Qualitative modeling of earthquakes and aseismic slip in the Tohoku-Oki area

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Constitutive law on the fault:
Rate-and-state friction at low slip rates +
Potential co-seismic weakening due to pore pressure

\[ \tau = (\sigma - p) f = (\sigma - p)\left[f_o + a \ln \frac{V}{V_o} + b \ln \frac{V_o \theta}{L}\right]; \quad \frac{d\theta}{dt} = 1 - \frac{V \theta}{L} \]

\( V \) constant, \( \theta_{ss} = L / V \), \( \tau_{ss} / (\sigma - p) = f_{ss} = f_o + (a - b) \ln(V / V_o) \)

\( a - b > 0 \), velocity strengthening \( a - b < 0 \), velocity weakening

\( f_{ss} \)

\( f_{ss} \)

\( \log V \)

Aseismic slip under slow loading

Seismic slip in large enough regions

Aseismic slip in smaller regions
Potential co-seismic weakening due to shear heating and pore fluids

- Rapid shear heating during seismic slip causes expansion of pore fluids.
- This expansion may lead to increased pore pressure, depending on permeability.
- This could lead to **co-seismic fault weakening**, additional to any slow-slip friction behavior.

\[ \tau = f(\sigma - p) \]

\[ \frac{\partial p(x, y, z, t)}{\partial t} = -\alpha_{hy} \frac{\partial^2 p}{\partial y^2} + \Lambda \frac{\partial T}{\partial t} \]

\( \alpha_{hy} \): Hydraulic diffusivity (depends on permeability)
\( \Lambda \): Fluid pressure change / temperature change

Rare unexpected event: 2011 Mw 9.0 Tohoku-Oki earthquake

- Extremely large unexpected seismic slip (> 50 m) in shallower areas which had been assumed to be stably moving (and hence barriers to earthquake rupture).

- Inconsistency with prior ~Mw 8 events at the bottom of the subducting interface.

- Areas of lower slip generated more high-frequency radiation.

- Complex pattern of rupture: first down, then up, then down again (Ide et al., Science, 2011).

Can we understand these observations in a single physical model?

Yes!

1999 (\(M_w\) 7.6) Chi-Chi earthquake in Taiwan

- Fault area with lower slip generated more high-frequency radiation [e.g. Ma et al., 2003].

Qualitatively the same behavior as in Tohoku-Oki!
1999 (M_w 7.6) Chi-Chi earthquake in Taiwan

Ma et al., 2000

Its fault properties have been measured in the lab using samples obtained by drilling (Tanikawa and Shimamoto, 2009).

North:

Velocity-strengthening, “stable”

Lower permeability, susceptible to weakening through pore fluids

South:

Velocity-weakening, susceptible to nucleation

Higher permeability

Caution:
The data is based on samples from shallow depths (200-300 m).
Model with simple geometry but realistic, lab-measured fault rheology and its correspondence to Tohoku-Oki and Chi-Chi earthquakes


Numerical simulation methodology for long-term fault slip punctuated by earthquakes with all wave effects: Lapusta et al., 2000; Lapusta and Liu (2009); Noda and Lapusta (2010)
Snapshots of slip rate distribution on the fault
Snapshots of slip rate on the fault
Snapshots of slip rate on the fault
Snapshots of slip rate on the fault
Qualitative match of long-term earthquake sequence behavior

Accumulation of fault slip

- A number of smaller events in the left patch per each event spanning both patches (as for both Tohoku-Oki and Chi-Chi faults)

- Large coseismic slip in the right patch which can also be creeping

Prior smaller events in relation to Tohoku-Oki, from Simons et al., 2011
Rich behavior of the patch which is stable at low velocities but potentially unstable co-seismically.

The area of largest slip can be creeping ("stable", "decoupled") beforehand.
Complex rupture pattern during largest events

1. Rapid rupture with a sharp peak in patch A
2. Acceleration of a slower rupture without a sharp peak in patch B
3. Secondary backward-propagating rupture in patch A

Qualitatively similar to Ide et al. [2011]
Patch A has smaller slip but more high-frequency content, reproducing observations for Chi-Chi [Ma et al., 2003] and Tohoku-Oki earthquake [Meng et al., 2011].

This effect could act alone or in combination with other mechanisms for variations in frequency content, such as heterogeneity of friction properties [Meng et al., 2011].
Conclusions

- The model qualitatively explains observations on a range of temporal scales for two well-studied earthquakes (Chi-Chi and Tohoku-Oki).
  - Largest slip in the segment that may have been creeping interseismically
  - More frequent smaller events in the other segment
  - More high-frequency radiation from lower-slip areas; variations in rupture direction

- Patches stable at low velocities but susceptible to high-velocity (co-seismic) weakening show rich behavior in numerical simulations.

Implication for seismic hazard: The fact that a fault segment is creeping may not automatically make it a barrier or preclude large co-seismic slip.

Implications for Tohoku-Oki: The shallow fault region with the largest co-seismic slip may well have been creeping before the earthquake.

- We need more laboratory and theoretical studies to understand which materials/fault structures are/may be susceptible to co-seismic weakening and more field studies of whether creeping segments have had seismic events.
Can a large earthquake propagate through the creeping section of San Andreas fault?

Such a scenario is possible if we have:

- Velocity-strengthening friction at (low) interseismic slip rates
- Co-seismic weakening at (high) seismic slip rates

Evidence for such behavior from Chi-Chi and Tohoku-Oki earthquakes
Model ingredients and parameters

3D elastodynamics represented by a spectral boundary integral equation method
\( c_s = 3 \text{ km} \), \( v = 1/4 \), \( \mu = 30 \text{ GPa} \)  
[Laupsta and Liu, 2009]
Ambient effective normal stress \( \sigma_{e0} = 60 \text{ MPa} \)

Rate- and state-dependent friction coefficient (aging law)
State-evolution distance \( L = 8 \text{ mm} \) (A and B)
Direct effect parameter \( a = 0.0066 \) (A and B)  
[Tanikawa and Shimamoto, Personal communication]
Steady-state rate dependency \( a - b = 0.004 \) (A), \(-0.002 \) (B)
Friction coefficient at a reference \( (V_0 = 10^{-6} \text{ m/s}) \ f_0 = 0.4 \) (A), 0.7 (B)  
[Tanikawa and Shimamoto, 2009]

Frictional heating and resulting pore-pressure evolution (thermal pressurization) with diffusion of heat and pore fluids away from the fault [Noda and Lapusta, 2010]
Hydraulic diffusivity \( \alpha_{hy} = 7 \times 10^{-5} \text{ m}^2 \) (A), \( 3.5 \times 10^{-2} \text{ m}^2 \) (B)
Undrained pore pressure change / temperature change
\( \Lambda = 0.036 \text{ MPa/K} \) (A), 0.069 MPa/K (B)  
[T&S, 2009]
Half-width of the shear zone \( w = 8 \text{ mm} \) (A and B)

*We treat the lab measurements as motivational rather than precise values, since they are based on samples from two boreholes at shallow depths (200-300 m).*
Temperature and pore pressure evolution

Temperature evolution (with diffusion normal to the fault):

$$\frac{\partial T(x, y, z, t)}{\partial t} = -\alpha_{th} \frac{\partial^2 T}{\partial y^2} \frac{\omega}{\rho c}$$

Heat source:

$$\omega = \frac{\tau V}{w \sqrt{2\pi}} \exp\left(-\frac{y^2}{2w^2}\right)$$

Pore fluid pressure evolution (with diffusion normal to the fault):

$$\frac{\partial p(x, y, z, t)}{\partial t} = -\alpha_{hy} \frac{\partial^2 p}{\partial y^2} + \Lambda \frac{\partial T}{\partial t}$$

- $T$: Temperature
- $\alpha_{th}$: Thermal diffusivity
- $\omega$: Heat generation per unit volume
- $\rho$: Density
- $c$: Heat capacity per unit mass
- $\alpha_{hy}$: Hydraulic diffusivity (depends on permeability)
- $\Lambda$: Fluid pressure change / temperature change
2011 Great Tohoku-Oki earthquake

- Extremely large seismic slip (> 60 m) in shallower areas where the fault was assumed to be creeping.
- Inconsistency with prior events: Smaller events at the bottom of the subducting interface.
- Areas of lower slip generated more high-frequency radiation.

Seismic slip / slip rate:
Wei et al., 2012

“Old” coupling model:
Loveless & Meade, JGR, 2010

“New” coupling model:
Loveless & Meade, GRL, 2011

Back projection results:
Meng et al., GRL, 2011
Lab-measured permeability for the Chi-Chi earthquake fault

North: Less permeable

South: More permeable

Tanikawa and Shimamoto, 2009
Lab-measured rate-and-state parameters for the Chi-Chi earthquake fault

**North**: Velocity strengthening
(despite having much larger slip!)

**South**: Velocity weakening

Samples are collected from bore holes at 200-300 m depth in the Northern and Southern regions.

Tanikawa and Shimamoto, 2009