Modeling short-interval silent slip events in deeper subduction interfaces considering the frictional properties at the unstable-stable transition zone

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Reference
Shibazaki and Shimamoto (submitted to GJI, 2006)
Short-interval silent slip event

- Recurrence time
  - Cascadia subduction zone (Dragert et al, 2001); 14 mo
  - Southwest Japan subduction zone (Obara and Hirose, 2003); 3 - 6 mo

- Propagation velocities of these events are around 10 km/day.

- These events are accompanied by low frequency micro-tremors.
A silent slip event on the deeper Cascadia subduction interface

**Model of silent slip event**  Drager, Wang, and, James (2001)

![Model of silent slip event](image)

**The dates of occurrence (horizontal red bars) as a function of relative site positions** (Dragert et al., 2004)

![The dates of occurrence](image)

Recurrence interval: 14Mo (Rogers and Dragert, 2003)

The speed of migration along the strike: 5 to 15 km per day
A silent slip event on the deeper Tonanki and Tokai subduction interfaces

The speed of migration along the strike
\[ \sim 10 \text{ km per day} \]
2. Fundamental assumptions for modeling short-interval silent slip events

(1) Transitional behavior in the friction law for the unstable-stable transition zone
Experimental study: Shimamoto (1986)
Theoretical study: Brechet and Estrin (1994)

(2) Pore-fluid pressure is very high; the effective normal stress is low.
Seismological study: Kodaira et al. (2004), Shelly et al. (2006)

(3) Critical weakening displacement is very small in proportion to effective normal stress.
Contact area between asperities is small due to high pore-fluid pressure.
Steady state friction for halite around the unstable-stable transition (Shimamoto, 1986)
Friction for ductile materials
(Velocity weakening at low slip velocity and
velocity strengthening at high slip velocity)

Dieterich/Ruina friction law
with cut-off velocity

\[ \mu = \mu_s + a \ln\left(\frac{\nu}{\nu_1}\right) + b \ln\left(\frac{v_2 \theta}{D_c} + 1\right) \]

\( v_2 \) Cut-off velocity to an evolution effect

\[ \frac{d\theta}{dt} = 1 - \frac{\theta \nu}{D_c} \]

Steady state friction

\( \nu << v_2 \)

\[ \mu_{ss} \approx \mu_s + a \ln\left(\frac{\nu}{\nu_1}\right) - b \ln\left(\frac{\nu}{v_2}\right) \]

\( \nu >> v_2 \)

\[ \mu_{ss} \approx \mu_s + a \ln\left(\frac{\nu}{\nu_1}\right) \]

Relation between steady state friction and slip velocity

velocity weakening
velocity strengthening

unstable zone

Velocity weakening
Velocity strengthening

ductile zone

\[ z > 28\text{km} \]

\[ v_2 = 10^{-6.5} \text{m/s} \]
Depth distribution of constitutive law parameters in a rate- and state dependent friction law

Seismogenic zone

Generation zone of Short-interval silent Slip event

\[ a-b<0 \]

\[ v_2 = 10^{-6.5} \text{ m/s} \]

\[ \left. \frac{d \mu_{ss}(v)}{d \ln v} \right|_{v=10^{-10} \text{ m/s}} < 0 \]

\[ \left. \frac{d \mu_{ss}(v)}{d \ln v} \right|_{v=10^{-4} \text{ m/s}} > 0 \]
Pore fluid pressure is assumed to be very close to lithostatic pressure at the deeper part of the seismogenic zone.

\[ \sigma_{n}^{\text{eff}} = \sigma_{n} - P_{f} \approx 0 \]

The critical displacement is very small because of the small effective normal stress.

\[ D_{c} \approx 1 \text{mm} \]
Stress is accumulated by the delay of the fault slip from relative plate motion

\[ \tau_i = \sum k_{ij} (V_{pt} t - u_j) - \frac{G}{2\beta} \frac{du_i}{dt} \]

3. 2D Model for short-interval silent slip events

Stress is accumulated by the delay of the fault slip from relative plate motion.
\[ \sigma_{\text{eff}} = \sigma_n - P_f = 1.02 \text{MPa} \]

\[ v_2 = 10^{-6.5} \text{ m/s} \]

\[ D_c = 0.8 \text{mm} \]

Spatial distribution of slip velocity with time for a silent slip event

Slip and slip velocity for several cycles of silent slip events at a distance of 94 km
Time changes in slip velocity and recurrence intervals of a silent slip event during the interseismic period.

Approaching the mainshock, there is a rapid increase in the maximum slip velocity and a rapid decrease in the interval of silent slip events.
4. 3D Model for short-interval silent slip events

Model space

- zone of velocity weakening at low slip velocity
- 20°
Slip velocity distribution for the three silent slip event

Event 1
9.18-9.32 year

Event 2
10.48-10.57 year

Event 3
11.86-11.99 year

Log$_{10}$ Slip velocity (m/s)
Relationship between slip velocity and propagation velocity

\[ v_r = \frac{1}{\gamma} \frac{\mu}{\Delta \sigma_b} \dot{u}_{\text{max}} \quad \text{Ida (1973)} \]

\[ \mu = 30 \text{GPa}, \; \Delta \sigma_b \approx 0.1 \text{MPa}, \; \gamma \approx 1 \]

\[ \dot{u}_{\text{max}} = 3.0 \times 10^{-7} \text{ m/s} \Rightarrow v_r = 9.0 \times 10^{-2} \text{ m/s} = 7.8 \text{ km/day} \]
Relationship between propagation velocity and the slip velocity

SSE: Short-interval silent slip event
LSE: Long-interval silent slip event
Summary

To reproduce short-interval silent slip events we consider frictional properties at the unstable-stable transition regime.

Short-interval silent slip events can be reproduced in a condition where pore fluid pressure is very close to the lithostatic pressure and critical displacement is around 1mm. Propagation speed and slip velocity of these events are 4-8 km per day and 2-4 \(\times 10^{-7}\) m/s.

Approaching the main event, there are some changes in occurrence of silent slip events due to the slow precursory slip of the main event: shorter intervals and faster slip velocities.

More experimental work on rock friction is necessary for understanding whether switching between velocity weakening and velocity strengthening behavior occur at the condition of the depth where the silent slip event occurs.