Effects of Normal Stress Reduction on Seismic Triggering

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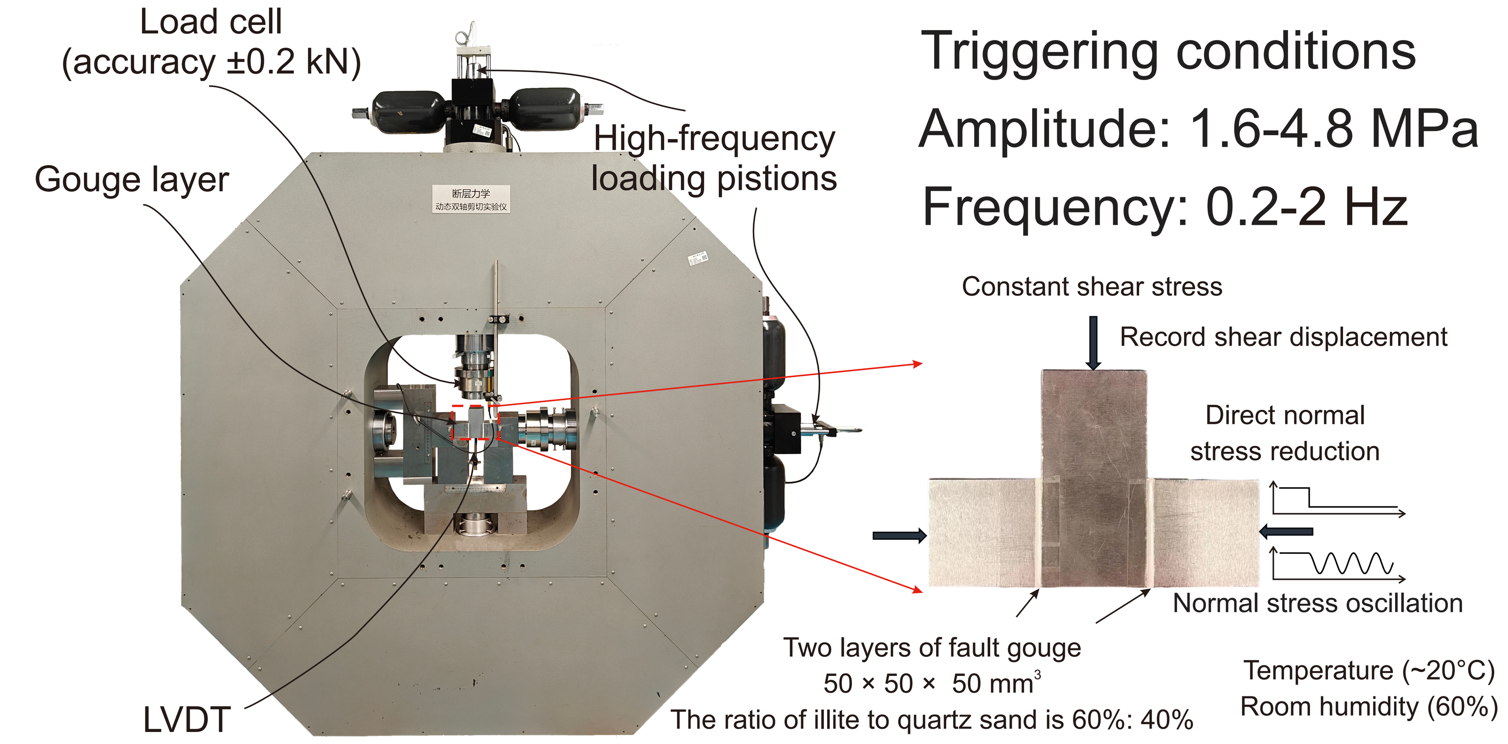
1. Introduction

- In hydraulic fracturing operations, elevated fluid pressures can reduce effective normal stress, promoting fault reactivation and potentially triggering seismicity.
- Different injection loading schemes can result in distinct slip behaviors in fault zones, and notably, cyclic pressurization has been observed to suppress seismicity.
- We employ the double direct shear apparatus to study the frictional behavior of fault gouges under sine-shaped normal stress oscillations and direct normal stress reductions, with constant shear stress applied.
- Our research reveals variations in fault slip behavior and the controlling factors under different triggering conditions.

2. Experimental Setup



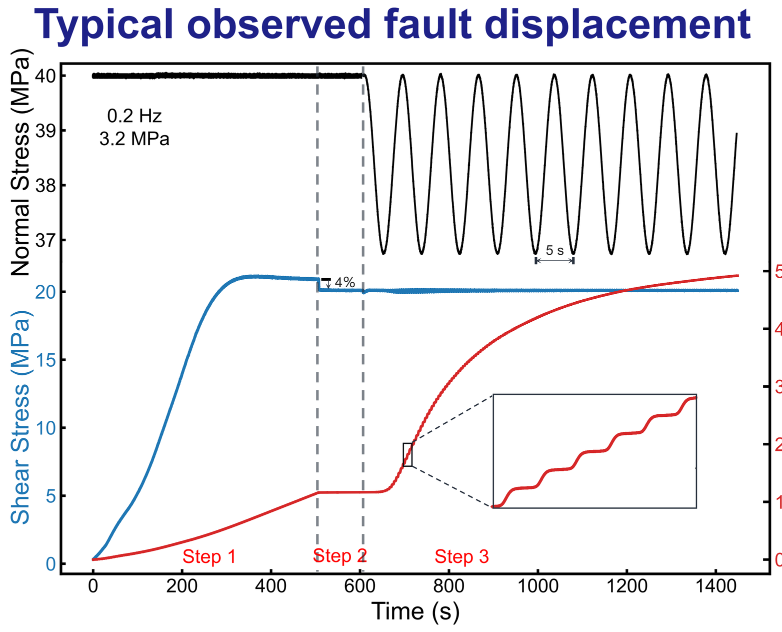
Triggering conditions
Amplitude: 1.6-4.8 MPa
Frequency: 0.2-2 Hz

Double-direct shear apparatus

Experimental Procedures

- **Step 1**: Shear loading is applied at a constant rate of 3 μm/s under a normal stress of 40 MPa to drive the faults to post-peak steady-state sliding over a same distance;
- **Step 2**: Shear stress is reduced to a set proportion of the steady-state frictional strength and held for 100 s;
- **Step 3**: We employ two approaches to reduce the normal stress and trigger fault slip.

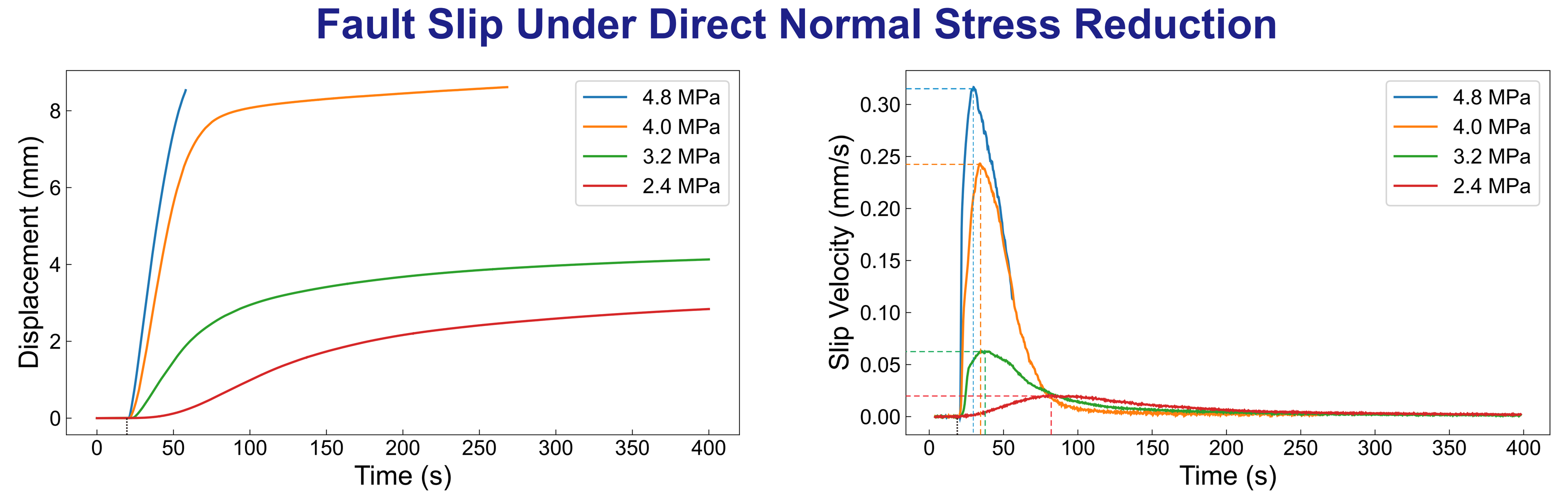
Typical observed fault displacement



3. Fault Slip Characteristics

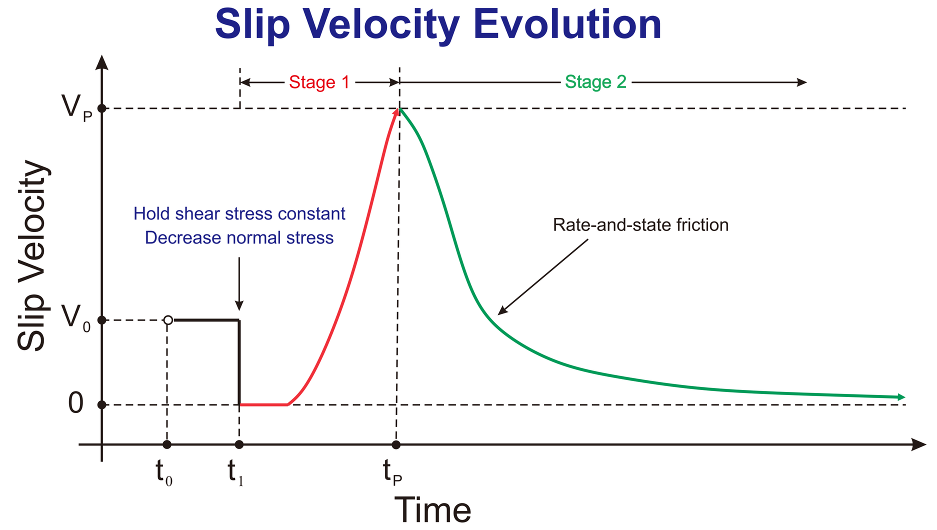
- We reduce the normal stress to trigger fault slip and maintain it for a sufficient duration to investigate its long-term behavior;
- Fault slip characteristics are analyzed based on measurements of slip displacement and slip velocity.

Fault Slip Under Direct Normal Stress Reduction



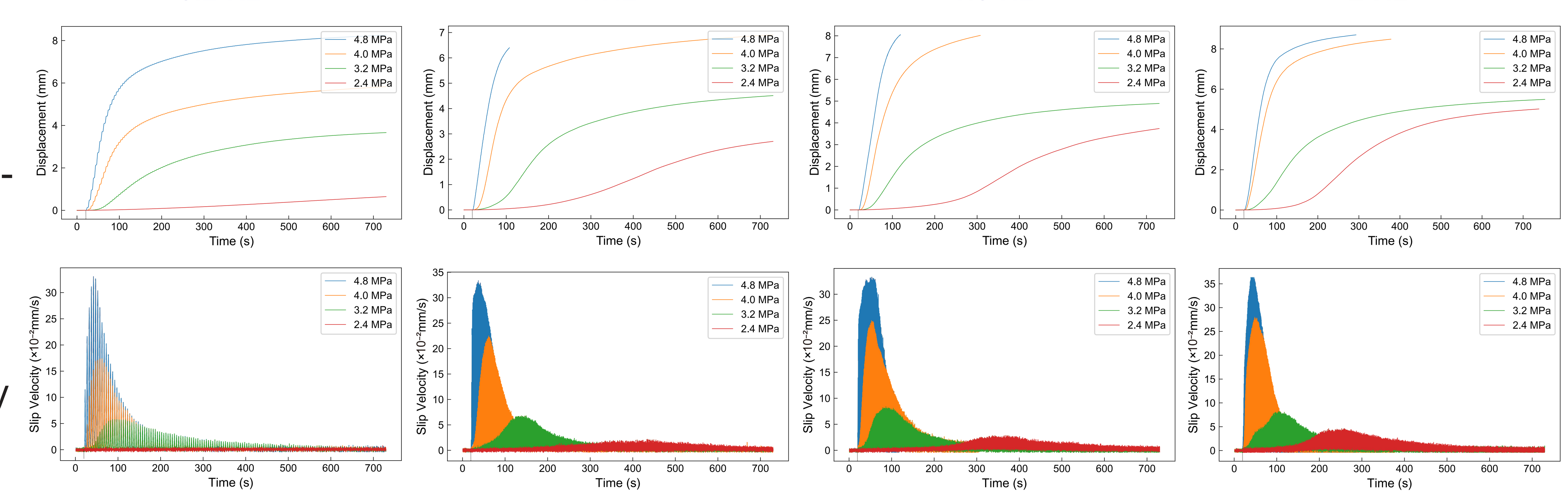
- The slip process exhibits a two-stage evolution: an acceleration phase (Stage 1), followed by a deceleration phase (Stage 2);
- As the magnitude of normal stress reduction increases, the peak slip velocity increases, and the time to peak velocity decreases;
- A larger reduction in normal stress leads to higher acceleration in Stage 1 and higher deceleration in Stage 2.
- Stage 1 corresponds to the nucleation process of the fault slip;
- The evolution of slip velocity in Stage 2 is consistent with predictions from the rate-and-state friction framework.

Slip Velocity Evolution

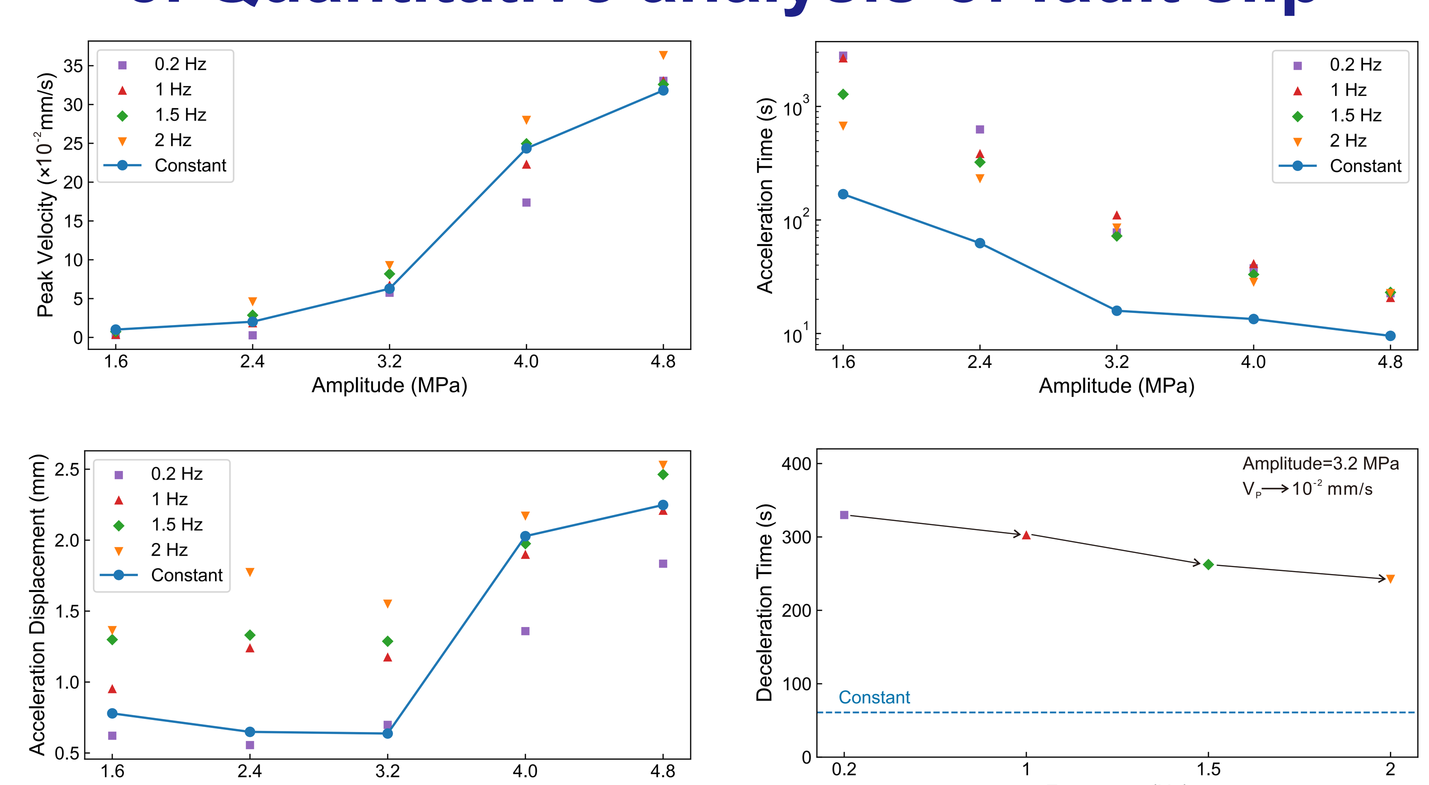


4. Fault Slip Under Normal Stress Oscillations

- Each normal stress oscillation cycle involves fault acceleration followed by deceleration and arrest.
- The influence of oscillation amplitude and the trend of the slip velocity envelope are consistent with the results obtained under direct normal stress reduction.
- The evolution of fault slip velocity is influenced by the frequency of normal stress oscillations.



5. Quantitative analysis of fault slip



6. Conclusions

- Our research identifies two characteristic stages of triggered fault slip: acceleration and deceleration, along with variations in slip velocity associated with the amplitude and frequency of normal stress;
- The fault slip velocity envelope triggered by normal stress oscillation is similar to that under direct normal stress reduction;
- Quantitative analysis reveals controlling factors of fault slip, which we believe are mainly related to the stress path;
- Our research provides insights into the potential impact of underground engineering activities on fault zones.