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Unified understanding of frictional instability based on Rowe's theory on constant minimum energy ratio

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1. Introduction

With respect to frictional instability, many studies on rate and state dependent friction law and the microstructural observations of a gouge layer have been conducted (e.g., Dieterich, 1979; Byerlee et al., 1978). Moreover, Ikari et al. (2011) indicated that frictional parameter (a-b) transits with shear localization. However, the theoretical background for the relationship between frictional parameter and shear localization has not been clear yet. To understand it, we need to assess deformation process of gouges (e.g., shear localization) quantitatively. Here, we focus on Rowe's theory on constant minimum energy ratio (Rowe, 1962) because deformation process of particles is treated quantitatively in terms of energy. We also conduct friction experiments of simulated fault gouge to test the validity of the theory. So, based on the results, we aim to discuss frictional instability and particle deformation quantitatively in terms of analytical dynamics and thermodynamics.

2. Theoretical background

A stability of a system (e.g., a block slider model) depends on a non-linear effect of a damping (e.g., Thompson, 1982). Thus, stable slip is a result of a damping. In contrast, negative damping, or self-excited oscillation leads to unstable slip. The damping is decided by a damping constant; the system is stable when the damping constant is positive. Moreover, it is clear that displacement is controlled by the damping constant from the equation of motion. The damping constant derives from a friction force to a system. So, positive or negative of the damping constant means directions of friction force. Then, we consider that the frictional parameter deriving from coefficient of friction can be described as a ratio of tangential force (friction force) to vertical force. Therefore, frictional parameter has a close relationship with the damping force. Additionally, the relationship between stored energy in a system and energy ratio, or the ratio of input energy to output energy, is obtained from Niiseki and Satake (1981) and Landau and Lifshitz (1976). From these results, the range of energy ratio (K) is clear; in case of $K > 1$, system behave stable. On the contrary, system behaves unstable when $0 \leq K < 1$.

3. Friction experiments

12 friction experiments with simulated fault gouge (quartz) were conducted in a gas medium apparatus (Pc: 140-180 MPa). A geometry of gabbroic split cylinders sandwiching gouge were 20 mm in a diameter, 40 mm in a length and 50 degree precut from their cylindrical axis. The samples with gouge were loaded at a constant strain rate (10^{-3} /s). To obtain energy of gouge in directions of the maximum and minimum compressive stresses, strain gauges were placed. The loading and stop loading periods were repeated 4 times at differential stresses of about 190, 450, 640 and 800 MPa. After that, the sample was loaded again until strains exceeded the measurable range of strain gauges or unstable slip occurred.

4. Results and discussion

From our experiments, output energy can be expressed as a linear function of input energy. So, energy ratio of gouge is constant. Thus, gouge obeys Rowe's theory. However, in detail, the change in energy ratio was observed depending on each stress state. We consider that this change reflects the particle arrangement in each state, because energy ratio is a function of internal friction angle. Moreover, the change in energy ratio indicates the change in the damping constant. Additionally, frictional parameter is equivalent to the direction of friction force decided by a damping force. Thus, the change in the damping constant leads to the change in frictional parameter.

5. Summary

We investigated frictional instability of gouge by theoretical and experimental study. As a result, the physical and energetic background for the relationship between frictional parameter and shear localization become clear by using the damping constant based on Rowe's theory.

Keywords: frictional instability, simulated fault gouge, friction experiments, a gas-medium apparatus, Rowe's theory on constant minimum energy ratio