Frictional Properties and Structural Evolution in the Sheared Granular Medium of Halite

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1. Introduction

In conventional friction experiments (e.g., double direct shear, rotary shear, biaxial shear, etc.), a very thin shear zone is defined by the amount of gouge that is initially sandwiched between hard host rocks or generated during experiments. The simulated shear zone cannot become thicker because of restricted slip displacement or confined geometries. However, the thickness of gauge in natural faults could be much larger (e.g., Engelder, 1974). In the upper crust, cataclasis occurs during faulting of porous rocks (sandstone) and in macroscopic flow (e.g., rock avalanche), where original grains are fragmented, and gouge can be severely deformed within the matrix of crushed grains. Therefore, attempts to refine lab frictional measurements on faulting should take into account of grain comminution, structural evolution, and fault zone dimensions.

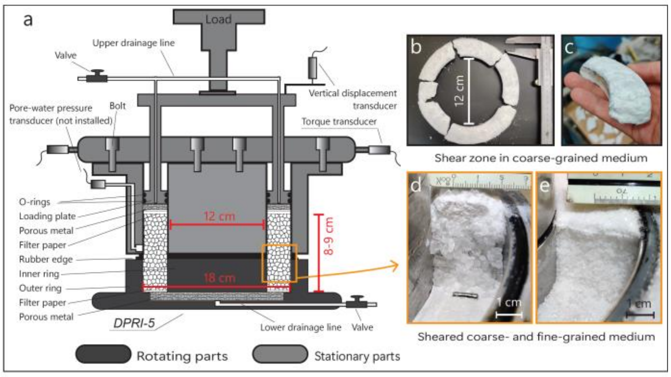

Fig. 1. Experimental setup and simulated fault zone.

In this study, we employed a ring-shear configuration (Sassa et al., 2004) (Fig. 1a) that had a large shear box (18 cm and 12 cm for outer and inner diameters, 10.9 cm for maximum sample height) to test a large volume of grains. Halite (NaCl) has been frequently used as an analogue for fault gouge (e.g., Shimamoto, 1986; Bos and Spiers, 2002) and the frictional measurement scatters across the literature upon different test conditions including normal stress, slip rate, and testing machine (Buijze et al., 2017). We employed halite grains to simulate grain comminution under the limited loading condition of ring-shear apparatus. As shown later, development of a large experimental fault zone was observed within the granular medium (Figs. 1b-1e).

2. Materials and methods

We used coarse-grained halite of 2-5 mm size and fine-grained halite was of 0.425-0.85 mm. In the ring-shear tests, we applied a constant slip rate V = 0.05 cm/s and varied normal stresses σ = 0.2, 0.6, and 1.0 MPa. Friction coefficient was obtained by taking the ratio of shear resistance over normal stress.

After the sliding over 2 m, microscopic observation using a micro X-ray Computed Tomography (CT) and a Scanning Electron Microscope (SEM) was performed to study the post-slip structure.

3. Results

Fig.2 shows time evolutions of friction coefficient during ring-shear experiments. Two distinct mechanical behaviors were clearly observed, i.e., a higher friction coefficient remained over a slip (stable regime), followed by frictional weakening (weakening regime) to a steady state. We applied a nonlinear least-square fitting with the following equations to constrain the evolution of friction $\mu(\delta)$ and height change of sample $\Delta h(\delta)$ with slip δ (Fig. 2). From the fitting, the characteristic lengths for the stable regime (L_0), weakening regime (L_w), sample compaction (L_h), and steady state friction (μ_{ss}) and height change (Δh_{ss}) were estimated.

$$\mu(\delta) = \begin{cases} \mu_0 \, , & \delta < L_0 \\ (\mu_0 - \mu_{ss}) \exp\left(-\dfrac{\delta - L_0}{L_w}\right) + \mu_{ss} \, , & \delta \geq L_0 \end{cases} .$$

$$\Delta h(\delta) = \Delta h_{ss} \left[1 - \exp\left(-\frac{\delta}{L_h}\right)\right].$$

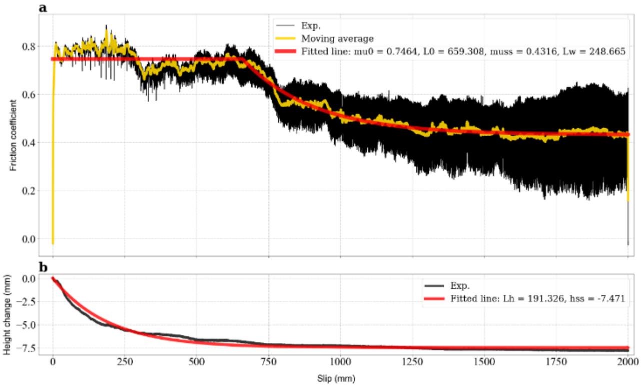

Fig. 2. One example for experimental data and fitting.

The sheared granular medium was characterized by intense grain comminution. The micro-CT images of the experimental fault zone present (1) cataclasis flow without shear localization under low normal stress, and (2) extremely localized slip in the middle of highly comminuted grain matrix under high normal stress (Fig. 3). The SEM images magnified the comminuted fines of ~10 μ m, that are densely packed on the localized slip surface with a number of nano grains (Fig. 3).

4. Discussion and summary

From the fitting, we found that the characteristic lengths decreased with the increase in normal stress. A power of 2 could be obtained approximately to scale the normal-stress-dependence for the stable regime and weakening regime:

$$L_0 \sim \sigma^{-2} \text{ and } L_w \sim \sigma^{-2}$$

The sheared granular system is expected to yield a higher comminution rate under larger normal stress. We propose that the characteristic length L_0 for the stable regime is determined by a comminuted-fines saturation process (Fig. 3). Within a characteristic thickness of shear zone, grain comminution generates fine granular particles to fill the voids. Grain segregation is also operative to that allows comminuted fines to migrate away from source and push large grains towards the active comminution zone. The fines might work as an interstitial fluid. Even after the fine granular particles saturates the shear zone, the comminution mechanism continuously supplies the particles and the pseudo fluid pressure p starts to build up. The effective normal stress between large grains decreases and the frictional weakening begins. Finally, shear localization matures, and a through-going slip surface is developed within the very thin layer of fines.

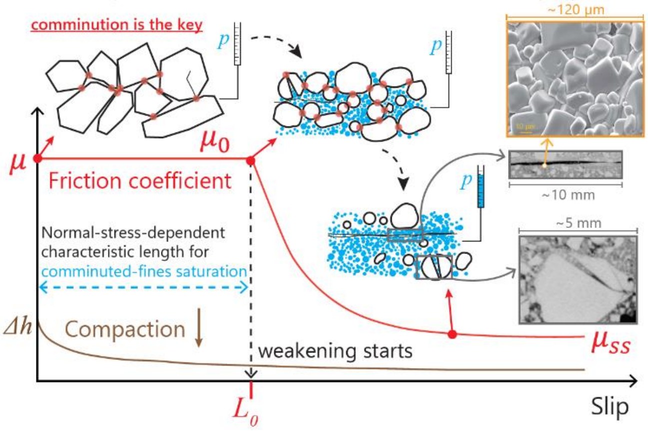

Fig. 3. Conceptual model for weakening mechanism combined with micro-observations.

In our experiment, the micro-structure and intrinsic comminution appear to be strikingly similar to natural fault zones (e.g., Chester and Chester, 1998) and rock avalanche deposits (e.g., McSaveney and Davies, 2007), which suggests our experimental model is possibly applicable to natural systems.

Reference

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