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Discrete Element Modeling of Rock Fracturing Using Functional Fluid

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INTRODUCTION

Hydraulic Fracturing

- Generates fracture around the borehole.
- Improves permeability and enhances productivity.
- Used for EGS to create artificial geothermal reservoir.
- Generates fracture in direction of maximum principal stress.

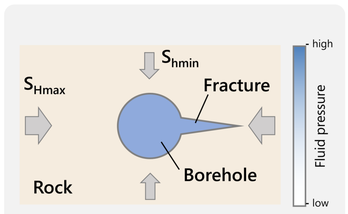


Figure 1. Diagram of fracturing.

Previous Research [1]

- Lab-experiment: Rock fracturing with shear thickening fluid (STF).
- **Multi-directional fracture formation.** <-> Only in direction of Max principal stress.
- **Repeated pressure build-up and drop.** <-> Once in conventional hydrofracturing.

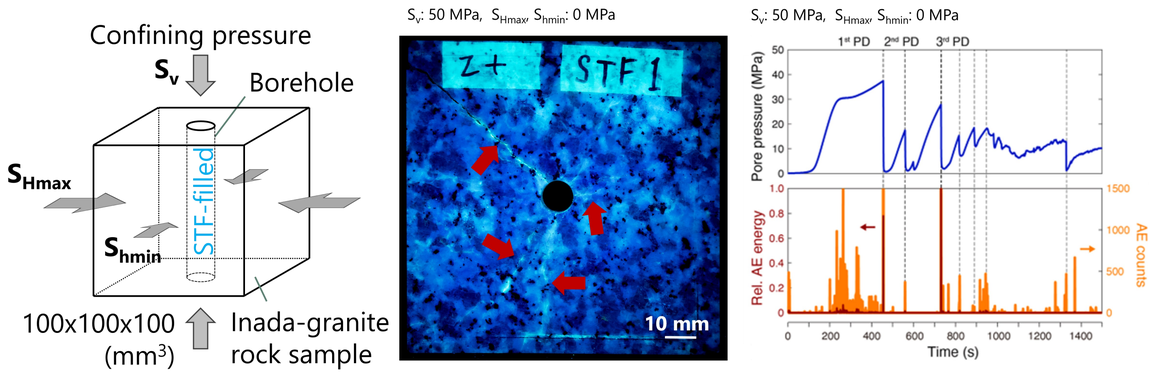


Figure 2. (a) Diagram of Lab-experiment, (b) Fluorescent photo of specimen, (c) Borehole pressure and AE. [1]

Shear Thickening Fluid

- STF is a Functional fluid.
  (its viscosity can be controlled as desired)
- Behaves like a solid under shear.
- Made by mixing powder particles and fluid.
- A kind of non-Newtonian fluid whose viscosity increases nonlinearly with shear rate.

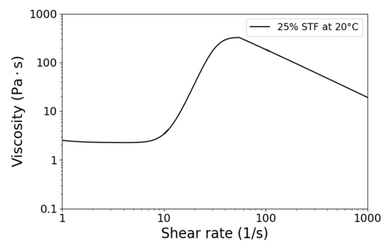


Figure 3. Rheology curve of STF. [2]

METHODS

Discrete Element Method

- Rock model is composed of rigid circular particle elements and spring bond.
- A simulator based on fluid-fluid coupled DEM by Shimizu et al. [3] was used.

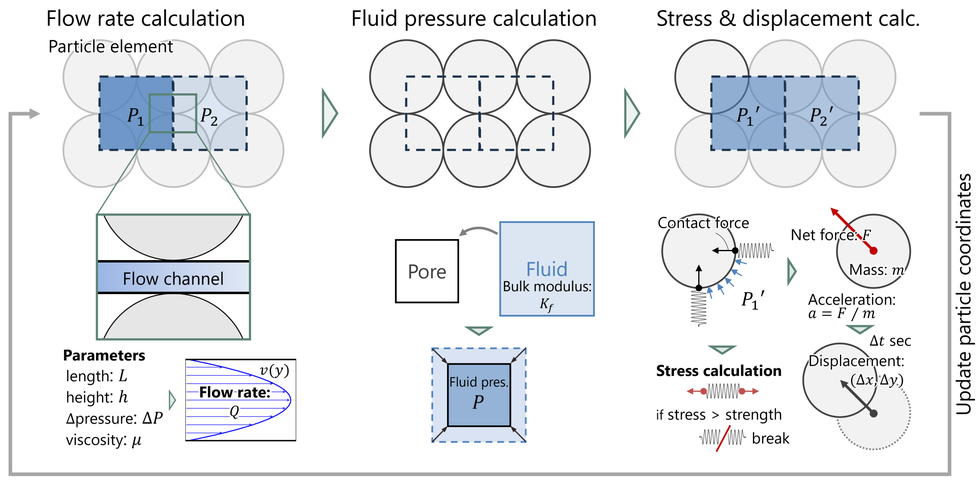


Figure 4. Diagram of flow-coupled DEM calculation.

Our modeling of STF flow calculation

- Each flow channel has different viscosity.
- In one channel, viscosity varies with time depending on the state of flow.
- Relaxation time was also considered.
- If the viscosity decreases, it is calculated according to the exponential decay curve with relaxation time τ, based on the maximum value of viscosity before the decrease, as
- $$\eta(t) = \eta_{max} \cdot e^{-\frac{t}{\tau}}$$
- Relaxation time τ was determined through a trial and error process in this study.

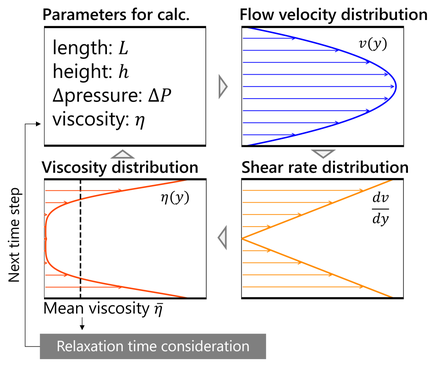
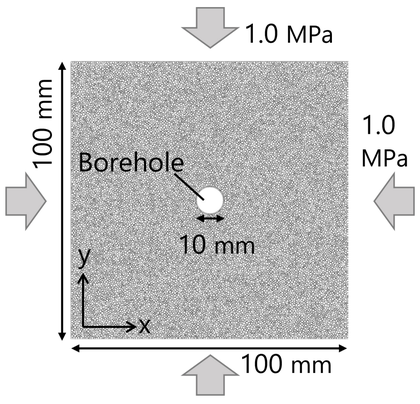


Figure 5. Diagram of the STF flow calculation.

SIMULATION CONDITIONS & RESULTS

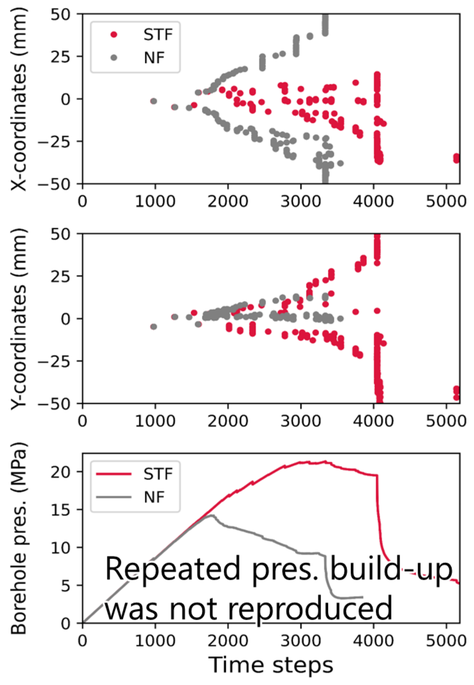
Table 1. Simulation Conditions

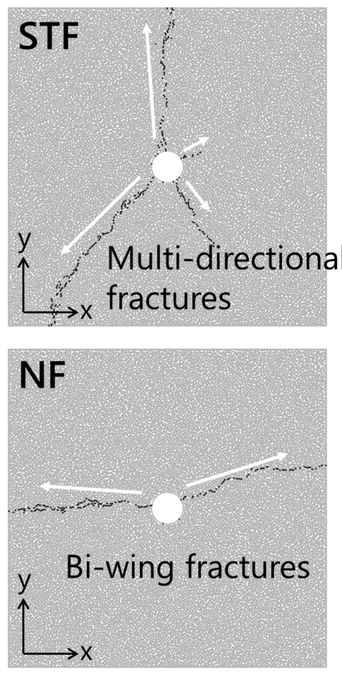
Properties	value
Number of particles (approx.)	20000
Radius of particles	0.23-0.46 mm
Viscosity of NF (Newtonian fluid)	3.3 Pa· s
Assumed concentration of STF	25 %
Range of viscosity of STF	3.3-327 Pa· s
Fluid bulk modulus	2.0 GPa



- Same size with the rock sample used in the experiment by Mukuhira et al. (2025)
- Physical properties were adjusted to match Inada granite.
- No differential stress for this simulation to verify simple conditions first.

Figure 6. Rock model and confining pressure.





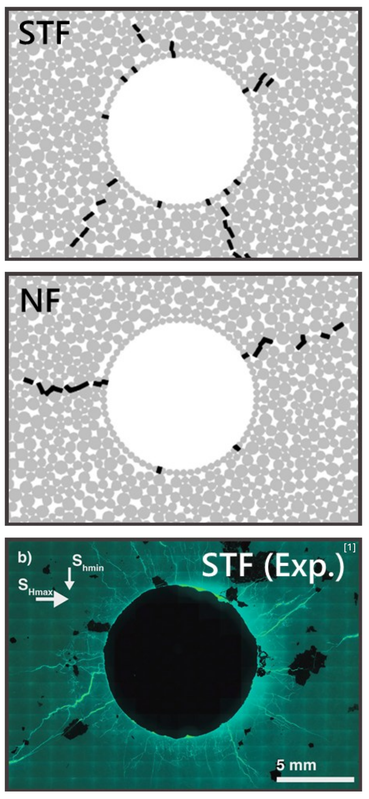


Figure 7. Time series change of x- and y-coordinates of microcrack generations, borehole pressure, and the rock model at the end of the calculation.

Figure 8. Microcrack generations of STF (step=2400), NF (step=1900), and microscopic photo around the borehole after the experiment. [1]

Findings

- Microcracks were generated in multiple directions in STF case.
- More multi-directional microcracks were seen in the STF case compare to the NF case.
- Multi-directional microcrack generation was also observed in the experiment. [1]
- Our simulation succeeded in reproducing the phenomena qualitatively.

DISCUSSION

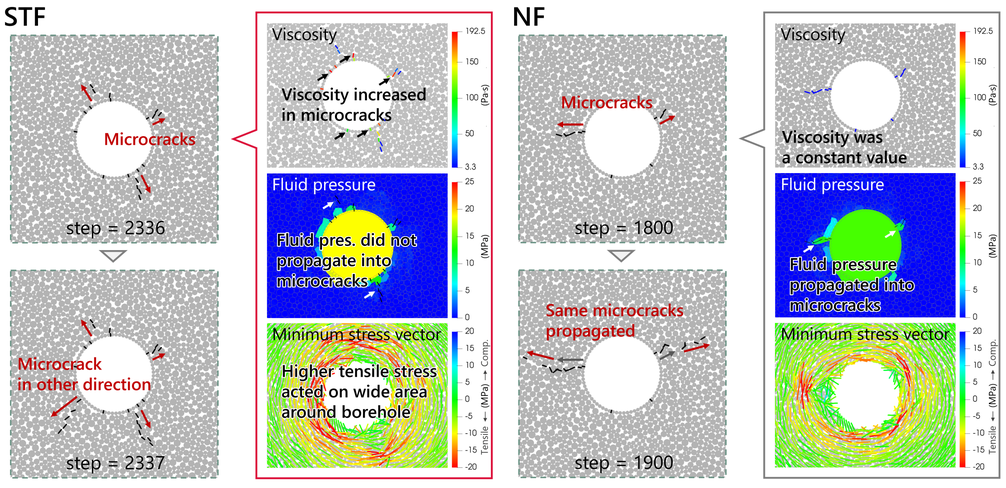


Figure 3. Viscosity, fluid pressure, and vector of minimum principal stress acting on particles

Mechanism of multi-directional fracture nucleation we propose

1. STF viscosity locally increased as start flowing into microcracks.
2. Viscosity increase suppressed fluid flow into microcracks.
3. Higher borehole pressure due to reduced fluid outflow.
4. Fluid pressure did not increase in microcracks.
5. High tensile stress acted on wide area around borehole.
6. Fluid pressure did not act on the tip of longest microcracks.
7. It allows time for other microcracks to propagate.

CONCLUSION

- STF fracturing can produce efficient permeability enhance by multi-directional fracture.
- Our DEM simulation was able to qualitatively reproduce the creation of fractures in multiple directions caused by STF fracturing and the results partially revealed underlying mechanism.
- Results suggest that multi-directional microcracks around borehole, likely caused by increased STF viscosity, could be a key factor in development of multi-directional fractures.

Future plan

- Conduct STF fracturing simulations under differential stress conditions.
- Discuss the relationship between initial stress and crack initiation behavior.

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