Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Experimental Study on Cyclic Soft Fracturing of Naturally Fractured Granite Cores

Rui Yang[1], Zixiao Xie[1]*, Xiaoguang Wu[1], Zhongwei Huang[1], Xianzhi Song[1], Gensheng Li[1]

1. State Key Laboratory of Deep Geothermal Resources, China University of Petroleum (Beijing), Beijing, 102249, China

Email address for *corresponding author: xiezx@cup.edu.cn

Keywords: Hydraulic fracturing; cyclic injection; hot dry rock; fractured geothermal reservoirs

INTRODUCTION

Deep geothermal resources are clean, abundant and not being restricted by the season, which reveals great development potential and has become a hot topic worldwide (Tursun et al., 2015). This kind of resource is usually stored in hot dry rock (HDR) reservoirs and are exploited through enhanced geothermal system (EGS), whose key point lies in establishing an efficient artificial heat exchanger between injection and production wells. Hydraulic fracturing (HF), a method widely adopted in oil/gas reservoir stimulation (Olasolo et al., 2016), is gradually applied for geothermal well development, aiming at building complex and well-connected fracture networks. However, the problems of induced large earthquake, high breakdown pressure and simple induced fracture networks during HF hinder HDR development.

To resolve these intricate difficulties, some scholars proposed a new injection protocol (Hofmann et al., 2018), cyclic soft fracturing (CSF), which uses alternating injection rate/pressure to release the stress concentration at the fracture tip, form multi-stranded fractures, and reduce earthquake risk. This soft fracturing method is based on conventional monotonous hydraulic fracturing (MHF), which uses a constant injection rate or pressuring rate to rapid pressurization and rock fracture and can be regarded as rigid fracturing method. The CSF method disperses the concentrated hydraulic energy into several stages and slows down the crack propagation rate, thereby reach the goal of “soft” fracturing the reservoirs and reducing seismicity risk. Besides, long-term pressure oscillation and fluid infiltration are benefit to the activation of natural fractures (NFs) and micro-crack.

However, HDR is mainly composed of crystalline granite which is much harder and denser than sedimentary rock. The hydraulic fatigue effect of CSF on intact granite is hindered (Zang et al. 2021). On the other hand, NFs are widespread underground and will affect the rock deformation and failure behaviors (Xie et al., 2023;2024). Lessons learn from many EGS projects shows that connection between NFs and hydraulic fractures is essential to establish an efficient heat exchanger (Axelsson 2024). Therefore, we propose to apply CSF on naturally fractured granite samples to activate the NFs and establish complexed fracture network. However, the effect of CSF on natural fractures is still unknown. Therefore, we perform laboratory CSF experiments on fractured granite samples from Gonghe geothermal outcrops to investigate the fracture interaction behaviors and induced seismic response.

1 SAMPLE PREPARATION AND EXPERIMENT PROCEDURE

The CSF experiments are performed on cylindrical granites that contains different types of NFs (weakly cemented NF and strongly cemented NF). The cylindrical samples with a diameter of 50mm and height of 95mm are drilling from large rock blocks where obvious NFs can be observed through the rock surfaces. A 10mm center borehole is cored to a depth of 60mm. And a 35mm long steel pipe is inserted to simulate the casing with 25mm open-hole reserved for fracturing and the NFs is located within the bottom 35mm height area, which do not contact with the open-hole section. Besides, intact granites are also prepared as control group to compared with previous studies and increase reliability.

The experiment procedure is as follows (Jia et al., 2021): First, water is injected at a pressuring rate of 0.15MPa/s into intact samples until rupture to obtain the unaffected breakdown pressure (BP). Then, cyclic injection tests were employed to two types of sealed NFs samples with a maximum injection pressure equal to approximately 80-90% of the average BP. Finally, the post-fracturing specimens are reinjected with ink-dyed water to observe the induced fractures. The experimental scheme and condition is shown in Table 1.

Table 1 injection scheme of MHF and CSF method.

Injection type	number	Axial stress	Confining pressure	Types of NF	The Maximum

		(MPa)	(MPa)		injection pressure
Monotonic injection	GH08	10	0	NO	PB
	GH09	10	0	NO	PB
	GH14	10	0	NO	PB
Cyclic injection	GH04	10	0	Strongly sealed NF	90%*PB
	GH06	10	0	Strongly sealed NF	90%*PB
	GH10	10	0	Strongly sealed NF	90%*PB
	GH01	10	0	Partially sealed NF	77%*PB
	GH03	10	0	Partially sealed NF	77%*PB
	GH11	10	0	Partially sealed NF	77%*PB

2 RESULTS AND CONCLUSION

2.1 Breakdown pressure and AE signal

The comparative tests (Fig.1) indicate that under the combined effect of NF and CSF, the BP can significantly decrease by 15-27%. While on the single effect of cyclic injection, it can decrease by approximately 10-20% (Zhuang et al., 2019). Besides, the existence of NF lowers the ultimate maximum cyclic pressure. Early study (Zhuang et al., 2019) found a threshold value of 80% Pb for CSF in intact rock, which means that when the maximum cyclic pressure lower than that, the rock cannot be fractured within limited time. Our experiment adopts a 73% maximum cyclic pressure for weakly cemented NF sample and the complete rupture occur within 40 cycles, proving the economic efficiency and feasibility of CSF on fractured HDR reservoirs.

Induced earthquakes are an inevitable issue during the EGS development. According to the AE signal of our experiments, when weakly cemented fractures exist, the maximum AE energy generated by CSF can increases by 41.2% (modified from dB). While for rock samples with strongly cemented NF, it can decrease by 47.9%. This indicates that for NF with low cementation degree, there is a risk of inducing earthquakes even for CSF. If the MHF is adopted in these samples, it is likely to generate a larger seismic magnitude for their more concentrated energy. These released large seismic energy may further activate the potential fault and trigger greater disaster.

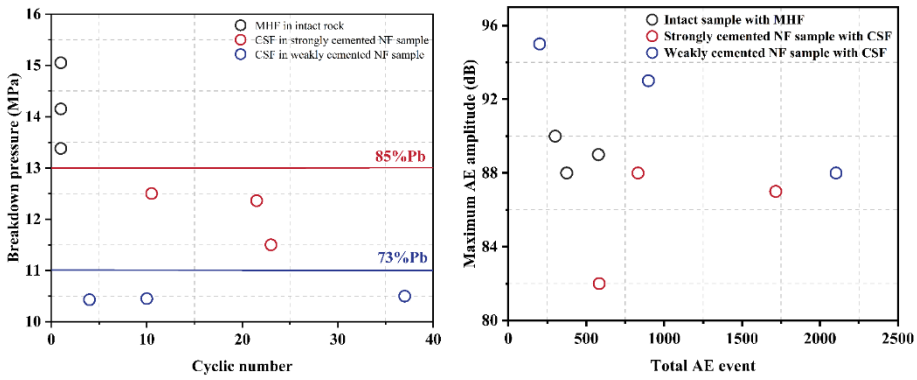


Figure 1. Experimental results of breakdown pressure (left) and the AE response (right).

2.2 Fracture morphology

As shown in Fig.2, the MHF all forms subvertical planar fractures under our experiments condition. While for CSF, the main hydraulic fractures are roughly the same as monotonic injection, but some branch fractures may occur locally and the preset natural fracture can be activated through long-term cyclic shock. There are four interaction mode between hydraulic fracture and NF in conventional HF, namely crossing, arrest, activate and their composite mode (Xie et al., 2025). The same mode is for CSF-induced fracture and NF. The difference lies in that CSF is more likely to activate the NF with shear failure. Our experiment adopts a large differential stress of 10 MPa, small included angle and large approaching angle of NF, MHF is inclined to directly cross the NF, especially

for strong cemented NF, forming a single main fracture. While CSF induces shear slip of the NF during cyclic injection, weakening the NF strength and increasing the possibility of fracture activation, it is easier for CSF-induced fractures to connect the weakened NF. Although the fracture width induced by CSF is not as large as that formed by monotonic injection, it activates more cemented NF to form a large-scale fracture network and enhance the overall permeability. Even for weakly cemented fractures that are easily be activated, due to the long-term injection of CSF, the shear slip can further increase the activated and rupture area of NF and increase the activation degree. Therefore, for naturally fractured reservoir, especially for the geological condition that NF are unfavorable to be connected. It is a better choice to apply CSF to activate the pre-existing NFs.

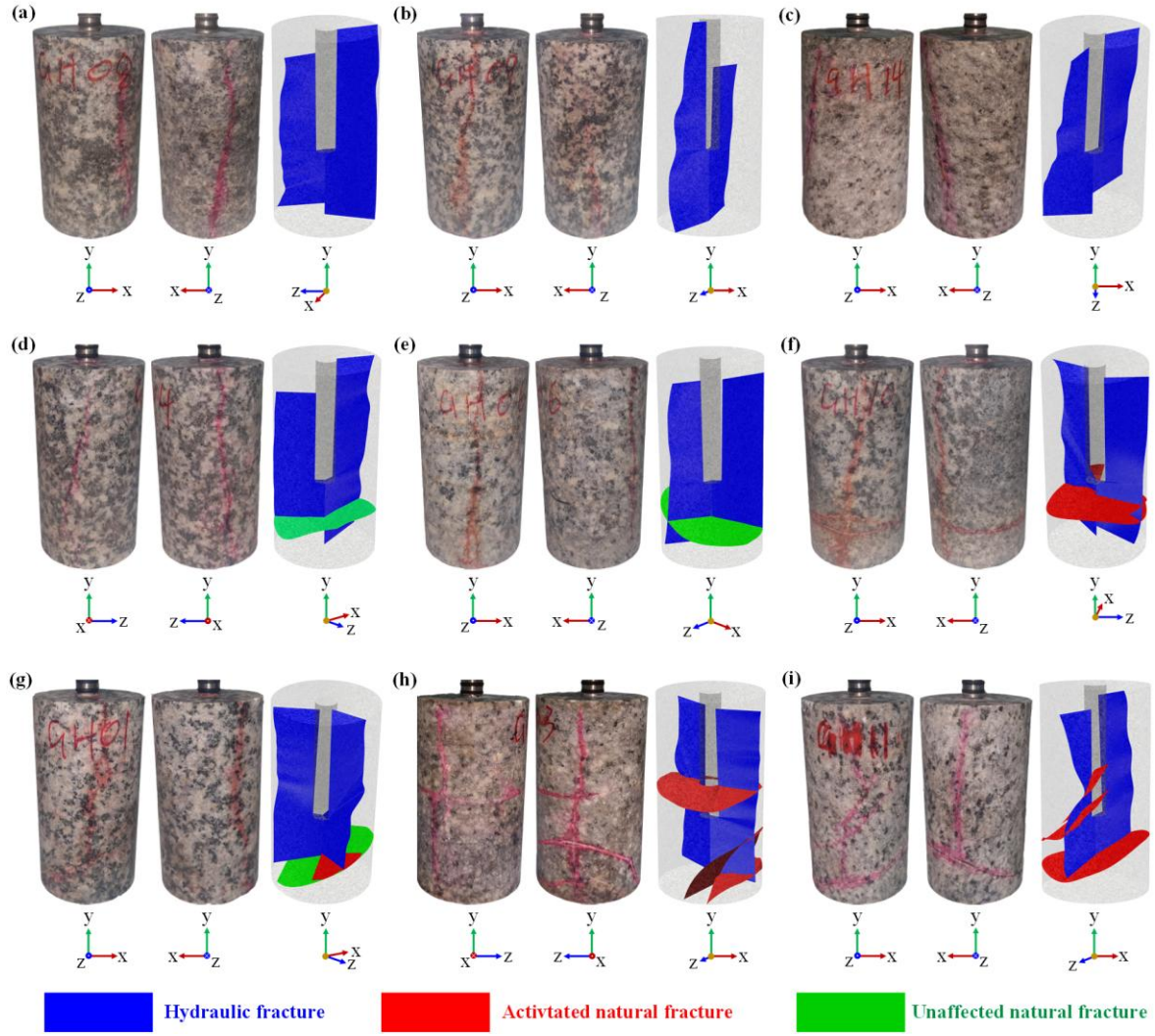


Figure 2. Fracture morphology under different injection protocol. (a) for MHF in intact samples; (b) for CSF in strongly cemented NF samples; (c) for CSF in weakly cemented NF samples.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support by the National Natural Science Foundation of China (No. U24B2032; No. 52421002; No. 52192621) and Science Foundation of China University of Petroleum, Beijing (No. 2462025XKBH018)

REFERENCES

Axelsson, G.: Chapter 20 - The future of geothermal energy. *In T. M. Letcher (Ed.), Living with Climate Change*, (2024), 397-422.

Hofmann, H., Zimmermann, G., Zang, A., et al.: Cyclic soft stimulation (CSS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments. *Geothermal Energy*, **6(1)**, (2018), 27.

Jia, Y., Lu, Z., Xiong, Q., et al.: Laboratory characterization of cyclic hydraulic fracturing for deep shale application in Southwest China. *International Journal of Rock Mechanics and Mining Sciences*, **148**, (2021), 104945.

Olasolo, P., Juárez, M. C., Morales, M. P., et al.: Enhanced geothermal systems (EGS): A review. *Renewable and Sustainable Energy Reviews*, **56**, (2016), 133-144.

Tursun O. T., Akyüz A. O., Erdem A., et al.: The state of the art in HDR deghosting: A survey and evaluation, *Computer Graphics Forum*. **34(2)**, (2015), 683-707.

Xie, Z., Huang, Z., Li, G., et al.: The effect of natural fractures on the failure mechanism of granite: Implication for enhanced geothermal systems. *Engineering Fracture Mechanics*, **299**, (2024), 109938.

Xie, Z., Huang, Z., Sun, Z., et al.: The interaction behaviors between the hydraulic fracture and natural fracture in hot dry rock. *Geoenergy Science and Engineering*, **247**, (2025), 213731.

Xie, Z., Wu, X., Long, T., et al.: Visualization of hydraulic fracture interacting with pre-existing fracture. *Petroleum Science*, **20(6)**, (2023), 3723-3735.

Zang, A., Zimmermann, G., Hofmann, H., Niemz, et al.: Relaxation damage control via fatigue-hydraulic fracturing in granitic rock as inferred from laboratory-, mine-, and field-scale experiments. *Scientific Reports*, **11(1)**, (2021), 6780.

Zhuang, L., Kim, K. Y., Jung, S. G., et al.: Cyclic hydraulic fracturing of pocheon granite cores and its impact on breakdown pressure, acoustic emission amplitudes and injectivity. *International Journal of Rock Mechanics and Mining Sciences*, **122**, (2019), 104065.