Discrete Element Simulations of Granular Shear Zones

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Granular Materials & Fault Zones

- Granular materials can exhibit distributed or localized deformation
- Persistent localizations are necessary for unstable, seismogenic sliding - under what conditions does this occur?
- And what happens within semi-localized granular gouge, i.e., rock fragments derived from the fault blocks?
- The intergranular contacts are probably subject to healing and weakening processes as in discrete rock surfaces.
- But in aggregate, granular materials show coordinated behavior that can affect the localization tendency.
Example:
Volcano Growth and Spreading
(e.g., Morgan and McGovern, 2005 a,b)

- Particles rain from above (not shown) onto sedimented surface
- Discrete slip surfaces (faults) develop, but cumulative effect is distributed flow
- Stratal thinning due to shearing along flanks
- Outward tilt of max compressive stress
- Slip planes match Mohr-Coulomb theory

Frictional Sliding - Planar Surface

- Lab experiments, on many different materials show: **frictional strength varies with sliding velocity**
  - **Rate- & State-Dependent Friction**
  - Stability depends on relative change in friction with velocity
    - a: Direct effect
    - b: Evolutionary effect

(Dieterich and Kilgore, 1994)
Rate- & State-Dependent Friction
(e.g., Dieterich, 1979)

\[ \mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) \]
\[ \frac{d \theta}{d t} = 1 - \left( \frac{V_0 \theta}{D_c} \right) \]

- Stability of sliding:
  - If \( a - b > 0 \)
    - \( \rightarrow \) velocity strengthening
  - If \( a - b < 0 \)
    - \( \rightarrow \) velocity weakening
  - \( \rightarrow \) unstable!!

Fault friction depends on sliding velocity, \( V \), and system “state”, \( \theta \), \( t \), \( D_c \), \( \sigma_n \).

(More than one state variable can exist)

Frictional Sliding - Fault Gouge

(Marone, 1998)
What defines material “State”

GRANULAR GOUGE
- Similar contact effects are likely at interparticle contacts
- But what else controls:
  - Magnitude of contact force
  - Force distribution (fabric)
  - Number of contacts (grain size, and distribution, porosity)
- Dilatancy also important; requires work against $\sigma_n$, adding to friction

PLANAR FAULT
- Solid contact area increases w/ log(time), increases adhesion
- $D_c$ is slip distance required to define new contact population

(Dieterich & Kilgore, 1994)

Laboratory Experiments
Dilatancy Effects in Fault Gouge

- Velocity increase
  - dilation
- Friction increases
- Shear zone is stabilized
  - velocity strengthening

(Sliding friction relates to rate of volume change w/ strain)

\[ \tau = \tau_f + \sigma' \frac{d\phi}{d\gamma} \quad \text{or} \quad \mu = \mu_f + \frac{d\phi}{d\gamma} \]
High-Displacement Experiments

- Small offsets
  - $\rightarrow$ velocity strengthening
- Large offsets
  - $\rightarrow$ velocity weakening
- Implies change in properties and aggregate response, i.e., state, with deformation

(Beeler et al., 1996)

Discrete Element Method

*(Cundall and Strack, 1979)*

Contact Laws

- Normal force: $f_n = k_n \delta$
- Shear force: $f_s = k_s \delta$
- $f_s^{\max} = \mu_f f_n$

Newton's Equation of Motion

- $F_p = m a$
- $F_p = \Sigma f^c$

(Note, Hertzian contact laws are used:
  - $k_n, k_s = f(R, G, \nu)$)

**Advantages of DEM:**

- Allows heterogeneous and discontinuous deformation.
- System can evolve through time and space.
- Can correlate behavior with physical properties and mechanical state.
- Constitutive behavior is a result, not an assumption.
Numerical Simulations of Granular Shear Zones

(Morgan and Boettcher, 1999)

- Look inside actively deforming systems
- Quantify displacements, interparticle forces, stress distributions
- Document grain scale micromechanics, and their intrinsic controls: (e.g., friction, grain size, grain strength, etc.)

Course-grained fault gouge

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Fine-grained fault gouge
DEM Simulations of Granular Friction

- Low sliding friction, $\mu \sim 0.3$.
- Stick slip and strain localization (gray bars).
- Strength and stress drop depend on particle size and size distribution.

Increasing abundance of small particles $\rightarrow$ (Morgan, 1999)

Fine Grained Gouge

- Force chain network spans shear zone.
- Low contact forces evolve rapidly.
- Distributed deformation
- Uniform strength, low stress drops.
Coarse Grained Gouge

- Force chain network spans shear zone.
- High contact forces.
- Paired force chains.
- Irregular strength, high stress drops.

Force Chains - Results

- Complicated, evolving networks of contact forces, dependent on grain size and distribution.
- Generally, contact force magnitudes scale up with particle size.
- Force chain distributions and evolution control shear zone friction and stress fluctuations.
Rate- and State Friction

Contact Healing

- Implement time-dependent healing at contacts.

\[ V = 0, \quad \mu = \mu_c, \quad b = \ln\left(\frac{f}{f_0} + 1\right) \]

\[ V > 0, \quad \mu = \mu_c, \]

Advantages:
- Fundamental property of system.
- Particle configuration defines "state".
- Simple to implement.

Healing

- No Healing

\[ V = 1E-2 \mu m/s \]

Cumulative strain is heterogeneous.
- Highly localized

Cumulative strain is homogeneous.
- Distributed
Velocity Steps: $1E^{-1} \rightarrow 1E^{-3} \mu m/s$

- Velocity steps produce both direct and evolutionary changes on sliding friction, as inferred from laboratory experiments.

>>> Velocity Strengthening <<<

Friction - Strain: $1E^{-3}$ and $1E^{-1} \mu m/s$

- Irregular stick-slip events:
  - $1E^{-3} \mu m/s$ -> elastic-plastic loading and sudden failure
  - $1E^{-1} \mu m/s$ -> symmetric loading and unloading
Slide-Hold-Slide Tests: 1E-1 \( \mu \text{m/s} \)

- Increased hold times result in logarithmic increase in yield strength, and suppressed dilation.

Summary

- Numerical experiments capture many of the processes of laboratory experiments, and natural gouge deformation (in non-fracturing regime).

- Rate- and state-dependent frictional effects are also reproduced, with simplest of contact laws
  - Both direct and evolutionary change in friction.
  - Fault strengthening during holds
  - Velocity strengthening throughout

- Velocity dependent friction fluctuations
  - Low-velocities -> stick-slip mode (w/ elastic & plastic)
  - Higher-velocities -> oscillating mode
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**Dilatancy Effects in Fault Gouge**

- Velocity increase
  - \(\rightarrow\) dilation
- Friction increases
- Shear zone is stabilized
  - \(\rightarrow\) velocity strengthening

(Marone et al, 1990)

**Try to fit friction data to relationship below:**

\[
\tau = \tau_f + \sigma' \frac{d\phi}{d\gamma} \quad \text{or} \quad \mu = \mu_f + \frac{d\phi}{d\gamma}
\]
Best fit to $\mu$ ($V_2$)

\[ \mu = \mu_f + \frac{a \cdot dA}{d\gamma} \]

$V_2 = 0.1 \cdot V_1$

Shear strain

Best fit to $\mu$ ($V_1$ & $V_2$)

\[ \mu = \frac{1}{1.6} + \frac{a \cdot dA}{d\gamma} + \frac{b \cdot \Delta}{\tau_c} \]

But does not capture evolution over $\tau_c$

$V_2 = 0.1 \cdot V_1$

Shear strain
Definition of “State”

- Friction in granular gouge friction depends on many parameters:
  - Intrinsic friction - elasticity of assemblage
  - Dilation rate (w/ shear strain), to do work against $\sigma_n$
  - And some internal property, relating to contact area…

- Is volume strain really the correct state variable defining contact area?? It does not capture $D_c$ evolution.

- Likely, volume strain is a proxy for other properties, which also vary with velocity and strain:
  - Interparticle force magnitudes, networks, fabrics
  - Contacts per particle (coordination number)
  - Proportion of sliding contacts,
  - Etc….

For Example….

- **Contact force**
  - Mean contact force decreases with $V_2 < V_1$

- **Coordination number**
  - Contacts/particle increases with $V_2 < V_1$

- **Proportion of sliding contacts**
  - Percentage of sliding contacts decreases