Rupture Dynamics at the Interface Between a Compliant Layer and Stiffer Underlying Half-Space

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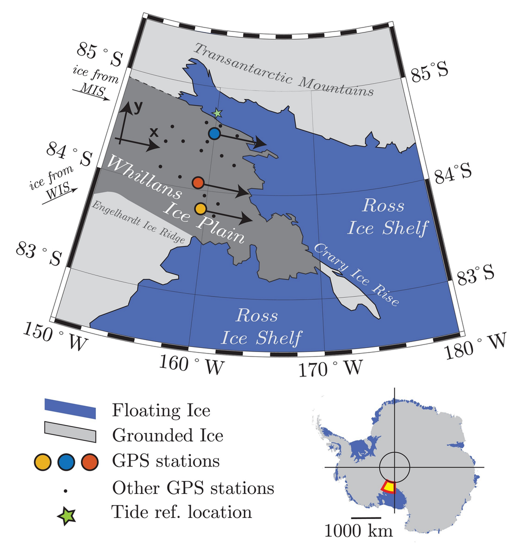
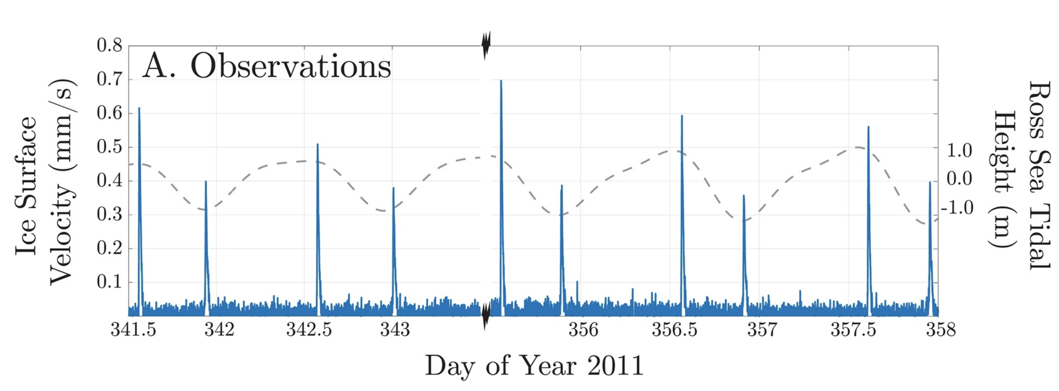
Introduction

Stability of sliding between elastic solids has been studied in a number of contexts; including:

- study of **elastic properties** above and below the interface (identical vs dissimilar)
- study of **geometries** (two half-spaces vs layer over half-space)



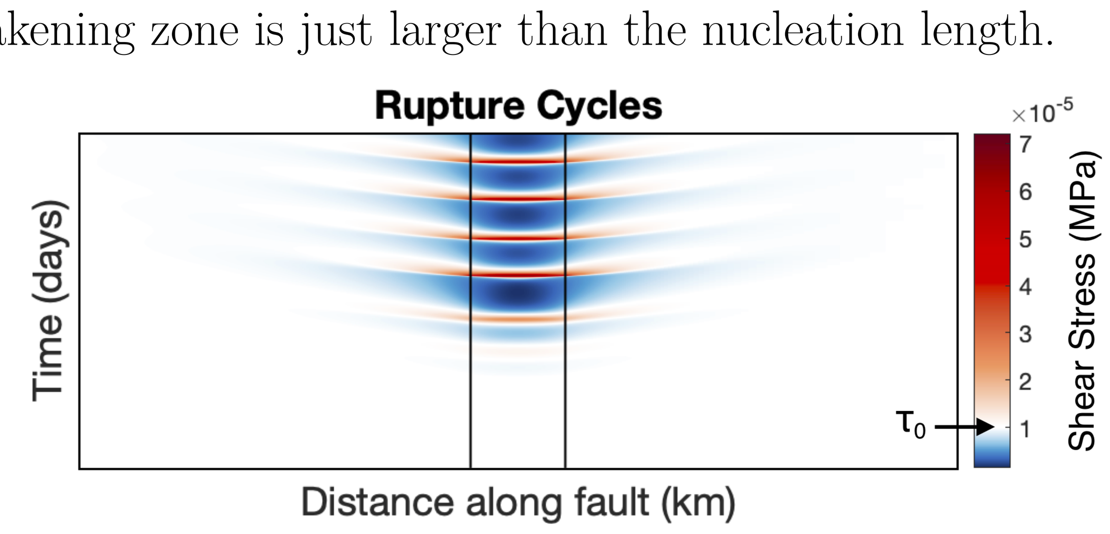
The layer over half-space problem arises in many contexts, ranging from shallowing dipping subduction zones to ice streams (in particular, the Whillans Ice Plain (WIP), which advances via twice-daily Mw 7 slow slip events). Our objective is to quantify sliding stability and rupture styles for layer over half-space geometry with rate-and-state friction.



GPS data of Ice surface velocities (solid blue) [Lipovsky Dunham, 2017]

Example Cycle Simulation

Slow slip events feature rupture propagation an order of magnitude slower than the shear wave speed. In the cycle simulations the slow slip events typically occur when the velocity-weakening zone is just larger than the nucleation length.



Earthquakes rupture in the velocity-weakening zone (between the black lines). White indicates steady-state.

Forcing Term

Ice streams move due to the push of steadily flowing upstream ice. Steady-state shear stress (τ_{ss}) is associated with steady slip from upstream ice.

Momentum Equation:

$$\frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} = F \qquad (1)$$

Hooke's Law:

$$\sigma_{xy} = \mu \frac{\partial u_x}{\partial y}; \sigma_{xz} = \mu \frac{\partial u_x}{\partial z} \qquad (2)$$

Steady-State Friction:

$$\tau_{ss} = \sigma_0 \left(f_0 + (a-b) \ln \left(\frac{V_{ss}}{V_0} \right) \right) \qquad (3)$$

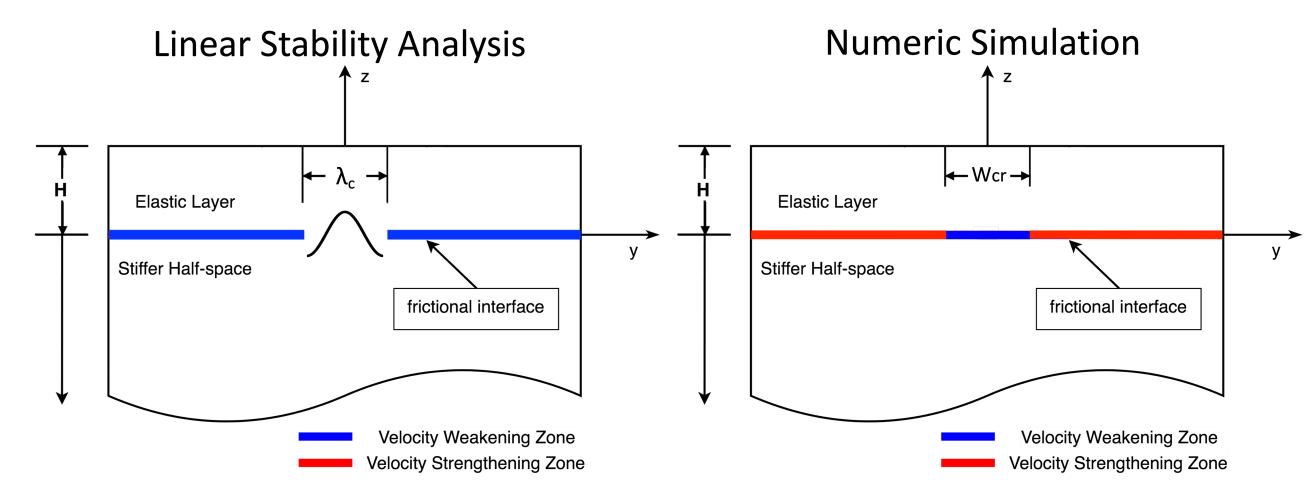
σ_0 is normal stress; f_0 and V_0 are reference friction and velocity; a and b are rate-and-state parameters; d_c is state evolution distance; μ is shear modulus of the elastic layer.

Problem Description

This study examines anti-plane shear sliding of a horizontal elastic layer over a stiffer elastic half-space. This problem is distinct because of the variable layer thickness (H) and dissimilar materials (shear modulus μ, density ρ, shear wave velocity c).

We studied the influence of layer thickness (H) on conditions for steady sliding vs. slow slip cycles on a 2D anti-plane shear sliding of a thin compliant layer over a stiffer half-space.

- In the **linear stability analysis** the fault is velocity-weakening, $W \to \infty$.
- In the **earthquake cycle simulations** we varied W to find the transitions between steady sliding and slow-slip for each H.

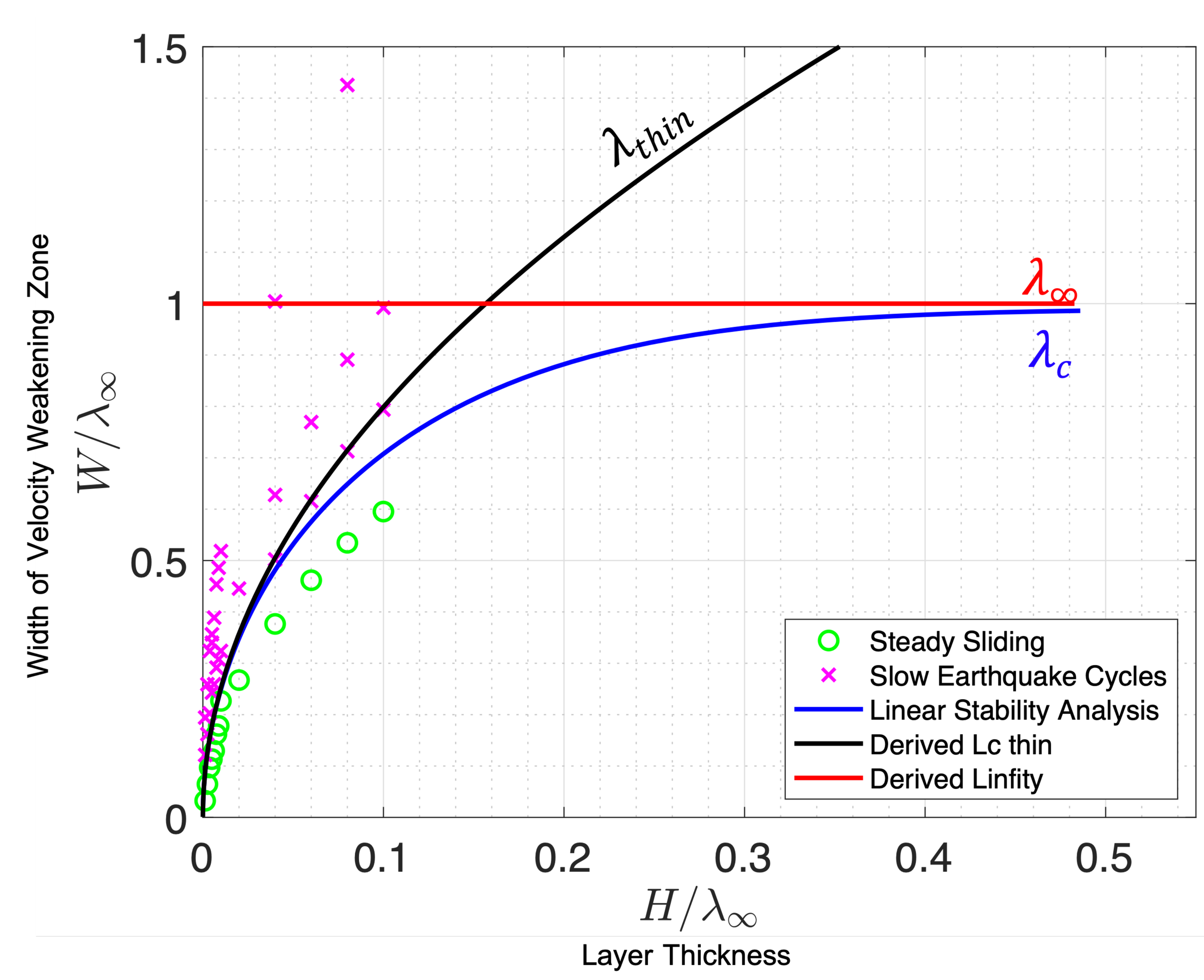


To understand the effects of layer thickness (H) we performed:

- A **linear stability analysis** to determine the critical wavelength for events to nucleate.
- **Earthquake cycle simulations** to find the transition between steady and slow slip.

Combined Results

We linearized the governing equations around the steady-state solution (where sliding is steady at a constant velocity) and perturb the system in slip velocity, stress, and state with a perturbation in the form e^{iky+st}. The goal is to find the critical wavelength ($\lambda_c = \frac{2\pi}{k_c}$). If the perturbation wavelength is larger than λ_c for steady sliding with velocity-weakening rate-and-state friction **then the fault is linearly unstable**.



When $H \to \infty$, critical wavelengths obtained from the linear stability analysis correspond to *Rice Ruina, 1983* for an elastic half-space over a stiff half-space (red line).

$$\lambda_\infty = \frac{2\pi\mu d_c}{(b-a)\sigma_0} \frac{1}{\sqrt{1+q^2}} \qquad (4)$$

$$q = \frac{\mu V_0}{\sqrt{a(b-a)}\sigma_0 c} \qquad (5)$$

When $H \to 0$, critical wavelengths correspond to *Lipovsky and Dunham, 2017* when the half-space is stiff (black line).

$$\lambda_{thin} = 2\pi \sqrt{\frac{H\mu d_c}{\sigma_0(b-a)}}, \qquad (6)$$

The critical W_{cr} is the transition between steady sliding (green circles) and slow slip cycles (magenta x's). For a given H we varied the W and recorded what kind of sliding style occurred. It was found for thin layers the critical W depended on H; as H increased so did the critical W.

Conclusions

- As H is increased the problem geometry will change from a thin layer over a half-space to a half-space over a half-space.
- As $H \to 0$ the critical wavelength $\lambda_c << \lambda_\infty$. Therefore, thin layer geometries can not be treated the same as half-spaces.
- The linear stability analysis shows $\lambda_c \propto \sqrt{H}$ for small H values; this is confirmed in the cycle simulations.
- If the velocity-weakening zone is barely wider than the nucleation length the earthquakes that occur are in the slow-slip regime, as observed at the Whillans Ice Plain.

Future Work

- Run more simulations to fully map out the transition between the thin layer to half-space.
- By incorporating inertia into the problem, find the transition between slow-slip and fast-slip rupture styles.
- To mimic the Whillians Ice Plain: apply viscoelastic and thermomechanical effects to this problem

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