Probing frictional properties on seismogenic faults with constraints from near-field data

Hongfeng Yang and Suli Yao

Acknowledgement:
- CUHK, RGC, and NSFC/RGC grants
An earthquake occurs when stress exceeds the fault strength. Unfortunately we don’t know the stress, strength, and $D_0$ on seismogenic fault.
Constrain strength on faults

**heat flow measurements**

(Gao & Wang, 2014)

**stress orientation: $\theta$ 45~60°**

(Hardebeck, 2015)

**Long-term average Apparent friction coefficient : $\mu' < 0.15$**

- Experiments of rock samples
- Postseismic drilling measurements (e.g. temperature)
- Seismic studies/Rate-state simulations
- Dynamic source parameters of large earthquakes
Frictional/dynamic source parameters

To determine $D_0$ requires deriving stress history during coseismic ruptures, which is often approached by the following:
1. Kinematically inferred stress history/$D_0$ from data.
2. Dynamic model to search for best-fit $D_0$
3. Near-field measurement of fault-parallel ground displacement ($D_0'$, $D_0''$)

- $D_0$: 1 – 500 cm
- Scale with final slip $D_0 = k u$, where $k$ ranges from ~0.1 to ~1 (Tinti et al., 2005)
Previous approaches suffered from the trade-off between the strength and $D_0$. The product of the two yields fracture energy that can be determined robustly. However, separating them is extremely difficult.
A new method to remove the trade-off

A single parameter (e.g. ground velocity) leads to trade-off, while multiple parameters with different trends can remove the trade-off.

Using the 2015 Nepal earthquake as an example.
Critical distance during the Nepal EQ

Weng and Yang, 2018, JGR

Average $d_0 \sim 0.6$ m, $\bar{\tau}_s - \tau_d = 4.8$ MPa

Galetzka, et al., 2015, Science

$D_0 = 5$ m (???)
The 2012 $M_w$ 7.6 Nicoya earthquake

- Anticipated by locking models
- Well recorded by near field measurements (high/low rate GPS + strong motion)
Dynamic rupture parameters

\[ S = \frac{\tau_s - \tau_0}{\tau_0 - \tau_d} \]

\[ d_0 = Cu \]

\[ \overrightarrow{\tau_d} = \text{Constant} \]

\[ \overrightarrow{\tau_0} = B \Delta \tau + \overrightarrow{\tau_d} \]

\[ \tau_s = (1 + S)(|\overrightarrow{\tau_0}| - |\overrightarrow{\tau_d}|) + |\overrightarrow{\tau_d}| \]

Kinematic slip was used to calculate static stress drop, assuming a constant dynamic/final stress.

We start with an assumed effective normal stress, and then search for the best-fit value to determine strength (S) and d0 (C).
Comparison of data and synthetic

Both amplitudes and shapes match very well with data. Slightly worse on horizontal components.

Synthetics match well with campaign GPS data

For each run, we quantify the misfit between synthetic static (displacement) and high-rate GPS (velocity) and data.

Yao and Yang, submitted
Although heterogeneity of friction should exist on faults, near-field data may not be able to distinguish. Here we tested cases with heterogeneous and homogenous distribution of $D_0$, the average value is close.

The best-fit model yields $D_0 = 0.12$ m ($\bar{D_0} = 0.25$ m), $S = 0.4$ ($\tau_s - \tau_d = 3.4$ MPa)
Low strength

D₀ is scaled with slip and thus displays same pattern as final slip. The peak value is 0.5 m. By assuming the dynamic friction coefficient of 0.2 or lower, strength is estimated to be lower than 7.5 MPa on average, indicating near-lithostatic pore pressure on the megathrust.

Average strength drop <5 MPa

Yao and Yang, submitted
Seismic observations indicate high P

High $v_p/v_s$ by RF

Coseismic velocity reduction: NCC

Audet and Schwartz, 2013

Chaves and Schwartz, 2016
Although featuring different parameterizations, RS laws exhibit slip weakening under seismic slip rates;
Dynamic rupture simulations using rate- and state-dependent friction law can obtain similar rupture process with simulations using linear slip-weakening law under the same fracture energy;
Under the same fracture energy, RS friction laws with higher initial weakening rates at small slip lead to more energetic rupture fronts and consequent higher rupture speeds compared to the SW law. The differences are slight on planar faults, but can be significant on nonplanar faults.
Slip weakening curves from laboratory experiments

**Power law slip-weakening law:**

\[ f = f_s - (f_s - f_d) \left( \frac{D}{D_0} \right)^p \]

**Fracture energy:**

\[ G = \sigma_n (f_s - f_d)D_0 p / (p + 1) \]

- For linear slip-weakening: \( p=1 \)
- From laboratory experiments, the range for the exponent \( p \) is 0.2-0.5.

\[ \overline{D_0} = 0.25 \text{ m} \]

\[ \overline{\tau_s - \tau_d} = 3.4 \text{ MPa} \]

Assuming that fracture energies are well constrained by dynamic rupture simulations using the linear slip-weakening law, considering the range for exponent \( p \) of 0.2-0.5, the product of \( D_0 \) and strength drop can be underestimated by a factor of 1.5-3.

(Di Toro et al., 2011)
Exponential slip-weakening law:
\[ f = f_d + (f_s - f_d) \exp\left(\frac{\ln(0.05)D}{D_0}\right) \]
Fracture energy:
\[ G = 0.33\sigma_n (f_s - f_d) D_0 \]

(Mizoguchi et al., 2007)

\[ \overline{D_0} = 0.25 \text{ m} \]
\[ \overline{\tau_s - \tau_d} = 3.4 \text{ MPa} \]

Assuming that fracture energies are well constrained by dynamic rupture simulations using the linear slip-weakening law, considering the exponential slip-weakening law, the product of \( D_0 \) and strength drop can be underestimated by a factor of 1.5.
Conclusions

1. We derive frictional parameters (strength drop and $D_0$) on seismogenic faults.
2. Based on constraint from near-field ground displacement and velocity recordings, the best-fit model yields an average $D_0$ of 0.25 m (peak 0.5 m) and strength of ~7.5 MPa (maximum 20 MPa) for the Nicoya EQ. $D_0$ of 0.6 m for the Nepal EQ.
3. Small difference between heterogeneous and homogeneous distribution of $D_0$.
4. Slightly underestimate comparing to non-linear slip weakening law.
Ongoing efforts – higher frequency

Yao and Yang, in prep.