Dynamic Fault Weakening and Strengthening by Gouge Compaction and Dilatancy in a Fluid-Saturated Fault Zone

Evan Hirakawa and Shuo Ma
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Stress and heat-flow paradox for San Andreas Fault

- Observations indicate that SAF is weak
- Indicates friction coefficient of \(~0.1 – 0.2\)
- Byerlee’s Law: static friction should be around 0.6 – 0.85
Why is the SAF weak?

Statically weak?
- Anomalous low-friction materials (e.g. clays)
- Permanently elevated pore pressure

Statically strong but dynamically weak?
- Flash heating of microscopic asperity contacts
- Thermal pressurization of fluids
- Acoustic fluidization
- Elastohydrodynamic lubrication
- Silica gel formation

See a critical review by Scholz (2006)
A Possible Drawback of Current Dynamic Weakening Mechanisms

“They offer no mechanism by which the static friction can be reduced.” -- Scholz (2006)

• All mechanisms require slip to occur

• ~100 MPa strength drop (static friction minus dynamic friction) is inevitable.

• Leads to huge slip velocities (~300 m/s) and fault-parallel strain (~0.1)

Noda, Dunham, and Rice (JGR, 2009)
Simulations with Off-Fault Plasticity

- Used Drucker-Prager plasticity
- Peak slip velocities drop to ~10 m/s with plasticity.
- But it is harder to drive rupture at low shear stress

Dunham et al. (2011)
**Generic structure, mature fault zones:**


Internal Structure of Principal Faults of the North Branch San Gabriel Fault

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30-100 m
(Damage ≈ highly cracked rock. Zone with macro faults or fractures extends ~ 10x further.)

1-10 m
(Sometimes described as foliated gouge, or for some faults, simply as gouge.)

10s-100s mm
(But principal failure surface can be much thinner, typically < 1-5 mm!)

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Fig. 2. Schematic section across the North Branch San Gabriel fault zone illustrating position of the structural zones of the fault. The diagram is not to scale.

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Slide from Jim Rice
“...a more complete understanding of the earthquake process will probably require measurements of the permeability of fault zone materials, the width of the active shear zone, and studies of fault gouge dynamics.”

Lachenbruch (1980)
Mechanical Characteristics of Fault Gouge

The damage zone rocks experience brittle failure.
The gouge readily compacts and deforms more ductilely.

Chester and Chester (1998)
Chester and Logan (1986)
Creep, compaction and the weak rheology of major faults

Norman H. Sleep* & Michael L. Blanpied†

* Department of Geophysics, Stanford University, Stanford, California 94305, USA
† United States Geological Survey, Mail Stop 977, Menlo Park, California 94025, USA

Field and laboratory observations suggest that the porosity within fault zones varies over earthquake cycles so that fluid pressure is in long-term equilibrium with hydrostatic fluid pressure in the country rock. Between earthquakes, ductile creep compacts the fault zone, increasing fluid pressure, and finally allowing frictional failure at relatively low shear stress. Earthquake faulting restores porosity and decreases fluid pressure to below hydrostatic. This mechanism may explain why major faults, such as the San Andreas system, are weak.
Two-Phase Undrained Gouge Deformation

Compaction → pore pressure increase → Weakening

Dilation → pore pressure reduction → Strengthening

Gouge behavior in a dynamic rupture model?
Finite Element Model: Geometry

\[ \rho = 2670 \text{ kg/m}^3 \]
\[ V_P = 6000 \text{ m/s} \]
\[ V_S = 3464 \text{ m/s} \]

Element size: 1 cm

\[ \sigma_N^0 = -126 \text{ MPa} \]
\[ \tau_b^0 = 35 \text{ MPa} \]
\[ \frac{\tau_b^0}{\sigma_N^0} = 0.2778 \]
Rate-and-State Friction with Strongly Velocity-Weakening

\[
f(V, \psi) = a \sinh^{-1} \left[ \frac{V}{2V_0} \exp \left( \frac{\psi}{a} \right) \right],
\]

State variable evolves via the slip law:

\[
\dot{\psi} = -\frac{V}{L} (\psi - \psi_{ss}), \quad \quad f_{ss} = f_w + (f_{LV} - f_w) \left[ 1 + \left( \frac{V}{V_w} \right)^8 \right]^{-\frac{1}{8}},
\]

\[
\psi_{ss} = a \ln \left[ \frac{2V_0}{V} \sinh \left( \frac{f_{ss}}{a} \right) \right]. \quad \quad f_{LV} = f_0 - (b - a) \ln \left( \frac{V}{V_0} \right),
\]

<table>
<thead>
<tr>
<th>Direct effect parameter</th>
<th>(a)</th>
<th>0.016</th>
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</thead>
<tbody>
<tr>
<td>State variable evolution parameter</td>
<td>(b)</td>
<td>0.2</td>
</tr>
<tr>
<td>State variable evolution distance</td>
<td>(L)</td>
<td>(1.3717 \times 10^{-4}) m</td>
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<tr>
<td>Reference friction</td>
<td>(f_0)</td>
<td>0.7</td>
</tr>
<tr>
<td>Reference slip velocity</td>
<td>(V_0)</td>
<td>1.0 (\mu m/s)</td>
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<tr>
<td>Weakened friction coefficient</td>
<td>(f_w)</td>
<td>0.13</td>
</tr>
<tr>
<td>Weakening velocity</td>
<td>(V_w)</td>
<td>0.17 m/s</td>
</tr>
</tbody>
</table>
Constitutive Modeling

Mohr-Coulomb yielding at low stress:
\[ \tau = c + \mu \sigma \]

Elliptical cap at high stress:
\[ \left( \frac{\sigma - S_0}{a} \right)^2 + \left( \frac{\tau}{b} \right)^2 = 1 \]
Constitutive Modeling

\[ dS_0 = 0.5 \ K_{drained} (-d\varepsilon_{kk}^p) + 0.2 \ G \ d\eta \]

\( \eta \) : inelastic shear strain

\[ dS_1 = 3 \ dS_0 \]
Constitutive Modeling

Dilatancy rule

\[
\dot{\varepsilon}_{kk}^p = -\frac{V_{ev}}{L} (\varepsilon_{kk}^p - \varepsilon_{kk}^{p,ss})
\]
\[
\dot{\eta} = \tan \beta \ \dot{\varepsilon}_{kk}^p
\]
\[
\varepsilon_{kk}^{p,ss} = \xi \sinh^{-1}\left(\frac{V_{ev}}{2V_0}\right)
\]
\[
V_{ev} = \xi V \exp\left(-\frac{x^2}{2s^2}\right)
\]

• Simulates dilatancy of frictional surface

analogous to Segall and Rice’s (1995) porosity evolution
Pore Pressure Change in Undrained Condition

\[ \dot{p} = -B \frac{\ddot{\sigma}_{kk}}{3} - \frac{KB}{\alpha} \dot{\varepsilon}^p_{kk} \]

- **B**: Skempton’s coefficient (0.6)
- **K**: drained bulk modulus
- **\( \alpha \)**: Biot’s coefficient (0.45)

Viesca et al. (2008)
Pore pressure change on the Fault

We average the pore pressure changes on both sides of the fault (i.e., ignoring damage-induced poroelastic parameter changes)
Snapshot at $t = 8$ ms

- **Slip velocity**
- **Pore Pressure**

**Inelastic shear strain**
- Rupture front
- 12.97 m/s

**Inelastic volumetric strain**
- Localization and dilatancy during sliding
- Prerupture compaction

**Pore pressure change**
- Dynamic pore pressure reduction from dilatancy
- Prerupture pore pressure increase
- 35.21 MPa
On-Fault Time Histories at 15 m from Hypocenter: Elastic vs. Inelastic

- Slip velocity
- Shear stress
- On-fault pore pressure

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Slip velocity</th>
<th>Shear stress</th>
<th>On-fault pore pressure</th>
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<tbody>
<tr>
<td>3</td>
<td>20</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
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</tr>
<tr>
<td>6</td>
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<td>60</td>
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</tr>
<tr>
<td>7</td>
<td>60</td>
<td>70</td>
<td>40</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>80</td>
<td>50</td>
</tr>
</tbody>
</table>

Graphs show the comparison between Elastic, MC model, and Cap model for slip velocity, shear stress, and on-fault pore pressure over time (ms).
Effect of Dilatancy

Slip contour

$\varepsilon_{kk}^{p}$

Pore pressure change

$\xi = 0$

$\xi = 0.01$

$\xi = 0.1$

$\xi = 1.0$

Along fault distance (m)

Along fault distance (m)

Along fault distance (m)

Quickly arrests

108.19 MPa

96.70 MPa

82.05 MPa

12.65 MPa
Self-Healing Slip Pulse

Fig. 5. Slip distribution (cm) for the $M = 6.2$ 1984 Morgan Hill, CA, earthquake derived by Hartzell and Heaton (1986) from the inversion of strong motion waveform data. The large dot denotes the hypocenter and the stippled region denotes the approximate region that is slipping at a particular instant in time.
Effect of Background Shear Stress Level

(Slip contours are at 0.5 ms)
Strain localization in fault gouge

End-cap model

Mohr-Coulomb model
Conclusions

• The presence of well-developed fault gouge might explain the weakness of mature faults, such as the SAF.

• Gouge compaction due to large shear stress increase ahead of rupture front increases the pore pressure and reduces static friction, weakening the fault.

• Gouge dilation during stress breakdown reduces the pore pressure and strengthens the fault, promoting slip pulses.

• Rapid gouge dilatancy and softening during sliding highly localizes shear strain to the fault surface; reduction in strength drop leads to less plastic strain in the damage zone
Thank you!

Questions?