The scientific objective of this proposal is to investigate the influence of inelastic volume changes and pore fluid pressure variation on the mechanical response of saturated gouge layers sheared in the presence and absence of acoustic vibrations. For this purpose, we use a 2D version of the Shear Transformation Zone (STZ) theory, recently implemented by our group at UIUC in the Multiphysics Object-Oriented Simulation Environment (MOOSE) – a finite element software from Idaho National Lab - to describe the pressure dependent visco-plastic response of the fault zone. We have incorporated pore fluids in the new model to explore the effects of this non-monotonic volume changes on pore pressure variations and consequently on strength evolution and shear banding. Furthemore, we have investigated the effect of vibrations on strain localization and stick slip dynamics in a 1D fault zone model and are currently extending the implementation to higher dimensions. This modeling approach enables quantitative description of fundamental processes in fault zone inelasticity that complements and add to the widely studied thermal weakening mechanisms, and opens new pathways for multiscale modeling of earthquakes with high resolution fault zone physics.

The long-term goal of this research is to provide a consistent framework for fault zone inelasticity incorporating the effect of different physical mechanisms that are expected to play a role in the evolution of fault strength. These include (1) Pore fluid pressurization, (2) Flash heating, (3) Thermal decomposition, (4) Phase transformation and the role of glass transition, (4) Grain fragmentation, and (5) Acoustic fluidization. While several of these mechanisms have been investigated in the context of 1D fault zone model, our point of departure is to incorporate them in a 2D continuum setting coupled with gouge visco-plasticity. This will enable a fundamental understanding of the details of the localization process including the onset and propagation of complex shear bands. It will also allow for more complex feedback pathways between the different physical mechanisms that were not investigated before (e.g. the effect of vibration induced compaction and pore pressure buildup). This in turn may motivate designing new experimental setups for studying gouge friction. Furthermore, the challenge of coupling small scale physics as revealed by this modeling framework with large scale rupture dynamics and wave propagation requires development new numerical schemes capable of bridging several decades in spatial and temporal scales.

For the previous funding period, we have focused on athermal poro-visco-plasticity and numerical methods for multiscale modeling of rupture dynamics.

**Applicability to SCEC4 Research Objectives**: The project addresses short-term objectives in Fault and Rock Mechanics (3a, 3c, 4b and 3e) by developing models that provide a fundamental understanding of small scale processes controlling strength evolution of gouge-filled fault zones. A better quantification of this issue will aid long-term objectives in Earthquake Source Physics and Ground Motion, informing models of dynamic rupture propagation, fault system evolution, and physics-based hazard analysis. Understanding the complex behavior of fault zone and eventually its influence on rupture dynamics is also essential for the interpretation of seismic observations and for the problem of seismic inversion. This is particularly relevant for evaluating impacts of future seismic events on Southern California.

**Motivation and relevance to Southern California and beyond**: Fault mechanics, earthquake dynamics and rupture termination processes are linked to the physical properties of fault zones. A unified framework for modeling saturated fault gouge deformation coupled with seismic and aseismic loading conditions is a key to resolving many outstanding geophysical problems such as the heat flow paradox [Sibson, 1973; Lachenbruch, 1980], dynamic weakening mechanisms [Rice, 2006]variation of fault zone thickness with depth [Scholz, 1988], and scaling of stress drops in earthquakes as well as estimates of seismic efficiency and energy partitioning [Kanamori and Heaton, 2000, and references therein]. Furthermore, triggered seismicity is increasingly becoming a major concern in both Southern California and the stable continental US. Understanding the response of fault gouge to vibrations, over different time and length scales, is thus crucial to better constraining the susceptibility of faults for dynamic triggering. Thus, the problems addressed in this proposal, as well as their future extensions, are not only theoretically significant but they also have important practical implications in the analysis of seismic hazard and risk.

**Over the past year we worked on**: (1) Improved Implementation of the STZ viscoplasticity model in MOOSE (enabling implementation of diffusion like operators); (2) Coupling viscoplasticity with pore pressure evolution models to investigate athermal pore pressure variations (due to inelastic dilatancy); (3) Investigation of vibration effects on shear band evolution; and (4) Development of a coupled finite difference- spectral boundary integral method for efficient modeling of rupture dynamics with near fault nonlinearities/heterogeneities.

**Approach:**

Our starting point is the realization that shear deformation in granular material occurs by means of particle rearrangements, either through rolling or sliding. At high normal stresses, grain breakage may become necessary to facilitate further sliding. Furthermore, strain localization may be triggered by the presence of static or dynamic heterogeneities in the material. The shear transformation zone (STZ) theory, a non-equilibrium statistical thermodynamics framework for describing non-affine irreversible transformations associated with granular rearrangements in amorphous materials, will be our primary tool in providing a micromechanics model for inelasticity at small scales. The premise is that inelastic strain occurs only at rare localized spots known as shear transformation zones (STZs). These STZs are defect-like structures associated with extra free volume that facilitate irreversible non-affine rearrangements of the particles. Each STZ transition event generates a finite amount of local plastic strain. Overall, the macroscopic plastic strain is the cumulative result of many local events. An effective temperature (or compactivity), which evolves according to the laws of thermodynamics, governs the density of the STZs and provides a measure of the system disorder that is in one-to-one correspondence with the system porosity. The theory has been successfully applied to shear deformation in a variety of systems, including granular fault gouge [Daub and Carlson, 2008; Daub et al., 2008; Daub and Carlson, 2010; Hermundstad et al., 2010; Lieou et al., 2014a, 2014b, 2015; Elbanna and Carlson, 2014; Kothari and Elbanna, 2016], and glassy materials [Falk and Langer, 1998, 2000; Langer and Manning, 2007; Manning et al., 2009]. More recently the theory reproduced the non-monotonic volume changes as a function of strain rate observed in granular material experiments subjected to shear and vibration [Lieou et al., 2015a, der Elst, 2014].

We have implemented the STZ framework in the Multiphysics Object Oriented Simulation Environment (MOOSE) [Gaston et al., 2008]; a finite element platform developed by Idaho National Labs for modeling tightly coupled physics problems. MOOSE provides an advanced modular computational infrastructure including libMesh finite element library [Kirk et al., 2006], and the PETSc solver library [Balay et al., 2014], The program requires as an input the weak form for partial differential equations to be solved as well as the material model but it provides a variety of shape functions, stabilization options and locking control algorithms. We adopt a multiplicative decomposition of the deformation gradient into elastic and plastic parts. The plastic velocity gradient is given by a product of a flow rate and and flow direction (both are provided by the STZ theory construct). The STZ plastic rate of deformation is the symmetric part of the plastic velocity gradient. The flow rates are updated following a fully implicit return mapping algorithm and the resulting system of equations is solved using Jacobian-Free-Newton-Krylov method. The Cauchy stress is recovered from the elastic strain tensor using standard procedures in continuum mechanics. I am already in contact with MOOSE team members and I have meetings with them, whenever necessary, to discuss any technical challenges or implementation bottlenecks as well as other collaborative efforts in dynamic rupture and seismic hazard for nuclear power plants.

We modeled an amorphous gouge strip between two rigid plates. The plates are sheared at a constant rate after a ramping transient. Vertical pressure is applied at both plates and periodic boundary conditions are assumed at the lateral boundaries. The initial effective temperature is assumed to be spatially uniform except for a localized circular perturbation in the center of the strip. Our preliminary results suggest some interesting physical phenomena that are not apparent from the 1D studies. Complex shear localization patterns (including boundary, Riedel, X and Y-bands [Marone, 1998]) naturally develop in agreement with field and lab observations (Figure 1). A 1D model is capable of only capturing the Y-shear and thus misses the more complete picture of shear band nucleation and propagation.

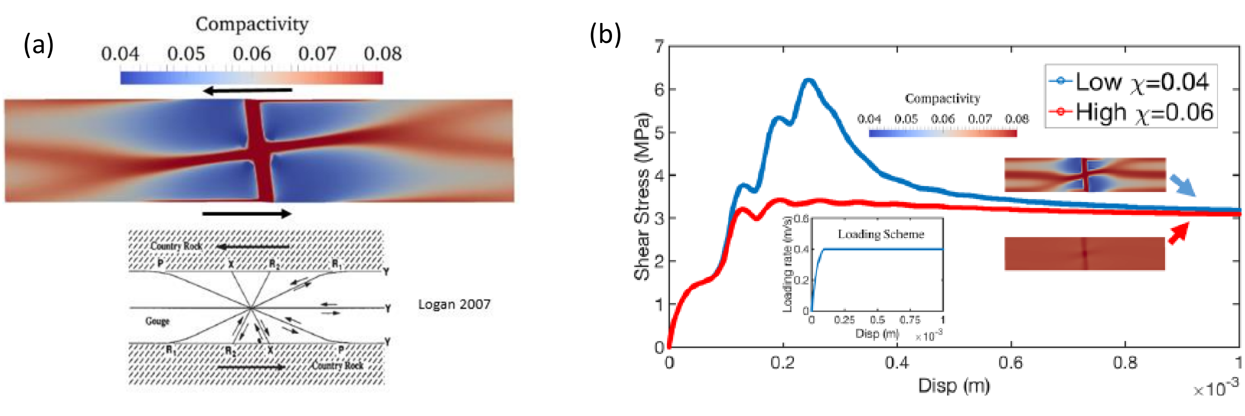


*Figure 1: (a) Predictions of localization patterns in a computational model with STZ theory (top) consistent with the schematic complex patterns observed in the field and lab (bottom). The contours in the top plot represent the distribution of effective temperature (darker is higher disorder and more localization). The angle between the bands will depend on the pressure sensitivity and dilation. (b) Brittle to ductile transition in sheared gouge layer (loading rate =0.4m/s) as a function of initial preparation. The loading protocol is shown in the insert. Initially dense gouge is brittle (blue curve) and exhibits strain localization (top contours) while initially loose gouge is ductile (red curve and bottom contours). [Wiggles in the pre-peak regime are well-resolved. They occur due to load ramping and inertia effects. Slower ramping eliminate them.]*

## Key Results

**1.**Emergence of complex strain localization patterns (Reidel, X, Y, and Boundary shears) and correlation with strength evolution

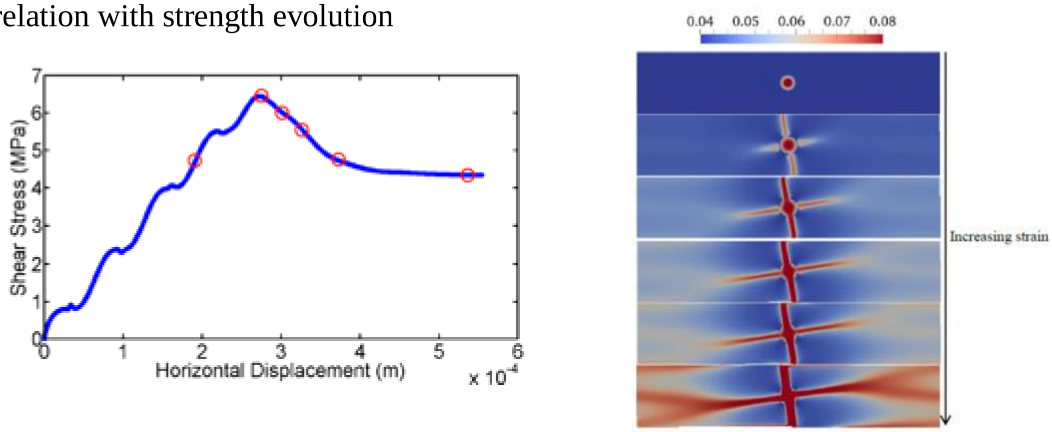


*Figure 2: Fault gouge strength evolution and the shear band formation. (a) Stress slip response. (b) The distribution of compactivity at successive time steps corresponding to the order of the red circles on (a). At first the specimen is deforming elastically. With the initiation of the shear band from the center inclusion, diagonal bands start to form, and grow to the upper and lower boundary forming the X and Riedel shear band, and then the Riedel shear band bifurcates to Y bands which fully develop near steady state.*

2- Brittle to ductile transition with decreasing dilatancy

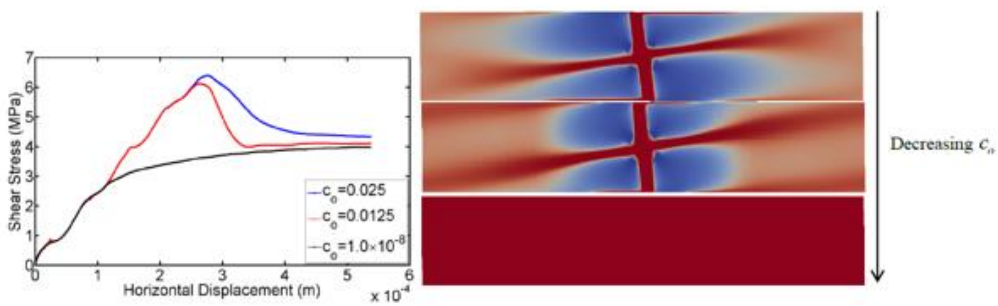


*Figure 3: Dilatancy effect on strength evolution and strain localization. (a) The stress slip response for different (b) Distribution of compactivity for different at final slip. With decreasing value of $c_o$, the specimen shows a ductile behavior with no noticeable strain localization is formed when is negligible.*

3- Increasing pressure leads to increased flow stress and a transition into more ductile response

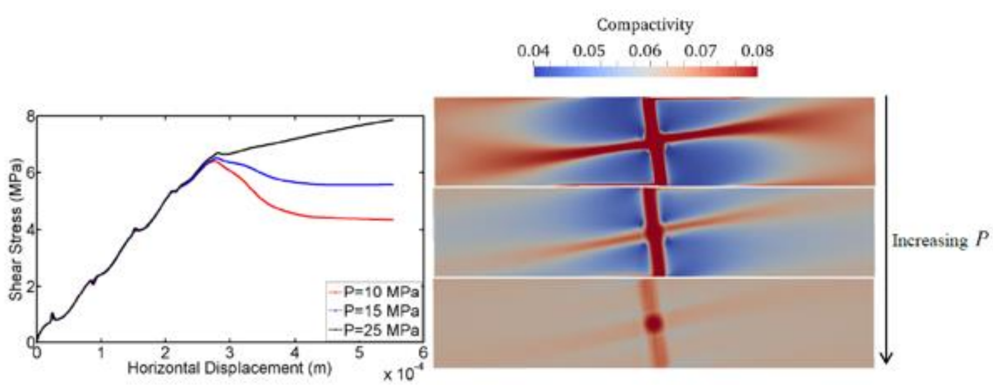

*Figure 4: Effect of confining pressure on shear localization. (a) Shear slip response with different confining pressure values 10MPa, 15MPa, 25MPa.With increasing pressure, the peak and flow stress increase while the strength drop decreases (b) The compactivity distribution for the different confining pressure at the final slip. From top to bottom, the confining pressure is increasing. The plasticity is distributed across the sample at higher pressure while the strain is more localized in bands at lower pressures.*

4- Inelastic dilatancy leads to strengthening relative to the drained shear case (Fig. 5)

5-Application of acoustic vibrations leads to de-localization of the shear band (Fig. 6)

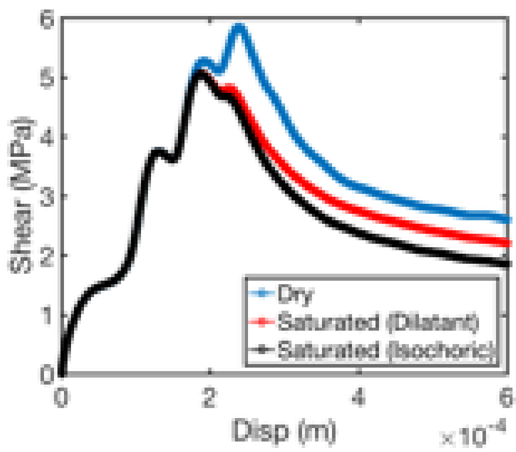


*Figure 5: Stress slip response for different interaction scenarios with pore fluids. Blue: Dry case – no pore fluids. The layer has maximum peak and flow strength. Black: Saturated but drained. Pore pressure is constant. The effective stress is reduced by the amount of the initial pore pressure and thus the peak strength and flow stress are reduced. Red: The layer dilates with shearing and the pore pressure is allowed to vary (decrease).This is the case of dilatant hardening.*

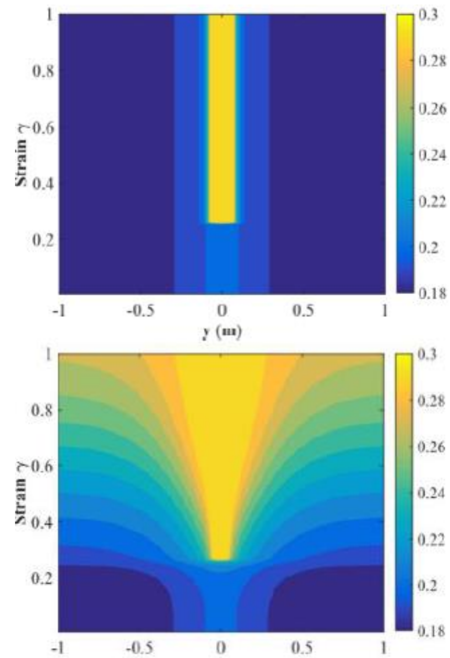


*Figure 6:* Spatio-temporal evolution of effective temperatures in a 1D inhomogeneous sheared gouge model. (a) In the absence of vibration, persistent narrow shear band develops. (b) In the presence of vibrations, slip delocalizes and disorder is distributed across the layer width [Kothari and Elbanna, 2016].

## Publications:


Lieou, C. K., Elbanna, A. E., & Carlson, J. M. (2016). Dynamic friction in sheared fault gouge: Implications of acoustic vibration on triggering and slow slip. *Journal of Geophysical Research (Solid Earth)*, *121*, 1483-1496.

Kothari K., and Elbanna A. E. (2017), Localization and instability in sheared granular materials: Role of friction and vibration, Phys Rev E **95**, 022901 [http://journals.aps.org/pre/abstract/10.1103/PhysRevE.95.022901]

Ma X., and Elbanna A. E. (2017), A Model for Athermal Strain Localization in Dry Sheared Fault Gouge, **submitted**, arXiv:1701.03087

Hajaroalsvadi S., and Elbanna A. E. (2017), A new hybrid numerical scheme for simulating fault ruptures with near-fault bulk heterogeneities, **submitted,** arXiv:1702.04802

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