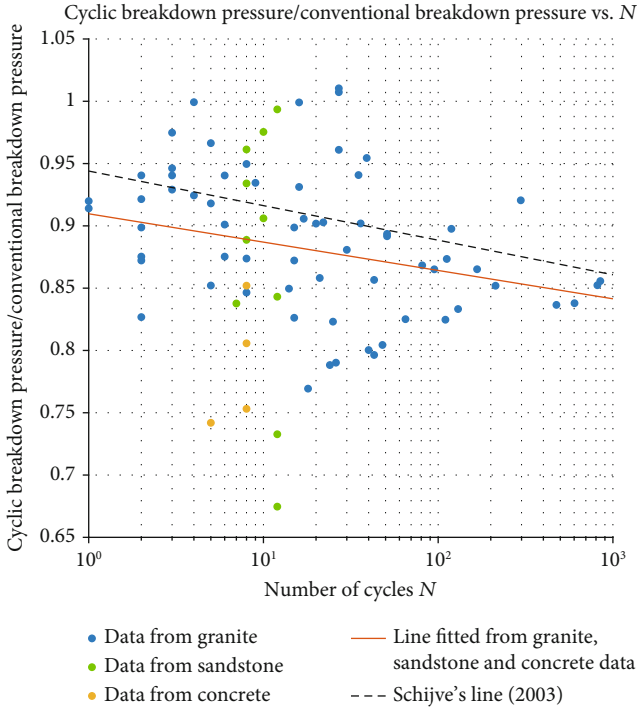
$$\sigma_a = \sigma_f'(2N_f)^b, \tag{6}$$

Figure 9: Normalized breakdown pressure (cyclic breakdown pressure/conventional breakdown pressure) versus the number of cycles N.
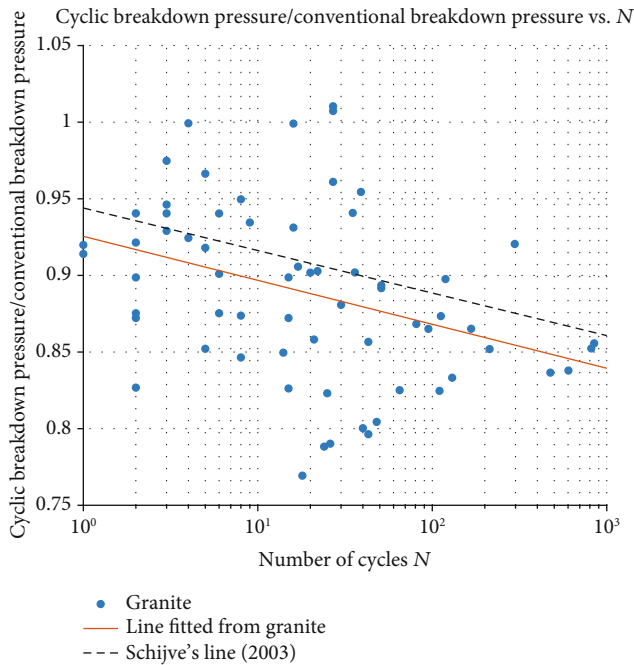

Figure 10: Normalized breakdown pressure (cyclic breakdown pressure/conventional breakdown pressure) versus the number of cycles N.

where b and σ_f' are empirically fitted parameters, which are called the fatigue strength exponent and the fatigue strength, respectively. Figure 12 illustrates the concept of the σ_a versus N_f curve.
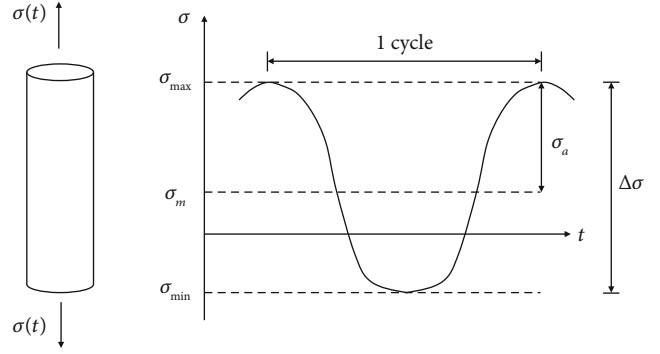

Figure 11: Illustration of the stress parameters for a cylindrical specimen under the time-varying axial stress $\sigma(t)$.

For cyclic injection tests in rock, Equation (6) can be modified as

$$\frac{P_a}{P_{\mathrm{con}}} = a\left(N_f\right)^b, \tag{7}$$

where P_a is the injection pressure amplitude, N_f is the number of required tests until failure, and a and b are curve-fitted parameters. In this research, only the results with the same injection pressure between different cycles (constant pressure injection method) were analyzed. The injection pressure amplitude is defined as

$$P_a = \frac{\left(P_{\mathrm{max-inj}} - P_{\mathrm{min-inj}}\right)}{2}, \tag{8}$$

where $P_{\mathrm{max-inj}}$ is the maximum injection pressure and $P_{\mathrm{min-inj}}$ is the minimum injection pressure. Since the amount of data for sandstone and concrete is very limited, the data analysis for granite will be reported. Figure 13 summarizes the P_a/P_{con} versus N_f relationship for granite, and the relationship can be expressed as

$$\frac{P_a}{P_{\mathrm{con}}} = 0.4258\left(N_f\right)^{-0.01909}. \tag{9}$$

Although the data points in Figure 13 are scattered ($r^2 = 0.09$), there is a visible trend. The P_a/P_{con} decreases with N_f, which indicates that if the injection pressure amplitude increases, a smaller number of cycles are required to achieve the formation breakdown.

It is also worth noting that between different points, the injection pressure, injection frequency, and confining pressure are different. In the future, if there are more data available, we could further fix some of the above-mentioned experimental parameters (e.g., confining pressure) to reduce the data scattering.

4.3. Loading Stress Amplitude at Each Cycle versus the Number of Cycles for Dry Cyclic Tests. Similar to Section 2, we also summarize some results for dry cyclic tests. We select
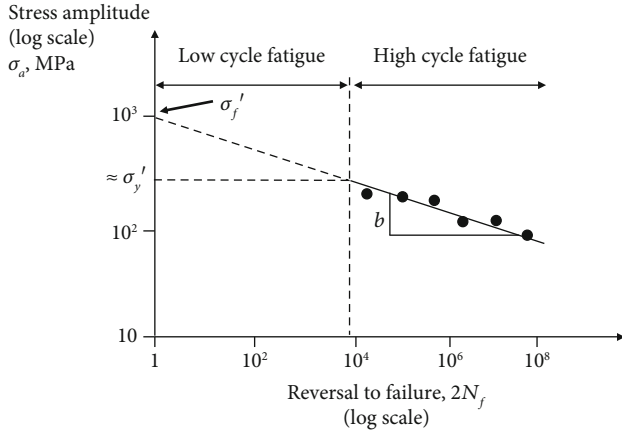
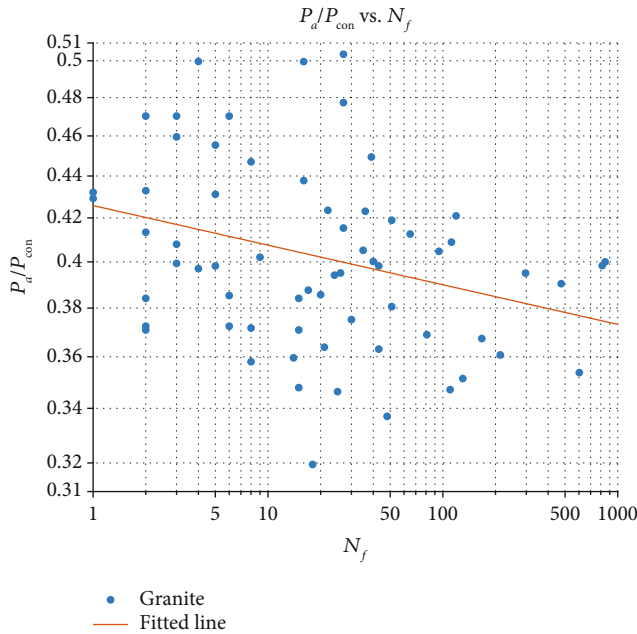Figure 12: Illustration of the σ_a versus N_f curve [23].

Figure 13: P_a/P_{con} versus N_f for cyclic injection tests on granite. The red line is the fitted line.

the results from three papers: Singh [24], Haimson and Kim [25], and Guo et al. [26]. Figure 14 summarizes the σ_a/σ_{con} versus N_f relationship, and the relationship can be expressed as

$$\frac{\sigma_a}{\sigma_{con}} = 0.5443 \left(N_f\right)^{-0.1098}. \tag{10}$$

Compared to Figure 13, the data points in Figure 14 show less scattering ($r^2 = 0.65$). This indicates that, compared with the effect of injection pressure amplitude in cyclic injection tests, the effect of loading stress amplitude on the required number of cycles to fatigue failure may be more significant in dry tests.
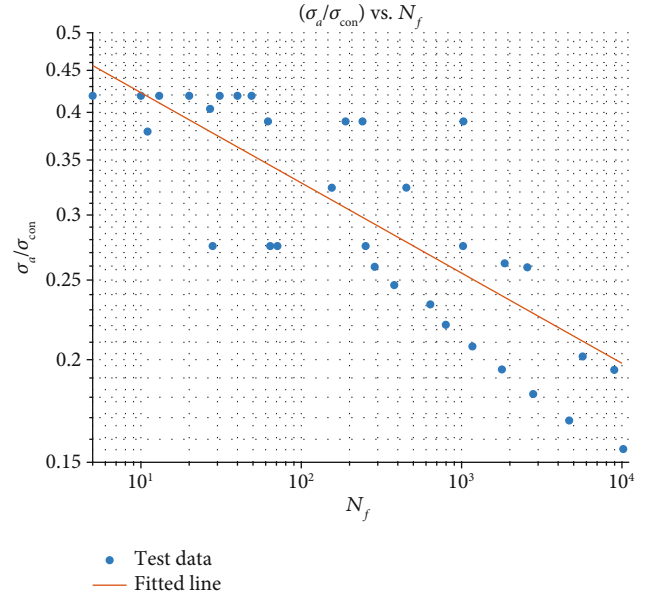

Figure 14: σ_a/σ_{con} versus N_f for dry cyclic tests. The red line is the fitted line.

5. Conclusions and Recommendations

Since cyclic injection could reduce the formation breakdown pressure, it is of interest for hydraulic fracturing on reservoir rocks, especially for tight and strong rocks such as the Xujiahe sandstones. This research systematically investigated the effect of cyclic injection on the breakdown pressure of the Xujiahe sandstones. The results indicate that the breakdown pressure can be reduced by cyclic injection in hydraulic fracturing, and the effect of cyclic injection is more significant for stronger and tighter rocks. The average breakdown pressure was reduced by 18.9% in very tight sandstone and by 7.18% in normal sandstone. We also empirically related the breakdown pressure for conventional injection tests to the tensile strength. The breakdown pressure increases as the tensile strength increases. The rock tensile strength plays a more important role in the formation breakdown pressure with a rock strength factor of 2.85. This suggests that the breakdown pressure is higher than expected.

In addition, empirical curves for cyclic injections from different experiments, including the data obtained from publications, have been fitted. Based on this analysis, we proposed empirical equations relating the breakdown pressure reduction to the number of injection cycles and the injection pressure amplitude. The empirical equations imply that the breakdown pressure decreases with increasing the number of cycles and the injection pressure amplitude. Therefore, cyclic injection can be used to reduce the breakdown pressure in the field of hydraulic fracturing. To further reduce the breakdown pressure in cyclic injection, the number of cycles or the injection pressure amplitude can be increased.

The experiments also indicate possible future research directions. For the laboratory work, more tests can be conducted to systematically investigate the effect of the number of cycles, injection pressure amplitude, and cyclic frequency

on the breakdown pressure reduction. To explore the mechanisms of breakdown pressure reduction, acoustic emission or scanning electron microscopy (SEM) can be used to detect the growth of microcracks. For the curve fitting, if more data are available in the future, empirical equations with less data scattering can be fitted by fixing some experimental parameters (e.g., confining pressure and injection frequency). Practically, the current laboratory and curve-fitting results can provide relevant information for breakdown pressure reduction in field hydraulic fracturing operations.

Data Availability

The data used to support the results of this research are available from the corresponding author upon request.

Conflicts of Interest

None of the authors have any conflicts of interest.

Acknowledgments

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