Numerical Simulation of Slow Slip Triggered Tremor Migration and Rapid Tremor Reversals

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I. Introduction
Slow-slip events (SSE) and non-volcanic tremors unveil a broad spectrum of earthquake behavior and offer a unique window into fault mechanics at the bottom of seismogenic zones. A hierarchy of migration patterns of tremors has been observed in the Cascadia subduction zone (Houston et al., 2011):

1. Large-scale, along-strike tremor propagation at about 50 km/day. Likely triggered by the migrating front of the slow slip event.
2. Rapid Tremor Reversals (RTRs): smaller-scale swarms migrating along-strike in the opposite direction, at about 100 km/day. Their origin is less obvious.
3. Along-dip streaky tremor swarms, migrating at about 1000 km/day (not addressed here).

II. Conceptual model
In an emergent view, the deep seismic/asismic/migration transition region of a fault has heterogeneous frictional properties and is composed of frictionally unstable patches (‘asperities’) embedded in a more frictionally stable fault matrix.

III. Model

A. Rate and State Friction

\[ r = \max(1, \min(r + \Delta t), \min(r + \Delta t, \sigma)) \]

- \( r \) : fault shear stress
- \( \sigma \) : effective normal stress
- \( r^* \) : reference value of the friction coefficient
- \( \sigma^* \) : reference value of the slip velocity
- \( V \) : sliding velocity
- \( a \) : constitutive parameter: direct effect
- \( b \) : constitutive parameter: evolution effect
- \( d \) : characteristic slip distance
- \( \dot{\varepsilon} \) : state variable

Response of a spring-block system to an external transient loading (a Gaussian pulse). The slip law is assumed. Each row has a characteristic pulse duration: \( T_{\text{rec}} > 100 \), \( T_{\text{rec}} > 50 \) and \( T_{\text{rec}} > 10 \) (top to bottom). Each column has different stiffness: sub-critical, critical and super-critical (left to right). The response highly depends on the ratio of recurrence time \( T_{\text{rec}} \) to pulse duration \( T \).

B. Friction Law with cut-off Velocity

Because we focus on modeling tremor migration, we conveniently generate the underlying SSE by adopting a friction law with transition from velocity-weakening to strengthening. We adjust model parameters to obtain a SSE propagation speed of ~10 km/day.

\[ \mu = \min(\mu^0, \max(\mu^0 - \alpha \cdot \log(1 + \beta \cdot \dot{\varepsilon}), 0)) \]

- \( \mu \) : cut-off velocity of direct effect
- \( \mu^0 \) : cut-off velocity of evolution effect
- Velocity weakening to strengthening transition

IV. Numerical simulations
We conduct 20 numerical simulations of heterogeneous rate-and-state faults under the quasi-dynamic approximation with a spectral Boundary Element Method. We first simulate several SSE cycles on a homogeneous fault. We then add a collection of small asperities defined as patches of velocity-weakening friction (no velocity cut-off, to allow seismic slip) with shorter \( D_c \) and larger and at bove than their surroundings.

V. Future work
- Identify the factors controlling the propagation speed and distance of RTRs
- Examine the interaction between tremor swarms and SSEs
- Review the effects of complex fault geometry

VI. References
1. P. Ampuero, and A. M. Rubin (2009), Earthquake subduction on rate-and-state faults: Aging and slip events, JGR, 113, B00A12
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5. Houston et al. (2015), Rapid Tremor Reversals in Cascadia generated by a waveguide plate interface, Nature Geoscience 8, 529–534