SCEC 2015 Progress Report:
Mechanisms for Stick-Slip, Dynamic Triggering, and Acoustic Emissions in Granular Fault Gouge

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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. We examined the effect of microscopic properties and noise sources, such as grain shape, interparticle friction, and external vibrations, on the stability of granular flow rheology. This followed our recent analysis [Lieou et al., 2014b] where we showed that interparticle friction accounted for the non-monotonic dilatational effects in sheared gouge particles, seen in the experiments by van der Elst et al. [2012], hinting at inherent instabilities. We investigated the driving conditions under which stick-slip behavior emerges, and the shear rate regimes in which acoustic waves promote or suppress stick-slip, or remotely trigger slip events. This made direct connections to experiments and discrete element simulations by Paul Johnson, Chris Marone, and others (see, for example, Johnson et al. [2008]), which provide a platform for us to constrain our model parameters and improve the predictive power of our first-principles theory of deformation in granular gouge material. Our work addressed several SCEC priority science objectives in Fault and Rupture Mechanics (3c,3e and 4b) by developing physical constitutive laws for the fault zone, and evaluating their impact on rupture dynamics, faulting, and energy balance.

We accomplished the following:

- We developed a model that extends the STZ theory of granular materials to include frictional properties of angular particles. We investigate the system driven by shear and vibration. Results for auto-acoustic compaction are in excellent agreement with experimental measurements of van der Elst, et al (2012).
- Our model leads to stick-slip instabilities even in materials that are rate strengthening at higher shear rates (consistent with experimental observations). External vibration can accelerate or delay the onset and promote or suppress the amplitude stick-slip instabilities.
- We identified a new mechanism for slow slip, associated with increased vibration amplitude and quantified relationships between vibration intensity, clock advance, slow slip, and creep.

This work builds upon our accomplishments on previous SCEC projects which resulted in a reformulation of the STZ theory for hard-core materials of which granular fault gouge is a prime example [Lieou and Langer, 2012], and focused on 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].

Funds from the project were used to support the training and education of graduate student Charles Lieou at UCSB, who completed his PhD June, 2015. We also continue our collaboration with Professor Ahmed Elbanna, who has recently begun as an Assistant Professor at University if Illinois in Champaign-Urbanna.

Auto-acoustic Compaction:

Naturally occurring granular materials often consist of angular particles whose shape and frictional characteristics may have important implications on macroscopic flow rheology. In this reporting period, we developed a theoretical account for the peculiar phenomenon of autoacoustic compaction—nonmonotonic variation of shear band volume with shear rate in angular particles—recently observed in experiments of van der Elst, et al. (2012).

Our approach is based on the notion that the volume of a granular material is determined by an effective-disorder temperature known as the compactivity. Noise sources in a driven granular material couple its various degrees of freedom and the environment, causing the flow of entropy between them. The grain-scale dynamics is described by the shear-transformation-zone theory of granular flow, which accounts for irreversible plastic deformation in terms of localized flow defects whose density is governed by the state of configurational disorder.

To model the effects of grain shape and frictional characteristics, we proposed an Ising-like internal variable to account for nearest-neighbor grain interlocking and geometric frustration and interpret the effect of friction as an acoustic noise strength. We show quantitative agreement between experimental measurements and theoretical predictions and propose additional experiments that provide stringent tests on the new theoretical elements.

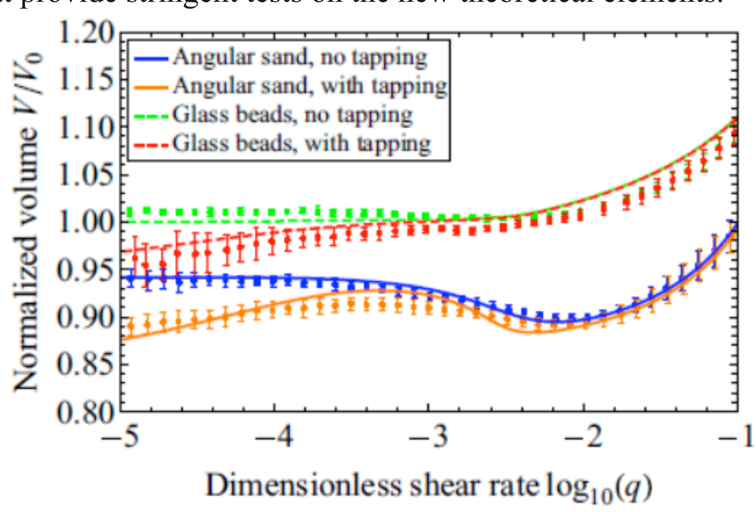

Figure 1: Comparison of our theoretical predictions (lines) and experimental measurements (points with bars representing variance in the measurements) from van der Elst (2102) for autoacoustic compaction. Results for the normalized volume versus the dimensionless shear rate show excellent agreement between our theory and the experimental measurements.

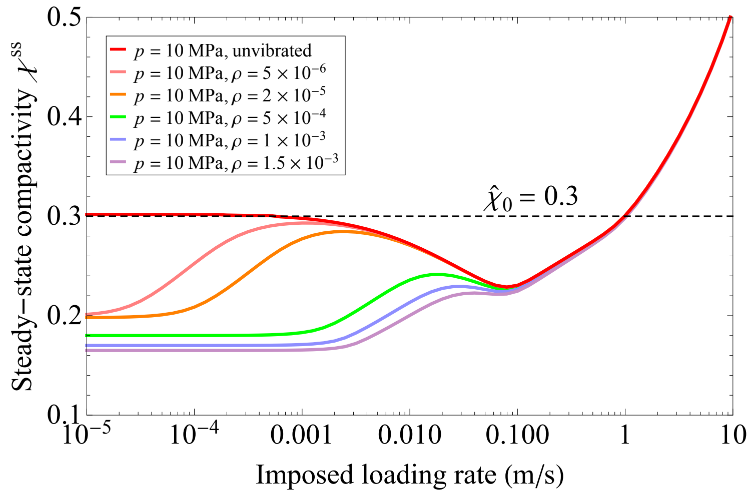

Figure 2: The compaction instability weakens with increased vibration amplitude.

Implications for Stick-Slip and Clock Advance:

Building on this success, our most recent work explores the combined implications of shearing and vibration for stick-slip instabilities. We propose a theory of shear flow in dense granular materials. A key ingredient of the theory is an effective temperature that determines how the material responds to external driving forces such as shear stresses and vibrations. We show that, within our model, friction between grains produces stick-slip behavior at intermediate shear rates, even if the material is rate-strengthening at larger rates. In addition, externally generated acoustic vibrations promote stick-slip instabilities at low shear rates, but suppress them at low confining pressures. We construct a phase diagram that indicates the parameter regimes for which stick-slip occurs in the presence and absence of acoustic vibrations. These results connect the microscopic physics to macroscopic dynamics, and thus produces useful information about a variety of granular phenomena including rupture and slip along earthquake faults. We find that in different parameter regimes, vibrations may suppress or promote stick-slip, impact the amplitude of stick-slip, and may advance or delay the onset of sliding.

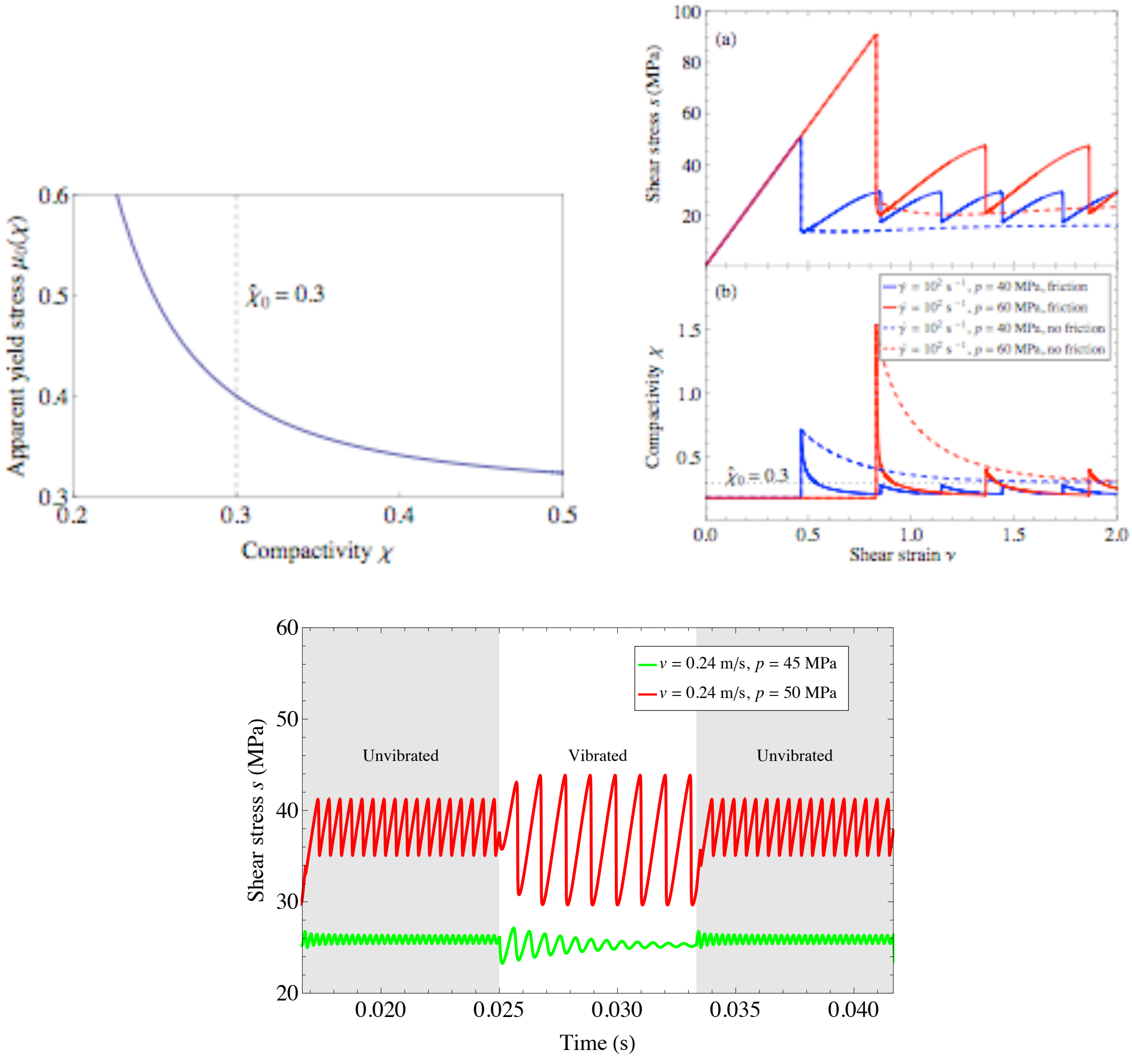

Figure 3: Including the weakening effect of increasing compactivity on yield stress, leads to stick-slip instabilities for certain ranges of parameters. Depending on the parameters, vibrations may amplify or suppress stick-slip instabilities, and may advance or delay the onset of slip. This has implications for remote triggering of seismicity and seismic hazard estimates.

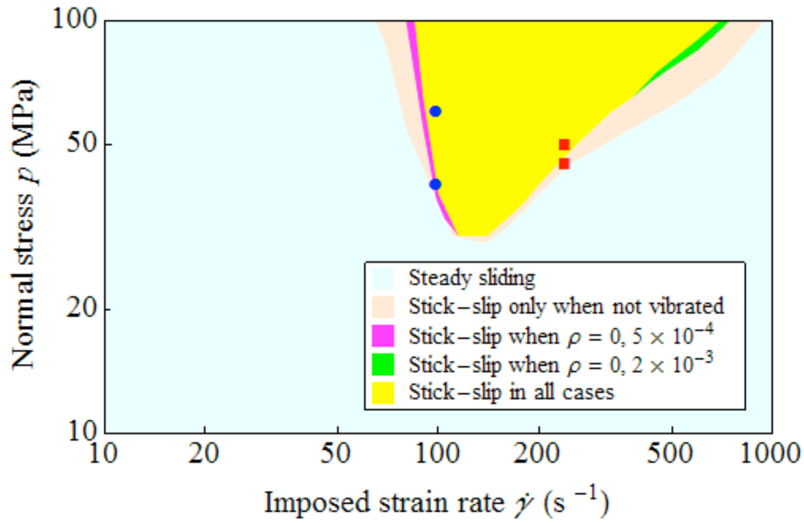

Figure 4: Phase Diagram for stick slip as a function of stress and strain rate, comparing systems with and without external vibrations.

Clock Advance and Slow Slip:

External vibrations have implications for dynamic rupture. Our numerical results in Fig. 5 and Fig. 6 show that increasing vibration intensity may advance clock time in the earthquake cycle and may lead to orders of magnitude slower slip times. This and our previous work treat vibration as an external noise source characterized by intensity. The results of this project motivate our comprehensive, ongoing theory of the effects of vibration on granular gouge that can be linked quantitatively to physical sources of external acoustic disturbance that impact faults. Using the augmented theory, in which vibration have structured coupling to the STZ dynamics, we are currently performing a quantitative assessment of the effects of vibration amplitude, frequency, duration, and timing on the dynamic behaviors of fault gouge, including stick-slip, steady-sliding, creep, slow-slip, dynamics triggering, and transient weakening and strengthening in close collaboration with SCEC DEM simulation, laboratory, and observational projects.

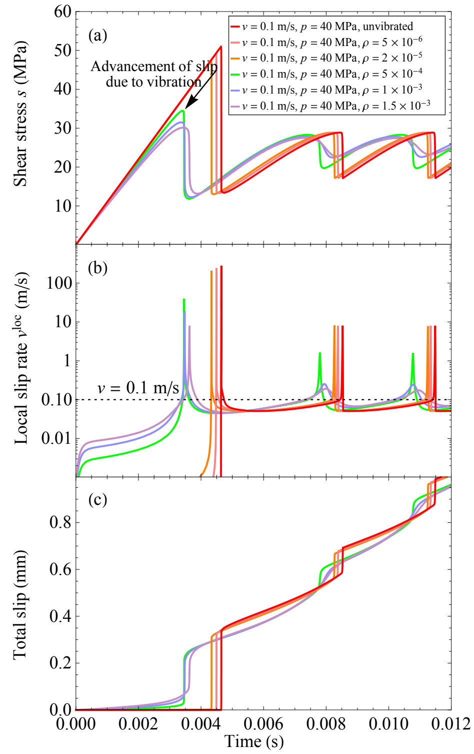

Figure 5: Increasing external vibration intensity increases clock advance (initially), and leads to slow slip, which qualitatively with results from discrete element modeling (Fedowski, et al., 2014), and experimental observations (Johnson, et al., 2008).

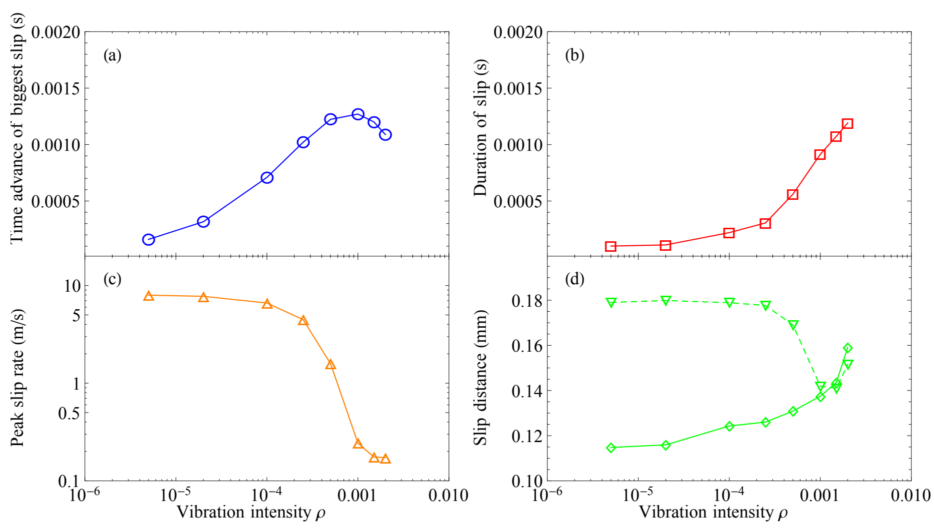

Figure 6: Impact of vibration intensity on the clock advance and slow slip. As the vibration intensity increases, the clock advancement increases, plateaus, then gradually decreases. Coinciding with the plateau, the peak slip rate drops significantly (slow slip), and the duration of slip (during periods of decreasing shear stress) increases. At higher vibration intensities the system transitions to steady sliding.

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Presentations

Carlson, J. M. Fragmentation, Acoustic Effects, and Flash Heating in Sheared Granular Materials Implications of Geophysical Processes and Physical Constraints for Dynamic Friction. Invited oral presentation at the American Physical Society March Meeting, San Antonio, TX (2015).

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Publications

Stick-slip instabilities in sheared granular flow: The role of friction and acoustic vibrations, Charles K. C. Lieou, Ahmed E. Elbanna, J. S. Langer, and J. M. Carlson, Phys. Rev. E 92, 022209 – Published 24 August 2015.

Dynamic friction in sheared fault gouge: implications of acoustic vibration on triggering and slow slip, Charles K. C. Lieou, Ahmed E. Elbanna, and J. M. Carlson, J. Geophys. Res.—Solid Earth (accepted for publication).