Static Friction, Healing, and Constitutive Laws for time- and slip-dependent friction

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Abstract

I summarize laboratory friction measurements on simulated granular fault gouge. Experiments were performed in the double-direct shear geometry. Static friction, frictional relaxation, and compaction increased linearly with log hold time. These parameters and the rate of frictional healing also varied systematically with loading velocity. The results indicate 1) that healing is closely related to gouge porosity and 2) that healing and static friction are not simply frictional properties, but rather are system responses that vary with loading velocity and elastic properties. Constitutive modeling indicates that both slip- and time-dependent state evolution laws can fit individual tests. However, constitutive parameters vary with velocity and hold-time. Thus, the parameters determined from one set of conditions cannot, in general, match data from other conditions. This indicates differences in the underlying processes and/or limitations in the current rate and state friction laws, in particular lack of a specific term to account for porosity changes.

Introduction

The rate at which frictional surfaces strengthen is of fundamental importance for many problems in mechanics, particularly those involving repetitive stick-slip. For earthquakes and faulting, the seismic cycle of repeated failure requires that faults restrengthen (heal) during the interseismic period, and the rate of healing plays a key role in determining fault strength, seismic stress drop, earthquake repeat time, and the mode of dynamic rupture propagation (*Marone, 1998a,b*). However, the rate of healing and the underlying deformation mechanisms are poorly understood.

Laboratory measurements on rock surfaces and simulated fault gouge indicate that frictional healing (defined as the time dependent increase in static friction) is approximately linearly with log time during quasi-stationary contact (*Dieterich, 1972; Beeler et al., 1994; Karner and Marone, 1998*). This is generally consistent with seismic estimates of fault healing (*Marone et al., 1995*). However, in the laboratory rock friction increases by only a few percent of its absolute value per decade in time, whereas seismic stress drop increases by a factor of 2 to 5 per decade increase in earthquake recurrence interval (*Kanamori and Allen, 1986; Scholz, et al., 1986; Marone et al., 1995*). The apparent dis-

crepancy may arise from a number of sources, however, previous studies have proceeded by direct comparison of laboratory and seismic estimates of fault healing. This approach assumes that healing and time dependent variations in static friction are intrinsic frictional properties. However, as shown here, healing varies with loading velocity. Related effects are summarized in *Marone 1998a*. The experimental data indicate that healing is a system response, for which modeling must be carried out to recover the intrinsic constitutive parameters for comparison between laboratory and field conditions.

The purpose of this extended abstract is 1) to summarize laboratory measurements of the effect of loading velocity on static friction and the healing rate of granular fault gouge and 2) to use these data to critically evaluate rate and state dependent friction laws. The laboratory data indicate a trade-off between healing time and loading velocity, with faster slip producing larger static friction for a given contact time. Such behavior is predicted by rate/state friction laws. However, detailed comparison of the friction parameters determined from different types of tests indicates a lack of internal consistency. The healing rate predicted by constitutive parameters obtained from velocity-step tests is faster than observed during relaxation tests. This may be attributed to changes in the underlying deformation mechanisms as a function of velocity or to limitations in the form of the friction laws as they are currently written.

Experiments

Friction experiments were carried out on rock and granular fault gouge (used to simulate breccia and wear material within fault zones) in a servocontrolled testing apparatus. The apparatus consists of two perpendicular load frames fitted with hydraulic rams capable of producing forces up to 1 MN. Each ram is controlled by a high-speed servo capable of running in load or displacement feedback. The experiments described here were performed in displacement feedback control to produce a constant loading rate.

To simulate natural fault roughness, gouge layers of granular quartz powder (initial particle size 50-150 μm) were sheared within granite surfaces roughened by sandblasting (rms. roughness • 200 μm). Shear was imposed in the double-direct-shear configuration by controlling displacement of a load point in contact with a central sample block as it was forced between two contacting blocks (Figure 1). Nominal frictional contact dimensions were 10 cm x 10 cm and gouge layers were initially 2.1 mm thick. Normal stress on the fault planes was held constant at 25 ±0.1 MPa and changes in layer thickness were recorded continuously to a precision of 0.1 μm. Shear stiffness of the apparatus is 250.0 MPa/cm expressed as shear stress per unit shear displacement, or $1x10^{-3}$/μm expressed as a change in the coefficient of friction per shear displacement for the normal stress used.

Results and modelling

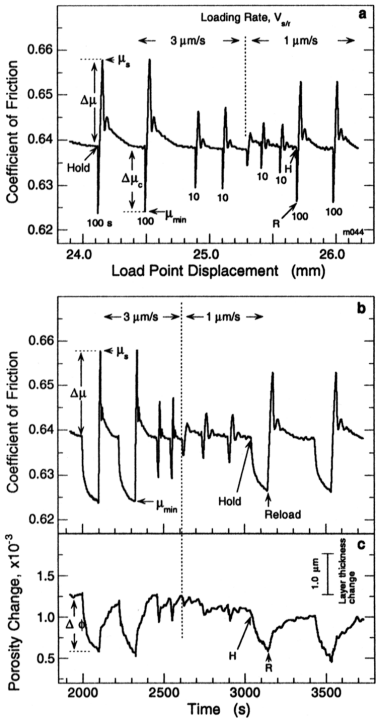

Figure 1: Friction and porosity data using slide-hold-slide tests at two loading rates. Hold times are given below in data in (a). The Friction data of panel (a) are plotted vs. time in (b). Panel (c) shows time dependent compaction during holds and dilatation upon reloading.

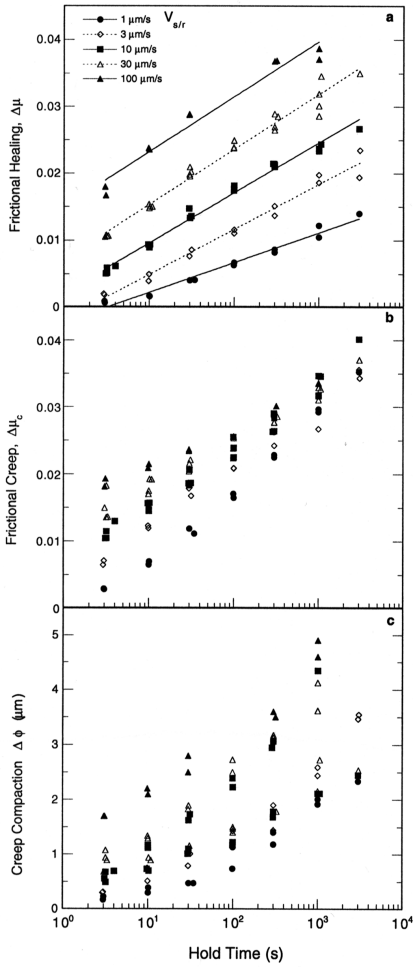

Figure 2: Friction and compaction data from slide-hold-slide tests performed at a range of loading velocities. All data are plotted vs. a common x-axis. (a) Healing varies systematically with hold time and loading velocity. Lines show best fit log-linear relations for each loading rate. (b) Creep relaxation during holds increases with log hold time and loading velocity. (c) Gouge compaction during hold (see Fig. 1c) increases systematically with hold time and loading velocity.

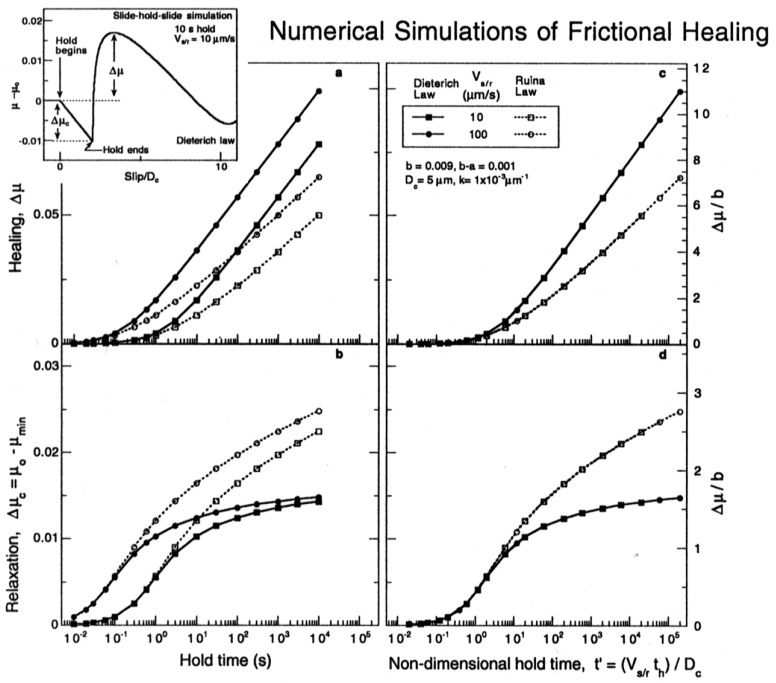

Figure 3: Numerical simulations of slide-old-slide tests. (inset to a) Simulation of a 10 s hold with slide and reload velocity = 10 μm/s. The relative change in friction is shown versus non-dimensional slip. Panels (a) and (b) show healing and relaxation versus log hold time. (c) and (d) are plot of the data from (a) and (b), respectively, versus non-dimensional hold time. Note that the ordinates are the same for panels (a)-(c) and (b)-(d), respectively. Simulations show a rate dependence of healing and relaxation, as observed in the laboratory data. Note that the Dieterich Law predicts greater healing and less relaxation for a given hold time and loading rate. All simulations were carried out using the constitutive parameters and elastic coupling indicated in panel (c).

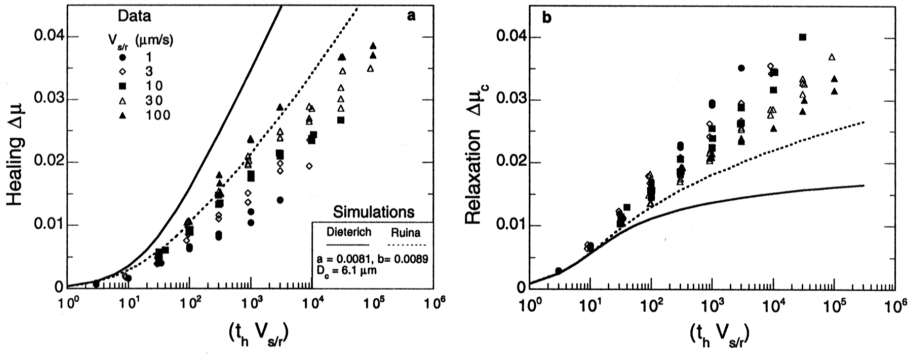

Figure 4: The laboratory friction data of Fig. 2 are plotted versus the product of hold time and loading velocity. As predicted by the rate state friction laws, the data define a single trend, within the scatter. Also shown are numerical simulations of healing and relaxation calculated using constitutive

parameters obtained from velocity-step tests. Parameters are given in panel (a). The Ruina law fits somewhat better than the Dieterich law, but neither law matches the data well.

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