Modeling shallow slow slip events along the Hikurangi margin: Insights into their segmentation and the effect of pore-pressure cycling

Presenter PhD student: Andrea Perez-Silva
Supervisors: Yoshihiro Kaneko, Martha Savage
Collaborators: Duo Li, Laura Wallace, Charles Williams

1 Victoria University of Wellington, New Zealand
2 Kyoto University, Japan
3 LMU, Germany
4 GNS Science, New Zealand
5 University of Texas, USA
Slow slip events (SSEs) along the Hikurangi margin show a rich diversity of characteristics.

- SSEs occur at both shallow (<15 km) and deep (> 20 km) depths.
- Deep and shallow SSEs at Hikurangi exhibit contrasting source properties.

<table>
<thead>
<tr>
<th>Source property</th>
<th>Shallow Hikurangi SSE</th>
<th>Deep Hikurangi SSEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>2-3 weeks</td>
<td>1-2 yrs</td>
</tr>
<tr>
<td>Magnitude</td>
<td>$M_w$ 6-6.6</td>
<td>~$M_w$ 7.0</td>
</tr>
<tr>
<td>Max. slip</td>
<td>1 - 10s cms</td>
<td>~20 cm</td>
</tr>
<tr>
<td>Recurrence interval</td>
<td>1 to 5 yrs</td>
<td>~5 yrs</td>
</tr>
</tbody>
</table>

Data from Ikari et al. GGG, 2020

Perez-Silva et al., JGR, 2022
Slip contours from Wallace et al. Annu. Rev., 2020
Several elements characterize the environment where slow slip occurs along the Hikurangi margin

- Interseismic coupling changes along the strike of the margin
- High pore fluid pressure at the source depths of SSEs
- Geometrical (e.g. seamounts), lithological and frictional heterogeneities at the plate interface

Wallace & Beavan, *JGR*, 2010

Our numerical simulations are motivated by two observations made on shallow Hikurangi SSEs

- The recurrence interval of shallow SSEs changes along the Hikurangi margin (Wallace *Annu. Rev.*, 2020).

- Pore fluid pressure has been inferred to cyclically vary during shallow Hikurangi SSEs (Warren-Smith et al. *Nat. Geosci.* 2019).
Part 1: Modeling the segmentation of shallow Hikurangi SSE recurrence intervals
Recurrence interval of shallow Hikurangi SSEs is segmented along the margin

Slip contours from Wallace et al. *Annu. Rev.*, 2020

Figure modified from Wallace et al. *Annu. Rev.*, 2020
To determine the mechanism behind the segmentation of shallow SSEs, we conduct numerical simulations

- Simulation code developed by Duo Li & Yajing Liu (2016)
- Governing equations:
  - Quasi-dynamic relation (Rice 1993):
    \[
    \tau = - \sum K(\delta(t) - Vp*l*t) - \eta \frac{d\delta(t)}{dt}
    \]
  - Rate-and-state friction law (Dieterich 1979):
    \[
    \tau = \sigma \left[ f_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0\theta}{d_c} \right) \right]
    \]

\[\frac{d\theta}{dt} = 1 - \frac{v\theta}{d_c} \quad \text{Aging law}\]
Model setup

We consider:

▷ 3D plate interface (Williams et al. 2013)
▷ Rate-weakening (a-b < 0) friction properties where SSEs occur.
▷ Plate rate ($V_{pl}$) increases northwards along the margin
▷ Low effective normals stress ($\sigma$) within SSE source depths (1 or 10 MPa)

Perez-Silva et al., JGR, 2022
Model setup - Effective fault stiffness ratio $W/h^*$

- $W$ depends on fault dip angle
- We assume a uniform $h^*$ along-strike
- Parameter $W/h^*$ is key to reproduce SSEs (Liu & Rice 2005)

Perez-Silva et al., JGR, 2022
We explore parameters $a/b$ and $W/h^*$ within the slow slip region.

$(a-b)_{vw} = -0.003$, $\sigma = 1$ MPa

$\triangleright$ $h^*$ ranges from 80 km to 300 km.

$\triangleright$ Parameter range that leads to SSEs along the whole margin is relatively narrow.

$\triangleright$ $h^* = 95$ km in best model.

Each simulation takes between $\frac{1}{2}$ to 2 days using 53 physical cores.
Model results - Representative model reproduces shallow Hikurangi SSE properties

Observed ranges (from Ikari et al. 2020’s catalog)

Perez-Silva et al. JGR, 2022
Model results - Representative model

→ Red: Above the plate rate
→ Blue: Below the plate rate
Model results - SSE recurrence changes along the margin

Perez-Silva et al. JGR, 2022
To understand the causes of segmentation, we conduct additional simulations to isolate the effect of plate geometry and plate converge rate.

To isolate the effect of the plate geometry, we consider a planar fault.

Note that for the planar geometry $W$ is uniform along-strike.

For each geometry we apply uniform and variable $V_{pl}$ along-strike.

Perez-Silva et al. JGR, 2022
Non-planar geometry

Variable $V_{pl}$

Uniform $V_{pl}$

Planar geometry

Variable $V_{pl}$

Uniform $V_{pl}$

Increasing segmentation of SSE recurrence interval

Perez-Silva et al. JGR, 2022
Change in recurrence interval correlates with changes in $W$ (or equivalently in effective fault stiffness ratio $W/h^*$) and $V_{pl}$.
Conclusions

▷ A relative simple model can reproduce the main source properties (i.e. duration, magnitude, recurrence interval) of observed shallow SSEs in Hikurangi.
▷ Segmentation of SSE recurrence interval is controlled mainly by the along-strike change in $W/h^*$, which in turn depends on the plate geometry (dip angle).

Limitations

▷ Parameter range that leads to SSEs comparable to observations is narrow.
▷ Model assumes constant pore fluid pressure over time.
▷ Model does not account for the presence of rate-strengthening behavior within the slow slip source region.
Part 2: Modeling pore fluid pressure fluctuations during shallow Hikurangi SSEs
Recent studies indicate that pore fluid pressure changes correlate with occurrence of SSEs

- Pore pressure fluctuations during shallow SSEs were inferred along the Hikurangi margin (Warren-Smith et al. 2019).
- Similar pore-pressure changes were proposed in other SSE regions such as Cascadia (Gosselin et al. 2020), Kanto (Nakajima & Uchida 2018) and Kii Peninsula (Kita et al. 2021).

![Schematic diagram representing conceptual model of pore-pressure cycle during shallow Hikurangi SSEs proposed by Warren-Smith et al. Nat. Geosci., 2019](image-url)

Modified from Warren-Smith et al. Nat. Geosci., 2019
Numerical models have shown that pore-pressure changes in a rate-strengthening fault zone lead to aseismic slip. 

- Numerical models (e.g. Dublanchet 2019, Heimisson et al. 2019, Yang & Dunham 2021) have shown that aseismic slip arise during pore-pressure increase in a rate-strengthening fault zone.

- These results suggest that SSE could be hosted in rate-strengthening faults during pore-pressure increase.
Building on previous models, we investigate whether periodic perturbations in pore pressure on rate-strengthening faults can reproduce observed SSE properties.

Pore fluid pressure perturbations are applied by varying the effective normal stress:

\[ \bar{\sigma} = \sigma - p(r,t) \]

**Note:** We do not account for porosity or permeability evolution as in Yang & Dunham *JGR*, 2021 and Zhu et al. *Nat. Comm.*, 2020.

**Important parameters:**
- \( a-b = 0.005, \, a/b = 1.25 \)
- \( \sigma = 3 \text{ MPa} \)
- \( L_b = \mu d_c / b \sigma = 4.17 \text{ km} \)

We use the 3D model developed by Lapusta & Liu *JGR*, 2009.
We assume two types of pore-pressure perturbation

Type I: Sawtooth perturbation


Type II: Fluid injection and diffusion

- Fluids are “injected” at the center of the fault
- We use the analytical solution of the diffusion equation (Turcotte and Schubert, 2014; Dublanchet 2019)
Model results

- Simulations take 1 to 10 hrs to run using 64 physical cores
- SSEs emerge during pore-pressure increase
- We find two representative models that reproduce the properties of shallow Gisborne SSEs.
Representative models that reproduce shallow Gisborne SSE properties

**Type I: Sawtooth perturbation**

- Slip velocity increases during pore pressure increase
- $\Delta p_0 = 2 \text{ MPa}$
- $R_0 = \sim 30 \text{ km}$

**Type II: Fluid injection and diffusion**

- $\Delta p_0 = \sim 1.5 \text{ MPa}$
- $t_{\text{inj}} = 30 \text{ days}$
- $D = 50 \text{ m}^2/\text{s}$
Representative models that reproduce shallow Gisborne SSE properties

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<table>
<thead>
<tr>
<th>Source property</th>
<th>Observed SSEs offshore Gisborne*</th>
<th>Best-fit Type I perturbation</th>
<th>Best-fit Type II perturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration</strong></td>
<td>18 \pm 9 days</td>
<td>22 \pm 0.07 days</td>
<td>21 \pm 0.03 days</td>
</tr>
<tr>
<td><strong>Magnitude</strong></td>
<td>$M_w 6.3 \pm 0.1$</td>
<td>$M_w 6.27 \pm 0.1$</td>
<td>$M_w 6.36$</td>
</tr>
<tr>
<td><strong>Max. slip</strong></td>
<td>12.6 \pm 8.6 cm</td>
<td>9.5 \pm 0.01 cm</td>
<td>10.1 \pm 0.2 cm</td>
</tr>
<tr>
<td><strong>Recurrence interval</strong></td>
<td>1.5 to 2 yrs</td>
<td>2 yrs</td>
<td>2 yrs</td>
</tr>
</tbody>
</table>

*From SSE catalog in Ikari et al. GGG, 2020.
Slip rate evolution during SSEs is different for each representative model.

**Type I: Sawtooth perturbation**

**Type II: Fluid injection and diffusion**

→ **Red**: Above the plate rate  
→ **Blue**: Below the plate rate
Can the model reproduce broader SSE properties?

- We explore a broader range of parameters for the diffusion-driven perturbation.
- The controlling parameter of the diffusion-driven perturbation is the characteristic size:
  \[(D_t_{\text{inj}})^{1/2}/L_b\]

- We explore:
  - \(t_{\text{inj}}\) from 10 days to 2 yrs
  - \(D\) from 0.1 m\(^2\)/s to 100 m\(^2\)/s

So that \(10^{-1.15} < (D_t_{\text{inj}})^{1/2}/L_b < 10^{1.3}\)
SSE duration and moment increase with \((D_{t_{\text{inj}}})^{1/2}/L_b\)

- Varying the characteristic length of the perturbation, the model reproduces a broad range of SSE properties.

- Caveat: Hydraulic diffusivity (D) is several orders of magnitude higher than estimates from lab and in-situ measurements.
Varying $(Dt_{\text{inj}})^{1/2}/L_b$, the model reproduces SSE duration and magnitudes from other subduction zones.

* Data from Ikari et al. GGG, 2020 (Hikurangi), Takagi et al. JGR, 2019 (Nankai), Michel et al. Nature, 2018 (Cascadia) and Radiguet et al. JGR, 2012 (Guerrero).
Conclusions

▷ Our model successfully reproduces the source properties of shallow Hikurangi SSEs offshore Gisborne under two different perturbation types.

▷ SSE moment and duration depend on the perturbation length scale (assuming diffusion-driven perturbation). Varying the perturbation length scale, the model reproduces a broad range of SSE properties from different subduction zones.

▷ Periodic pore-pressure perturbations in a rate-strengthening fault zone may be a viable mechanism to generate SSEs. This modeling approach is not constrained by the effective fault stiffness ratio ($W/h^*$) criterion.