Modeling Sequence of Earthquakes and Aseismic Slip on Fault Step-Overs with Off-Fault Plasticity

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Introduction

Fault step-overs are ubiquitously observed in on long strike-slip fault systems and are very likely to produce slip complexities through the interaction between nearby faults. However, resolving stress interactions among different fault segments throughout the entirety of an earthquake cycle remain challenging numerically. Here, we rely on the numerical efficiency of the hybrid finite element spectral boundary integral scheme (FEBE) to model two parallel faults having a compressional step over in a two-dimensional plane strain model. Full account of inertia is considered during rapid seismic rupture and radiation damping approximation is used for inertia during slow aseismic deformation. The off-fault bulk response is elastoplastic governed by a Drucker-Prager plasticity model with viscous regularization. Our results indicate that stress interactions between the two faults affect the long-term evolution of aseismic and seismic deformation, as well as lead to possible triggering mechanisms within the fault network.

We show that fault interaction leads to delays between ruptures in the two faults which were initially synchronous. Furthermore, we demonstrate that the plasticity response within the fault zone can enhance fault interaction resulting in additional seismic events. We show that off-fault plastic strain accumulates primarily near the fault ends and subsequently encompasses the over-lapping gap region between the two faults. Evolution of mean stress shows that over-lapping gap region experiences increasing compression with subsequent seismic events whereas regions near the fault ends tend to experience reduced compression and potentially tensile stresses. The significant increase in the mean stress suggests some limitations of classical Coulomb like plasticity models and points to the necessity of incorporating some more general formulations such as cap-plasticity models or a fully-resolved continuum damage breakage model. Furthermore, we observe significant rotations in the direction of the principal stresses within the overlapping region compared to the stress orientations in the far-field. This emphasize the critical role of resolving geometrical complexity and long-term deformation history in understanding the stress evolution in space and time. Our preliminary results uncover new insights into the mechanics of fault step-overs and contribute to the understanding of interaction dynamics in fault networks and geometrically complex fault zones.

Model Set-up and Methodology

- Two parallel step-over faults embedded in elastic- viscoplastic bulk.
- Regularized rate-and-state friction: $\tau(x,t) = \sigma_n\, a \sinh^{-1}[\frac{V}{2V_0}\exp(\frac{f_0+b\ln(V_0\theta/L)}{a})]$
- Drucker-Prager plasticity model with viscoplastic regularization.
- FEM discretization including fault and potential elastoplastic fault zone.
- SBI relation between boundary traction and displacement to replace the half space.
- Alternating quasi-dynamics and dynamics solver to account full inertial effects.

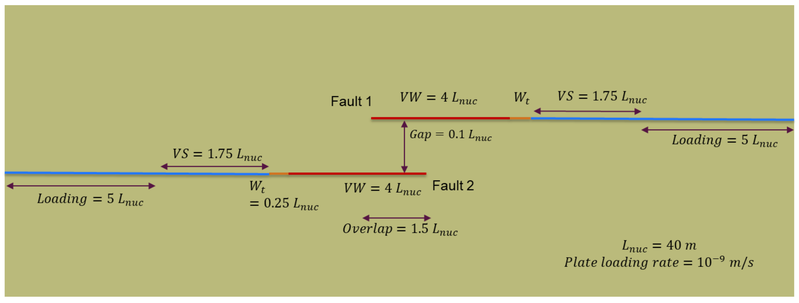


Figure 1: Compressional step-over with two parallel right lateral faults having velocity strengthening (VS) and velocity weakening (VW) patch.

Results

- Fault interaction leads to seismic complexity and asynchronous rupture in the two faults with various delay time.

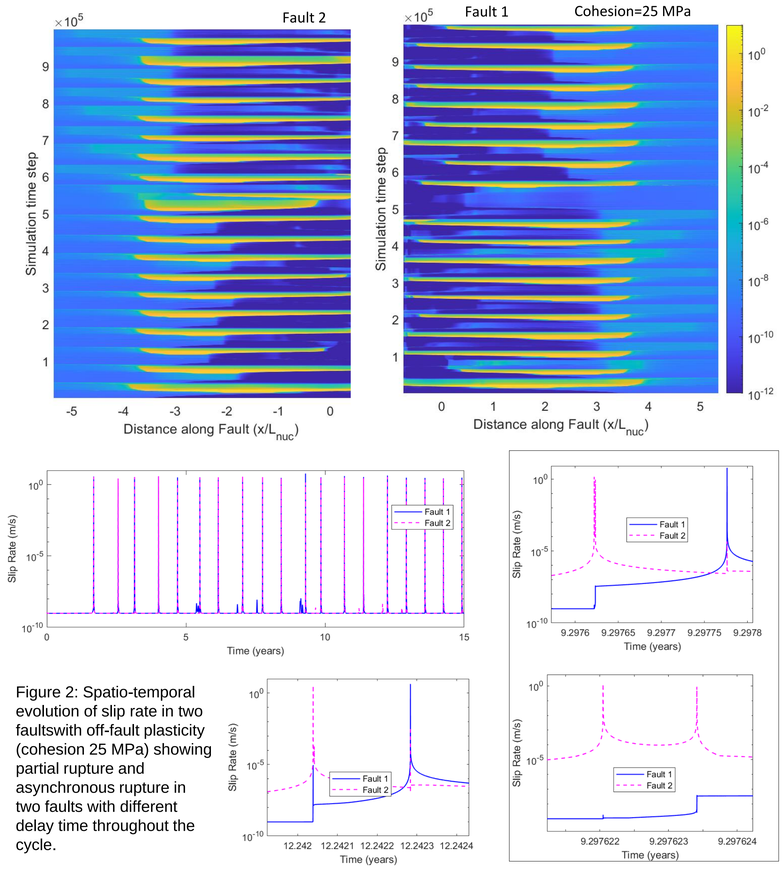


Figure 2: Spatio-temporal evolution of slip rate in two faultswith off-fault plasticity (cohesion 25 MPa) showing partial rupture and asynchronous rupture in two faults with different delay time throughout the cycle.

- Plasticity enhances the interaction resulting in additional seismic events.

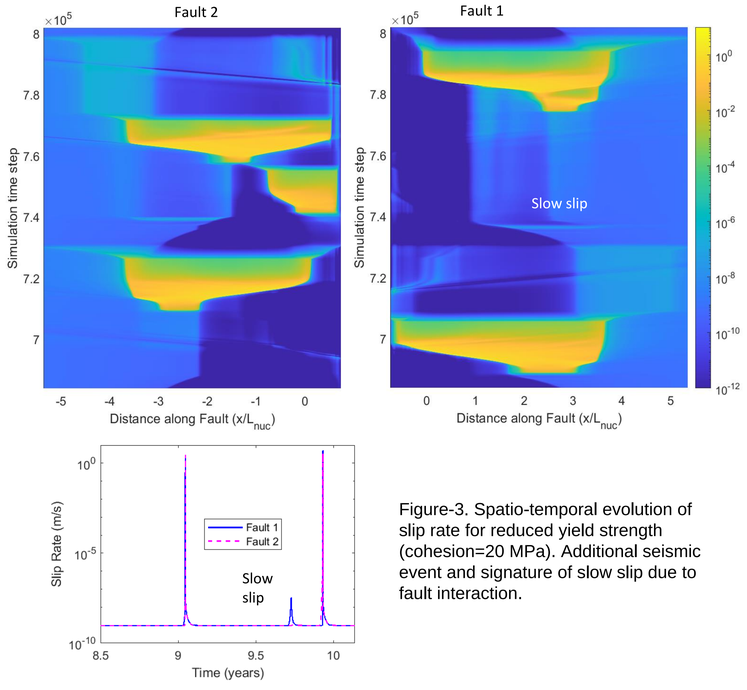
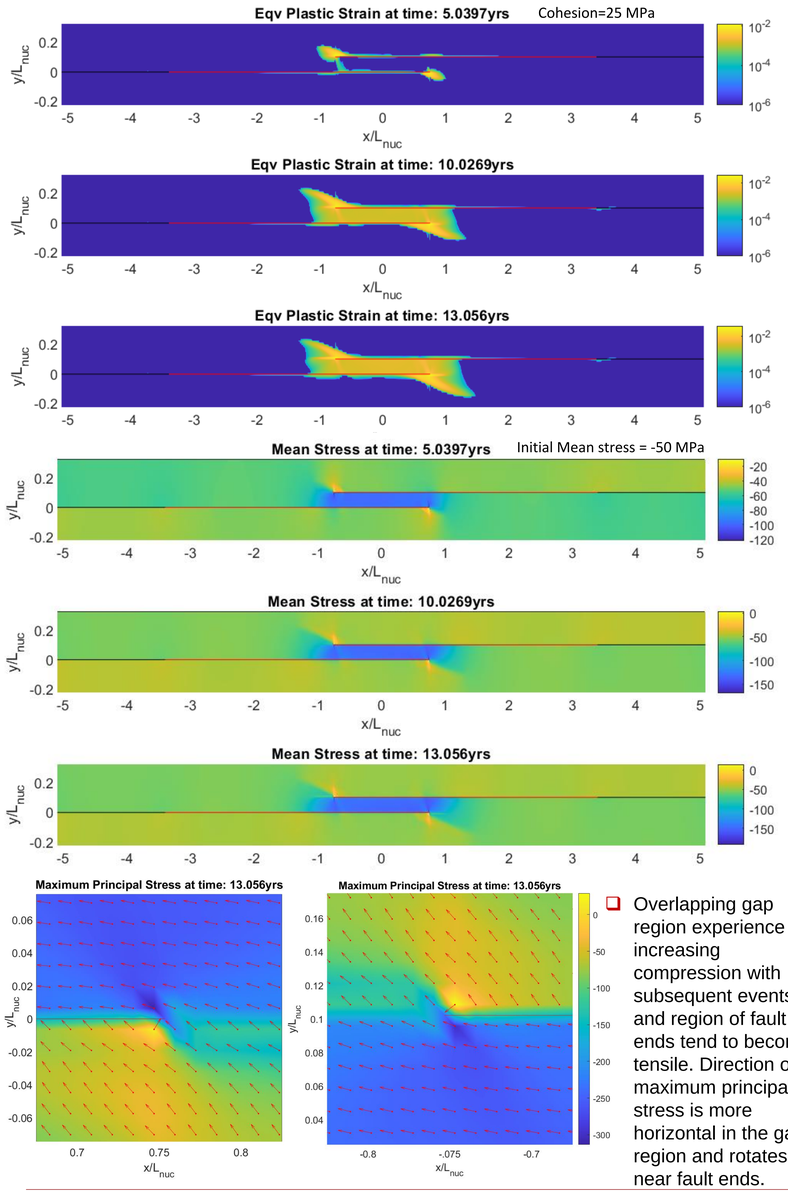


Figure-3. Spatio-temporal evolution of slip rate for reduced yield strength (cohesion=20 MPa). Additional seismic event and signature of slow slip due to fault interaction.

- Plastic strain accumulates near the fault ends and spreads in the overlapping gap region of the compressional step-over



- Overlapping gap region experience increasing compression with subsequent events and region of fault ends tend to become tensile. Direction of maximum principal stress is more horizontal in the gap region and rotates near fault ends.

Summary

- Fault interaction results in seismic complexity and leads to delays between ruptures in the two faults which were initially synchronous.
- Plasticity enhances interaction and results in additional seismic events and signature of slow slip.
- Off-fault plastic strain accumulates primarily near the fault ends and subsequently encompasses the over-lapping gap region.
- Stress state in step-over region becomes significantly different than far-field stress with subsequent events.
- Mean stress and maximum principal stress successively becomes more compressive in the overlapping gap region and tend to becomes tensile near the fault ends.

Future Study

- Cap-plasticity model
- Damage plasticity model

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