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Effects of Dynamic Stressing on the Strength and Stability of Creeping Faults

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Summary

A central problem in studies of fault interaction and earthquake triggering is that of quantifying changes in frictional strength and constitutive response caused by dynamic stressing. Earthquake-induced stress changes can trigger fault slip, cause changes in seismicity rate, and lead to additional damaging earthquakes. To date, studies of stress triggering have focused primarily on static stresses and simple failure models. However, dynamic stresses are also expected to be important in earthquake triggering, particularly at large distances from the mainshock. Moreover, studies of fault interaction and stress transfer commonly find that triggered seismicity is delayed relative to the arrival of dynamic or static stresses. Such delays are not predicted by simple, Coulomb failure models. Recent theoretical work shows that dynamic stressing can lead to destabilization of creeping faults and resonant behavior, characterized by large amplitude stick-slip instabilities. Numerical models are available to study dynamic stressing and their role in earthquake triggering and fault interaction. However, the laboratory data necessary to carry out such studies have been sparse. Laboratory data are needed to account for changes in fault strength and to understand the effects of dynamic stresses on frictional strength and stability. These data are important for NEHRP research objectives. The research conducted under this grant will help to reduce earthquake related losses in the US by improving models for fault interaction and short-term changes in seismic hazard.

This grant supported research on the effects of dynamic stressing on the strength and stability of granular and clay-rich faults. Laboratory measurements included the effects on frictional strength and stability of shear loading rate oscillations and normal load fluctuations. We investigated shear destabilization and resonant behavior for granular and clay-rich simulated fault gouges. Dynamic stresses were imposed during steady creep and the results used to test theoretical models based on friction constitutive laws. Normal load step tests, velocity step perturbations, and harmonic oscillations of shear loading rate were imposed to determine the material constitutive response under a wide range of conditions. Our preliminary results show that several factors, have important effects on the frictional response to dynamic stressing. Results of these experiments are expected to have significant impact on understanding fault mechanics and earthquake physics including triggering of seismic and aseismic fault slip, fault interaction, and seismic hazard assessment.

Introduction

Fault zones experience periodic deviations in their stress state at various magnitudes and timescales. These range from long time scale static changes, such as tectonic loading due to interaction with a nearby fault, to transient high-frequency changes such as seismic waves or solid Earth tides. Whereas static stress transfer alters the fault boundary conditions, transient stresses can change material response of the fault zone but do not permanently alter the stress state. Both static and dynamic stress variations induce changes in seismicity rates, however, only transient stresses can trigger remote earthquakes (greater than a few fault lengths from the source). The effects of static stress transfer have been relatively well-studied and are considered in earthquake hazard assessments. In contrast, the effects of transient stress transfer are poorly understood. For example, not all large earthquakes trigger remote seismicity and certain geographic regions seem more susceptible to triggering. Understanding transient stress effects on fault strength and stability would enhance our knowledge of how and when earthquakes are triggered.

Dynamic triggering in natural earthquake settings does not seem to depend on the magnitude of the trigger nor distance from the event, but could be a function of the oscillating stress frequency. Furthermore, the time delay between triggering and the triggered event varies. Triggered earthquakes may be events that were inevitable, such that dynamic triggering merely sped along their occurrence. Subsequently, the time delay between trigger and triggered event may depend on how close the fault was to failure. Time/stress path dependence of failure cannot be represented with a Coulomb failure model (which predicts failure at a particular stress state, independent of rate or time).

We analyzed shear stress response of a laboratory fault to periodic shear loading rate oscillations. In these experiments we oscillate shear loading rate while maintaining a constant normal stress. Additionally, our experiments are conducted on a granular material. A constant shear loading velocity, representing remote stress, was amended by a sinusoidal wave simulating a transient oscillation. We deciphered how these oscillations influenced the material response by varying loading rate, as well as amplitude and frequency of the oscillations. Our laboratory fault experienced stick-slip instabilities analogous to the earthquake cycle both during shear vibrations and under non-oscillating load conditions. We measured changes in the stick-slip cycle such as recurrence interval, failure strength, stress drop, and the pre-seismic duration and slip to determine how transient shear oscillations may affect fault stability.

Technique

Experiments were conducted using a servo-controlled, biaxial apparatus with a double-direct shear configuration (Fig.1 inset). The samples were loaded in shear displacement servo-feedback with 0.1 μm resolution to achieve a constant displacement rate of a load point at the top of the center block of the double-direct shear assembly (Fig.1 inset). The load point displacement history consisted of a linear function with a sinusoid superimposed to mimic a tectonic load and oscillating stress. A constant normal stress of 5 MPa was implemented with a servo-controlled load-feedback mechanism (with 0.1 kN resolution); such low normal stresses eliminate comminution of the sample and any associated changes in stick-slip behavior. The stiffness of the vertical loadframe is 5 MN/cm or 250 MPa/cm when expressed as the shear stress on a sample with nominal friction contact dimensions of 10 cm x 10 cm. Stiffness of the apparatus and sample assembly is 0.017 MPa/μm, as determined in-situ by measuring the instantaneous shear stress response to a step change in loading rate.

In one set of experiments, we sheared 3-mm thick layers of soda lime glass beads (size distribution 105-149 μm, Mo-Sci Corporation, Rolla, Missouri) at room temperature and humidity. Humidity has been shown to affect the shear strength and recurrence interval of laboratory faults, so we limit our inter experiment comparisons to experiments run at similar humidity. Glass beads have material properties similar to quartz and are an ideal substance for these tests due to the repeatability of the magnitude and recurrence interval of stick-slip events. The samples were sheared between 10*10*2 cm side steel blocks and a center block 10*15*3 cm so that a constant nominal contact area of 10*10 cm was maintained throughout shear. On the surfaces that are in contact with the sample, the steel blocks have triangular grooves 0.8 mm deep and 1 mm in wavelength cut perpendicular to the shear direction. These grooves force shear to occur within the sample layer instead of along the boundary. Guide plates were attached to the unconfined sides of the sample configuration to hold the blocks together until loaded and to prevent gouge loss.

The positions of both rams were measured by displacement transducers (DCDTs) throughout each experiment. Using the position of the vertical ram and correcting for the

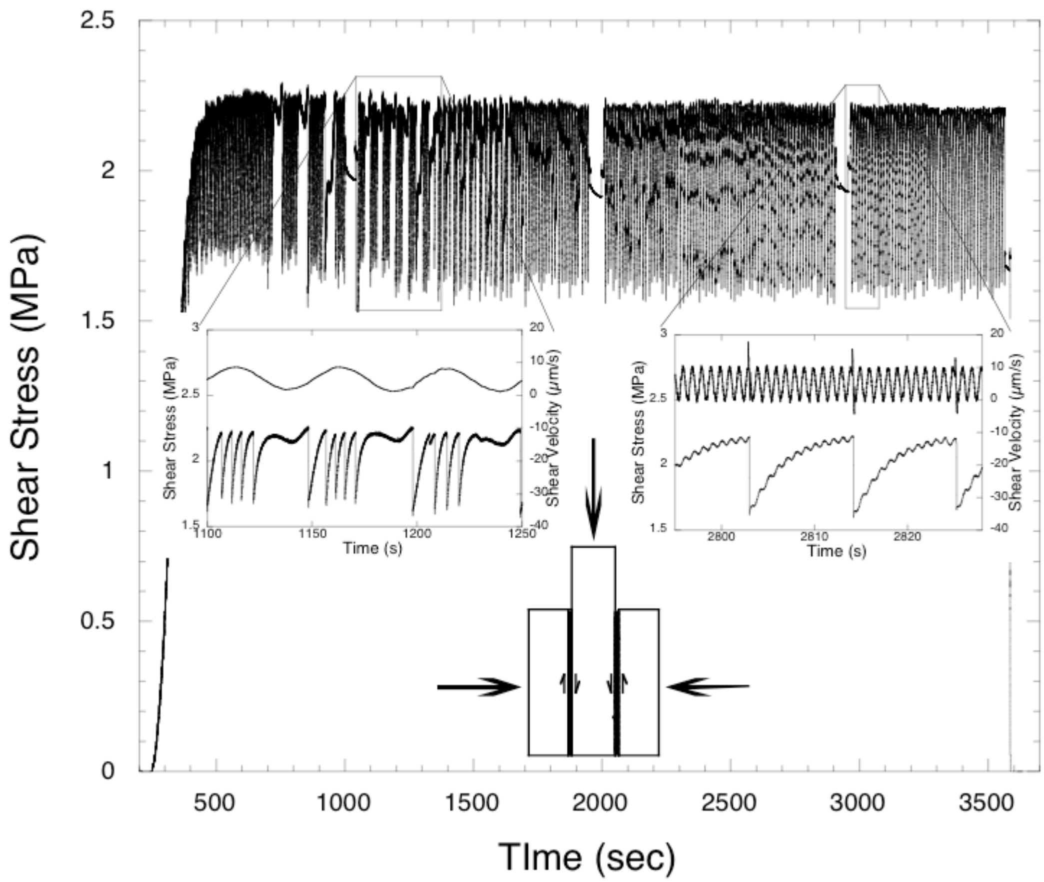

Figure 1. Time series of shear stress measured over one experiment. Rapid drops in stress illustrate stick-slip instabilities. On smaller time scales, changes to the stick-slip cycle can be identified between the high and low oscillation frequency sections of the experiment. Inset shows double-direct shear geometry.

stiffness of the loading apparatus allowed us to determine shear displacement at the gouge layer boundaries and shear strain within the layer. The amount of inelastic slip (creep) preceding instability and the dynamic slip was recorded at each instability. Recording the displacement of the horizontal ram throughout the experiment allowed for reconstruction of the change in gouge thickness both over the course of the entire experiment due to geometric thinning, as well as for dilation and compaction of the sample during the stick-slip cycle.

The amplitude and frequency of the oscillation, as well as background loading rate, were varied to study the material response. Three background loading velocities were used: 5, 10, and 20 μm/sec, which correspond to stressing rate oscillations of 0.085, 0.17, and 0.34 MPa/sec, respectively, Loading rate oscillation amplitudes ranged from 2 to 20 μm/sec, depending on the background loading rate. We present oscillation amplitudes in terms of shear stress amplitude, determined by integrating over one half of the oscillation period. We varied mean loading rate and amplitude such that the effective loading rate was always positive and finite shear load was maintained on the sample throughout the experiment. Frequencies ranged from 0.01 Hz to 4 Hz. At frequencies above 4 Hz and amplitudes smaller than a 1 μm/sec our signal to noise ratio was too large to allow accurate measurements of the material response, thus this established our limits on oscillation amplitude and frequency.

Samples were pre-conditioned at a constant shear velocity for approximately 1 mm of displacement until a steady-state maximum shear stress was reached (Figure 1). Because the glass beads behaved unstably throughout the experiment, maximum shear stress during stick-slip was used to assess whether a steady state had been reached. After achieving steady state conditions, the sinusoid was added to the computer controlled displacement signal. The sinusoid signal remained at a constant amplitude and frequency for 2 mm of displacement, which is the approximate displacement needed to induce more than 20 stick-slip instabilities.

Results and Discussion

The timing of the shear stress response, i.e. stick-slip instabilities, was measured in terms of the phase angle relative to the stressing rate sinusoid (Figure 2B and 2C). We define the peak in stressing rate as the zero phase of the oscillation. The phase angles at each failure time are tested for statistical similarity, which we call a correlation with the shear oscillation. Correlation between the oscillations and the stick-slip events was measured using a Schuster, or random walk test (Rydelek and Hass, 1994). The Schuster test assesses the probability that a series of events occurred at a specific, non-random phase by treating each event as a step of unit length. Starting at the origin of a circle, each step is placed head to tail at the phase angle in which the event occurred in the oscillation (Figure 3A). If each event occurred at a similar phase, the distance from the origin to the end of the walk, D, will be statistically significant. If the series of instabilities occur at random phases of the oscillation, the walk will end near the origin. The probability that a set of events is random is described by:

$$P = \exp\left(\frac{-D^2}{N}\right) \qquad (1)$$

where N is the number of events in the data set. We express non-randomness as a correlation percent, (1-P)*100%. Values above 99.5% correlation are deemed strongly correlated.

We find that correlation between stress oscillation and stick-slip instability depends on both the amplitude and frequency of the oscillations. Oscillation amplitudes are presented as shear stress values for comparison to similar studies of the correlation threshold (Lockner, 1999; Beeler and Lockner, 2003). The prescribed loading rate oscillation can be cast as a shear stress oscillation by multiplying the velocity by the system stiffness (including the apparatus stiffness and that of the sample assembly; 0.017 MPa/μm). The stressing rate curve is integrated to produce a stress oscillation amplitude. For example, a 1 Hz oscillation of velocity amplitude 10 μm/s is equivalent to a 0.17 MPa/s stressing rate amplitude and a 0.027 MPa stress amplitude. Additional experiments and analysis were planned in this study, but only partial support was awarded. We have requested additional funding to continue this work.

Conclusions

Shear loading rate experiments show that amplitude and frequency of shear stress oscillations determine whether instabilities are triggered. Two regimes of failure are documented: a low frequency regime where the correlation condition depends on both amplitude and frequency of the shear oscillation and a high frequency regime where the correlation condition was frequency independent. The phase lag of failure with respect to the stressing rate curve, the shear strength and the recurrence time between events are all influenced by frequency of the oscillation. Two important frequencies in determining changes in failure characteristics are the inverse of the time needed to break force chains and renew grain-grain contacts. Gouge layers experiencing vibrations faster than f_0 correlate more easily with the oscillation.

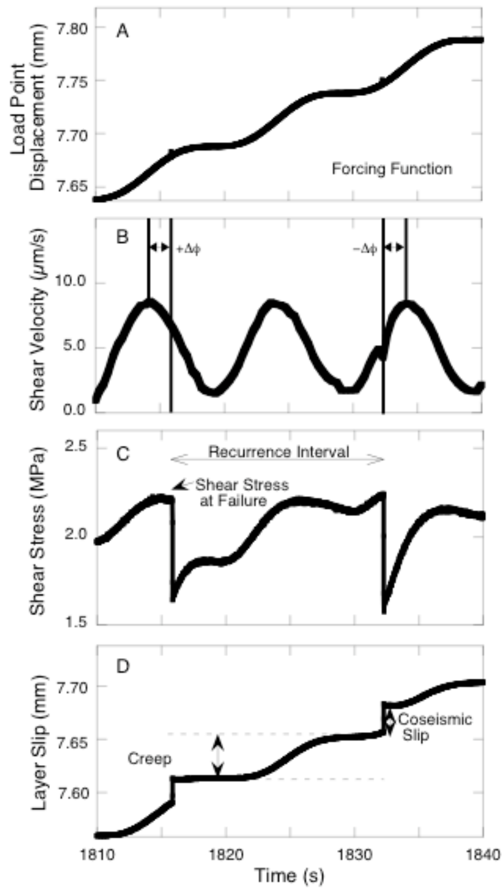

Figure 2. (A) Load point displacement was prescribed to have a constant slope with oscillations superimposed. Background loading rate is 5 µm/s or 0.085 MPa/s. (B) Phase lag is defined as the difference between the peak in the shear velocity curve and the oscillation phase at the time of failure. Instabilities occurring after the peak have a positive phase shift whereas failure prior to the peak is defined as a negative shift. (C) Shear stress at failure is the shear stress value at the onset of dynamic failure and recurrence interval is the time between successive stick-slip events. (D) The creep that occurs between stick-slips is preseismic slip and the displacement that occurs during dynamic failure is coseismic slip.

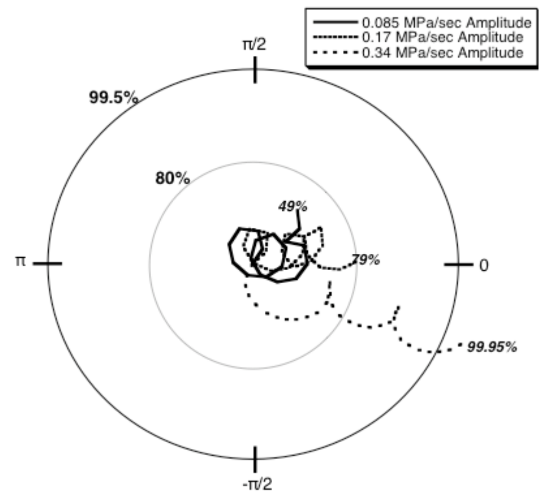

Figure 3. Correlation between instabilities and loading rate oscillations for experiments with a constant frequency of 0.05 Hz was determined using Schuster's test. Correlated series walked out a distance greater than the radius of the 99.5% probability circle (the experiment with a 0.34 MPa/s shear loading rate oscillation amplitude), while uncorrelated series did not walk far from the origin.

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*Student funded in part by this award and supervised by C. Marone

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The following web site contains information relevant to work completed for this proposal: http://www.geocs.psu.edu/~cjm/