SCEC 2010 Progress Report:
Earthquake dynamics with STZ friction:
a statistical physics approach to dynamic weakening, energy partitioning, and fault evolution

PIs: Professor Jean M. Carlson
and Professor James Langer
Department of Physics
University of California, Santa Barbara

Overview and Accomplishments

In this reporting period we continued our work investigating the physics of plastic deformation and strain localization and the corresponding implications for dynamic earthquake problems. Two new members, graduate student Charles Lieou and Postdoctoral Research Associated Ahmed Elbanna (formerly a graduate student with Heaton and Lapusta at Caltech) joined our group, and have begun making contributions to these efforts. We are extending Shear Transformation Zone (STZ) theory to include two new features, previously omitted in the model: (1) breakage of granular fault gouge, and (2) the broad distribution of particle sizes. Both are expected to be important to earthquake physics at multiple scales. Our work addresses several SCEC priority science objectives in Fault and Rupture Mechanics, including testing hypotheses for dynamic weakening (A8), examining heterogeneities in rupture models (A10), and examining the interaction between the brittle upper crust and the ductile lower crust (A11).

We accomplished the following:

- We are generalizing the STZ friction model, to include breakage, and computing the friction and energy partitioning during dynamic rupture.
- We generalized the STZ to include a broad distribution of barrier heights for STZ transitions, capturing the broad distribution of particle sizes in fault gouge.
- We are comparing results obtained from observations and models on the impact of heterogeneity on stress drops during earthquake rupture in order to better constrain physical fault parameters such as friction and prestress.

This work builds upon our accomplishments on previous SCEC projects looking at small scale physics of strain localization (Manning et al, 2009; Daub and Carlson, 2009), and the impact of strain localization on fault scale dynamic ruptures (Daub et al, 2008; Daub and Carlson, 2010) and energy partitioning (Hermundstad et al, 2010). We add new physical features—breakage and particle size distributions. These introduce time evolution, broad distributions of relaxation times, and stochastic and size dependent sampling effects to frictional behavior.

Fault Friction and Heterogeneity

The current understanding of crustal earthquakes suggests that they nucleate as frictional instabilities on preexisting surfaces of discontinuity, known as faults, under the action of the slowly moving tectonic plates. Once initiated, earthquakes propagate as dynamic shear ruptures along these interfaces, with rupture speeds close to the shear wave speed. Uncovering the physics controlling earthquake rupture is an inherently difficult task because ruptures are relatively infrequent and hidden from direct observation several kilometers below the ground surface. Nevertheless, with current computational resources it is becoming much more common for researchers to strive to reproduce the dynamics of natural earthquakes as well as the statistical trends of seismicity.

When tying earthquake numerical models to natural observations, several constraints have to be met including that i) faults have high static strength (friction coefficient 0.6-0.9); ii) ruptures tend to localize in very thin primarily slip zones with very low sliding friction coefficients (0.1-0.2) in order to prevent the occurrence of melting during dynamic ruptures; iii) interseismic shear stress is on average low consistent with the lack of significant heat flow anamolies near major mature faults; and iv) the average static stress drop ranges between 1~10 MPa with weak or almost no dependence of rupture size.

Continuum and discrete dynamic rupture models with strong velocity-weakening friction seem to satisfy many of these constraints. Models of faults that are statically strong but weaken significantly during rupture, due to processes such as flash heating, lead to reasonable temperature rise during earthquakes and low average shear stresses interseismically with stress values dependent on fault (rupture) length; longer faults (ruptures) have on average lower prestresses than shorter. Moreover, in cases where ruptures propagate as self-healing slip pulses or when there are significant stress or material heterogeneities, the pulse healing process or the generation of arresting waves from sites of heterogeneity lead to partial stress recovery in locations that have already slipped and consequently to smaller values of static stress drop once the rupture is over consistent with observations.

Finally, it is clear, based on decades of observations and simulations, that earthquakes exhibit a high level of spatio-temporal complexity. The origin of complexity is attributed in part to geometric factors such as the complex nature of fault systems, fractal rough surfaces and heterogeneous material properties, and in another part to dynamic factors stemming from the positive feedback inherent in the dependence of friction on slip and slip rate. Possibly those two sides are not independent. The complex dynamic rupture process may lead to the evolution of a heterogeneous scale-dependent stress, changes in surface roughness profiles due to wearing and healing, fault branching and changes in fault network geometry and in some scenarios ruptures may lead to phase transitions and material amorphousization which could lead to significant and uneven changes in material properties. This picture suggests that a complete understanding for the physics of the rupture process might not be possible until we set up a numerical model that can cover all these interrelated aspects. While such a model does not currently exist, the community is trying to use tools from fracture mechanics, tribology, statistical physics, material science and computational mechanics in order to progress towards that goal.

Incorporating Breakage in the STZ model

We model a sheared granular fault gouge using the shear-transformation-zone (STZ) theory appropriate for granular materials. The STZ theory, first developed as a continuum model of plastic deformation in amorphous solids, rests on the idea that the application of a shear stress results in local molecular or granular rearrangements which generate, flip and annihilate regions of local disorder, or STZ's, continually. Thus far, the STZ theory has been successful in predicting stress-strain relations of glassy materials as well as the onset of shear banding, in remarkable agreement with experimental data.

Unlike previous STZ theories of amorphous plasticity, our new theory for granular materials carries the additional ingredient that grains may break apart subject to applied shear stresses. We propose that the STZ formation energy now depends the average grain size, and that the evolution of the average grain size is a function of the applied shear stress as well as the strain rate. Our theory predicts that the breakage of grains provides a softening mechanism; under the same initial conditions, a granular fault gouge with breakable grains sees a substantially larger stress drop than one in which grains remain intact. In other words, grain fracture reduces the ability of a granular fault gouge to sustain a shear stress.

Below are a series of preliminary numerical results resulting from this work.

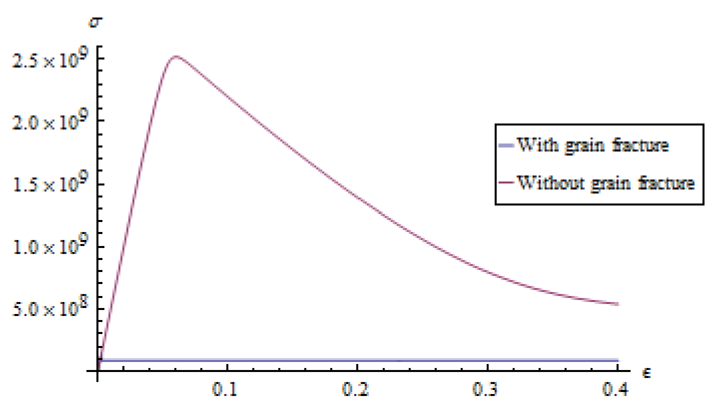


Figure 1: Stress-slip (equivalently, stress-strain) curve of a granular fault gouge composed of breakable grains (blue); and a comparison with the fault gouge (purple) made up of grains that do not break under shear. The initial grain size is r_0 = 10^{-3} m; all other physical parameters are equal. The two systems behave in an almost identical manner in the elastic regime, but the granular fault gouge quickly yields and approaches a steady-state stress that is just above the yield stress and roughly 5% in magnitude of the steady-state stress of the bulk fault gouge.

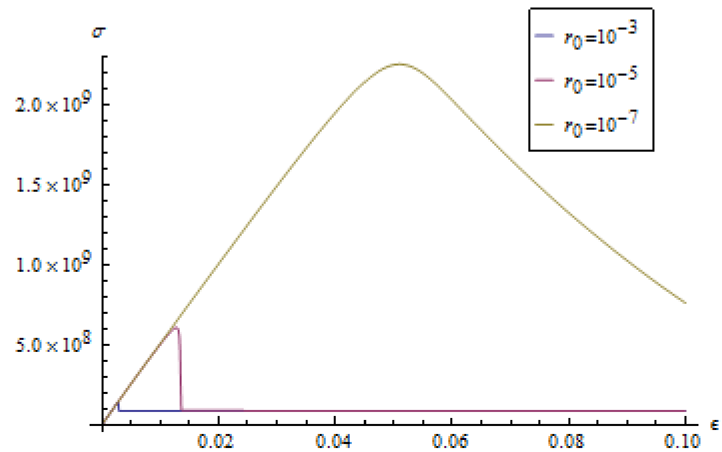
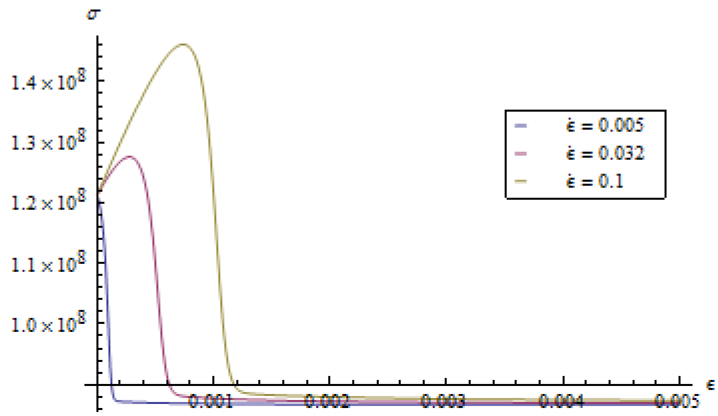
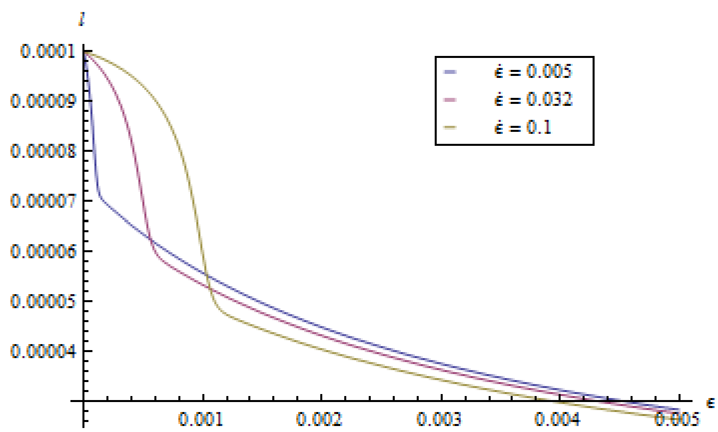


Figure 2: Stress-slip curves for the granular fault gouge at three different initial grain sizes: r_0 =10^{-3}, 10^{-5} and 10^{-7} m. The initial stress, as before, equals zero. Both the flow stress and the peak stress increase with decreasing grain size. The flow stress for r_0 = 10^{-3} m and r_0 = 10^{-5} m are roughly equal and about one-third that of the r_0 = 10^{-7} m case.



(a)



(b)

Figure 3: Evolution of (a) tensile stress and (b) average grain size with slip for three different slip rates 0.005, 0.032 and 0.1, with an initial stress of 121 MPa and an initial grain size of $r_0 = 10^{-4}$ m. Widespread grain comminution occurs for slips as small as 10^{-4}.

Broad Distributions of Grain Sizes in Fault Gouge

Another theoretical focus involves the effect of variable grain size in earthquake fault gouge. We expect this to give rise naturally to variable trapping energies, with a broad distribution of barrier heights and transition rates for STZ transformations. Previously, these effects were missing in the theory, which focused on the simplest case of a single characteristic size and energy scale for the STZs. Our recent work has been built on laboratory observations and corresponding extensions of the thermodynamic STZ theory to analyses of "soft glassy materials" such as colloidal suspensions or related, biologically relevant, complex materials. The crucial new theoretical ingredient is a broad spectrum of trapping energies that govern plastic flow. We have been able to use the effective disorder-temperature theory to predict the barrier-height distribution and, in this way, have predicted the oscillatory response of a bulk metallic glass over six decades of frequency, using only parameters determined from the steady-state viscosity.

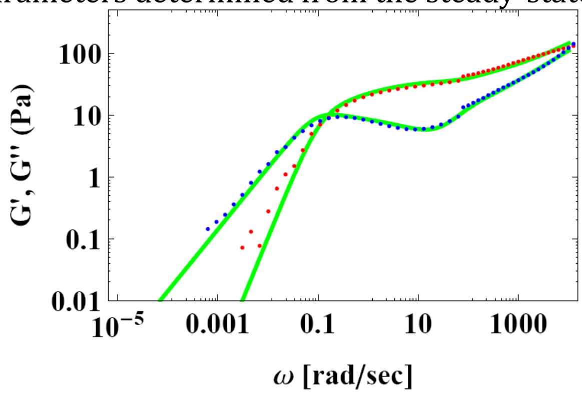


Figure 4. Frequency dependent storage and loss moduli (red and blue dots, respectively) for a concentrated, noncrystallizing colloidal suspension. The data are from [Siebenburger et al., 2009]. The green theoretical curves are discussed in the text.

An example of our results is shown in Figure 4. The data [Siebenburger et al., 2009] show the linear oscillatory response of a colloidal suspension. The volume fraction of the suspension is close to, but not quite at, the point where it appears to undergo a glass transition. Both the storage (out of phase) and loss (in phase) moduli are shown, along with our theoretical curves. As shown, the extended STZ theory accurately captures three central features of these measurements. First, it unambiguously predicts that there is a peak in the loss modulus centered at a frequency equal to the very slow, viscous relaxation rate of the system as a whole. Second, this peak is extremely broad, many decades broader than would be predicted by a single-mode Maxwell model. Third, and perhaps most interesting in the present context, the theory accounts quantitatively for the rise in both moduli at frequencies well above the characteristic Brownian relaxation rates for the colloidal particles. This behavior is known to be caused by the viscous forces acting between the particles and the fluid in which they are suspended. So far as we know, ours is the first theory that has been able to incorporate all of these effects into a first-principles analysis of such systems. The important point is that the extended, thermodynamic STZ theory is able systematically to include extra, dynamic, degrees of freedom of this kind. We hope to extend these ideas to seismological applications, where the broad distribution of particle sizes may have implications for variability and scale dependence of friction properties in seismology.

The progress described above is reported in two papers by Bouchbinder and Langer (2011a; 2011b): arXiv:1101.2015 and arXiv:1101.3539. The second of these has been accepted for publication in Physical Review Letters.

References

Bouchbinder, Eran and J.S. Langer, "Nonequilibrium thermodynamics of driven amorphous materials. I. Internal degrees of freedom and volume deformation," *Phys. Rev. E* 80, 031131 (2009a), 10.1103/PhysRevE.80.031131

Bouchbinder, Eran and J.S. Langer, "Nonequilibrium thermodynamics of driven amorphous materials. II. Effective-temperature theory," *Phys. Rev. E* 80, 031132 (2009b), 10.1103/PhysRevE.80.031132

Bouchbinder, Eran and J.S. Langer, "Nonequilibrium thermodynamics of driven amorphous materials. III. Shear-transformation-zone plasticity," *Phys. Rev. E* 80, 031133 (2009c), 10.1103/PhysRevE.80.031133

Bouchbinder, Eran, and J.S. Langer, "Shear-Transformation-Zone Theory of Linear Glassy Dynamics," arXiv:1101.2015 (2011a) (submitted to Phys. Rev. E)

Bouchbinder, Eran and J.S. Langer, "Linear Response Theory for Hard and Soft Glassy Materials," arXiv:1101.3539, (2011b), to be published in Physical Review Letters.

Daub, E. G. and Carlson, J. M., "Friction, Fracture, and Earthquakes," *Ann. Rev. of Cond. Matt. Phys.*Vol. 1: 397-418, August 2010, (doi:10.1146/annurev-conmatphys-070909-104025).

Daub, E. G., Manning, M. L., and Carlson, J. M., "Supershear, Crack-Like, and Pulse-Like Earthquake Ruptures with Shear Strain Localization," *J. Geophys. Res.* **115**, B05311 (2010).

Daub, E. G., M. L. Manning, and J. M. Carlson (2008), "Shear strain localization in elastodynamic rupture simulations," *Geophys. Res. Lett.*, 35, L12310, doi:10.1029/2008GL033835.

Hermundstad, A., Daub, E. G., and J. M. Carlson, "Energetics of strain localization in a model of seismic slip," *J. Geophys. Res., VOL. 115, B06320, 9 PP.,* (2010), *doi:10.1029/2009JB006960.*

Manning, M. L., Daub E. G., Langer J. S., and Carlson J. M., "Rate-dependent shear bands in a shear-transformation-zone model of amorphous solids," *Phys. Rev. E,* 79:016110, (2009), 10.1103/PhysRevE.79.016110

Siebenburger, M, M. Fuchs, H. Winter, and M. Ballauff, "Viscoelasticity and shear flow of concentrated, noncrystallizing colloidal suspensions: Comparison with mode-coupling theory," *J. Rheology* 53, 707, (2009).

Publications

Bouchbinder , Eran ,and J.S. Langer, "Shear-Transformation-Zone Theory of Linear Glassy Dynamics," arXiv:1101.2015 (2011a) (submitted to Phys. Rev. E)

Bouchbinder, Eran, and J.S. Langer, "Linear Response Theory for Hard and Soft Glassy Materials," arXiv:1101.3539, (2011b), to be published in Physical Review Letters.

Daub, E. G. and Carlson, J. M., "Friction, Fracture, and Earthquakes," *Ann. Rev. of Cond. Matt. Phys.*Vol. 1: 397-418, August 2010, (doi:10.1146/annurev-conmatphys-070909-104025).

Daub, E. G., Manning, M. L., and Carlson, J. M., "Supershear, Crack-Like, and Pulse-Like Earthquake Ruptures with Shear Strain Localization," *J. Geophys. Res.* **115**, B05311 (2010).

Hermundstad, A., Daub, E. G., and J. M. Carlson, "Energetics of strain localization in a model of seismic slip," *J. Geophys. Res., VOL. 115, B06320, 9 PP.,* (2010), *doi:10.1029/2009JB006960.*