Shallow slow slip events can nucleate on velocity-strengthening thrust faults

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November 21, 2022

Abstract

Recent observations of faults in the shallow regions of subduction zones have revealed slow slip events that nucleate up-dip of the locked zone. Clay-rich sediments are prevalent at shallow depths and a large body of experimental work has shown that these sediments have a tendency towards velocity-strengthening frictional behavior, although velocity-weakening behavior is observed as well. Models of deeper slow slip, down-dip of the locked zone, generally require velocity-weakening behavior for events to nucleate. Here I show that slow slip events can nucleate and propagate on shallow, velocity-strengthening thrust faults, in a numerical model of a thrust fault dipping in a homogeneous, elastic half-space. This behavior is due to the broken symmetry of the thrust fault geometry, and is similar to behavior previously reported on bi-material, and poro-elastic faults. The interaction of the fault with the free surface (i.e. the sea floor) creates a coupling between normal stress on the fault and fault slip. This coupling allows velocity-strengthening slow slip events to nucleate, and becomes stronger at shallower depths. Here I conduct a parameter analysis, and show how this behavior is limited to certain values of the frictional and elastic parameters on the fault.
Shallow Slow Slip Events Can Nucleate on Velocity-Strengthening Thrust Faults

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PRESENTED AT:
AGU FALL MEETING
New Orleans, LA & Online Everywhere
13-17 December 2021
Wiley

References:
- Key Points:
  - For velocity-strengthening parameters, the ratio of $v$ depends on whether the fault is velocity-strengthening or not.
  - $v$ increases for all positive values of $v$ and decreases for all non-positive values.
  - For velocity-strengthening parameters, the ratio of $v$ changes depending on the fault's behavior.
  - The relationship is similar to the simple case of frictional behavior in the upper mantle.
INTRODUCTION AND ELASTIC ANALYSIS

Introduction

- A common measure of frictional fault stability is the critical nucleation length $h_0^*$

$$ h_0^* = \frac{\pi G d_c}{\sigma_0 (1-\nu)(b-a)} $$

where $G$ is the shear modulus, $\nu$ is Poisson's ratio, $\sigma_0$ is the normal stress, and $a$, $b$, and $d_c$ are rate and state frictional parameters.

- The nucleation length as defined above, strictly applies only to a fault with constant frictional properties, embedded in a homogeneous and isotropic elastic full-space.

- As an idealized model of a subduction zone, here I analyze the sliding stability of a dipping thrust fault, embedded in a homogeneous and isotropic elastic wedge-space.

Elastic Analysis

- Consider a homogeneous, elastic semi-infinite wedge as illustrated above. Relative to horizontal, $\alpha$ is the slope of the upper surface, and $\beta$ is the dip of the fault.

- Define the complex coordinate $z = x + i y = re^{i \theta}$ where $(r, \theta)$ are radial coordinates with $\theta$ measured from the $x$-axis in the direction of the $y$-axis, as shown. Then the upper surface of the wedge is located at $z = re^{i \alpha'}$ and the fault is located at $z = re^{i \beta'}$, where $\alpha' = \pi + \alpha$ and $\beta' = \pi - \beta$. 

The stress and displacement fields throughout the wedge due to a distribution of slip along the fault can be expressed in terms of two analytic functions of $z$, $\omega(z)$ and $\Omega(z)$ [2]:

$$\sigma_x + \sigma_y = 2 \left[ \Omega'(z) + \Omega'(\bar{z}) \right],$$

$$\sigma_y - \sigma_x + 2i\sigma_{xy} = 2 \left[ z\Omega''(z) + \omega'(z) \right],$$

where primes denote differentiation with respect to $z$.

For zero traction along the entire upper surface of the wedge space, the potentials due to a single edge dislocation are:

$$\Omega(z) = -\gamma \left[ \ln(z^q - z_0^q) - \ln(z^q - \bar{z}_0^q) \right] + \frac{q\tau(z_0 - z_0^q)^{q-1}}{z^q - z_0^q},$$

$$\omega(z) = -\gamma \left[ \ln(z^q - z_0^q) - \ln(z^q - \bar{z}_0^q) \right] - \frac{q\tau(z_0 - z_0^q)^{q-1}}{z^q - z_0^q} + qz^q \left[ \gamma \frac{1}{z^q - z_0^q} - \frac{\gamma}{z^q - \bar{z}_0^q} - \frac{q\tau(z_0 - \bar{z}_0)^{q-1}}{(z^q - \bar{z}_0^q)^2} \right]$$

where

$$\gamma = -\frac{i G b e^{i\beta'}}{4\pi(1-\nu)}$$

and $b e^{i\beta'}$ is the Burger's vector for shear slip along the fault.

The method of solution that I've employed depends on a conformal transformation that maps the wedge space in the $z$-plane, onto a half space in the $\zeta$-plane, where

$$z = m(\zeta) = \zeta^{1/q}$$

and $q = \pi/\alpha'$.

For numerical computations, the changes in shear and normal stress along the fault are determined by the forms of the complex potentials above, and by considering a distribution of dislocations along the fault [1, 3, 6].

Using a piecewise continuous approximation to the slip distribution along the fault, the changes in shear and normal stress may expressed as products between linear operators $K_\alpha(\alpha, \beta, \xi)$, $K_\beta(\alpha, \beta, \xi)$ and the slip along the fault, where $\xi$ is along-dip distance on the fault.
VELOCITY WEAKENING FAULT

Linear Stability Analysis

- The stress change operators $K_r$ and $K_\sigma$ can be used to numerically conduct a linear stability analysis of the dipping fault system.

- Here I use a form of the linearized equation that governs frictional slip in terms of sliding velocity $v$, shear stress $\tau$, and normal stress $\sigma$. Explicit reference to the frictional state variable is suppressed [4, 5]:

$$\frac{d\tau}{dt} = \frac{a \sigma}{v_0} \frac{dv}{dt} + \mu_0 \frac{d\sigma}{dt} - \frac{\sigma_0}{v_0} \left[ \tau - \mu_0 \sigma - \frac{(a-b)\sigma_0}{v_0} (v - v_0) \right]$$

where subscripted zeros denote steady-state quantities.

- This equation can be cast as an eigenvalue problem, whose solution supplies values of the critical nucleation length as a function of location along the fault.

- I determined $h^*$ for a range of different wedge geometries. Upon normalization by the critical nucleation distance for a full-space, results are plotted against the depth of the fault, also normalized by $h_0^*$.

The qualitative behavior of the results depends primarily on the geometric parameters.
VELOCITY STRENGTHENING FAULT

Slow Slip Pulses

- The video below shows an example of a slow slip pulse, spontaneously nucleating on a dipping thrust fault with velocity-strengthening properties.

- The event nucleates from small, random fluctuations in the slip velocity, relative to the steady-state slip velocity $v_{\text{plate}} = 10^{-9}$ m/s.


Other parameter values are as above for the video.

Simulation Results

- The figure above shows the maximum slip velocity attained by slow slip pulses for a range of background normal stress values, and as a function of $(a - b)$. 
• Very small values of \((a-b) > 0\) are required for slow slip pulses to nucleate.

• Higher background normal stress enhances the slip velocities, and possibly the likelihood that slow slip pulses will nucleate.

• More work is needed to better understand what parameters control the maximum value of \((a - b)\) that will generate pulses.
CONCLUSIONS AND REFERENCES

Key Results

• For velocity-weakening properties, the value of \( h^* \) depends on location along the fault.

• \( h^* \) decreases from the full-space value when the depth of the fault is \(~0.6h_0^*\). 

• For velocity-strengthening properties, slow slip pulses can spontaneously nucleate on the fault when \((a - b)\) is positive, but small.

• This behavior is similar to that observed on bimaterial and poroelastic faults [4, 5].

References


ABSTRACT

Recent observations of faults in the shallow regions of subduction zones have revealed slow slip events that nucleate up-dip of the locked zone. Clay-rich sediments are prevalent at shallow depths and a large body of experimental work has shown that these sediments have a tendency towards velocity-strengthening frictional behavior, although velocity-weakening behavior is observed as well. Models of deeper slow slip, down-dip of the locked zone, generally require velocity-weakening behavior for events to nucleate. Here I show that slow slip events can nucleate and propagate on shallow, velocity-strengthening thrust faults, in a numerical model of a thrust fault dipping in a homogeneous, elastic half-space. This behavior is due to the broken symmetry of the thrust fault geometry, and is similar to behavior previously reported on bi-material, and poro-elastic faults. The interaction of the fault with the free surface (i.e. the sea floor) creates a coupling between normal stress on the fault and fault slip. This coupling allows velocity-strengthening slow slip events to nucleate, and becomes stronger at shallower depths. Here I conduct a parameter analysis, and show how this behavior is limited to certain values of the frictional and elastic parameters on the fault.