Rough Fault Rupture Simulations: Overview of Results

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DEFINITIONS

• By fault roughness, I mean components of morphology best treated as random field
  • Departures from planarity widely distributed in location and scale
  • Sufficiently complex to merit (require) stochastic representation

• What I mean by rupture simulation
  • Dynamic models, 2D or 3D, with slip- or rate-weakened friction
  • Neglect geometrical nonlinearity (i.e., minimum roughness scale $\gg$ slip)
  • Un-branched fault surfaces
  • Power-law roughness

Most examples (not quite all) have additional simplifications:

  Highly simplified initial stress state (stress tensor depth dependent only)
  Simple elastic or (pressure-dependent) elastoplastic continuum
  Self-similar roughness spectrum (Hurst exponent $H=1$)
• Self-similar over ~10 orders of magnitude
• Modeled as random field, Hurst exponent ~1
• Max Frequency > 10 Hz → Min scale ~100 m
SUMMARY

Roughness:

• Contributes to high-frequency GM (may be the principal source)
• Contributes to GM statistical variability
• Modifies kinematic parameter correlations
• **Nucleates** transient, buried supershear bursts
• **Suppresses** sustained, shallow SS events
• Creates frequency-dependent radiation patterns
• Produces power-law co-seismic surface slip fluctuations

GM = “Ground Motion”
SS = “Supershear”
• Fault roughness has essential role in HF ground motion excitation

• At least qualitatively consistent with observed features of ruptures and ground acceleration

(Dunham et al., 2011)
High-Frequency GM: 3D Models

Setup of Initial State

- Self-similar (80 m to 80 km scale range)
- RMS-offset ÷ scale-length = 0.005
- Rate-state with dynamic weakening
- Top 1 km velocity strengthening
- Computational cell 20 m

**Lithostatic stress**

\[
\sigma_{11}^0 = \sigma_{22}^0 = \sigma_{33}^0 = -\int (\rho - \rho_w)gdx_2
\]

\[
|\sigma_{31}^0/\sigma_{22}^0| = const.
\]

- Shear/normal stress ratio is minimum permitting system-wide rupture
- Resulting rupture is M 7.25
- Fits empirical magnitude-area relationship

*Shi and Day, 2013*
**Site-Corrected GMRotD50 Response Spectra Compared to the Next Generation Attenuation (NGA) Curves**

Site Amplification: SH plane-wave response of the generic rock structure representative of western North America rock sites [Boore and Joyner, 1997]

Site Attenuation: $e^{-\pi \kappa f}$ with site anelastic loss exponent (defined by Anderson and Hough [1984]) $\kappa = 0.04$ sec

$M_w = 7.23$

- CY: Choi and Young (2008)
- CB: Campbell and Bozorgnia (2008)
• Roughness is strong source of GM variability (sigma)
• Random-field heterogeneities moderate sigma

Withers et al. (2015)
Increased roughness → increased spread of RV distribution (reduced rupture coherence, diminished directivity)

Increased roughness → Rise time decorrelates with rupture velocity

Yao, 2017 (SDSU PhD Thesis)
Supershear Rupture

2D simulations (Bruhat et al., 2016):

- Overall roughness favors *nucleation* of SS transients
- Local smoothness favors *sustained* SS rupture

3D (Yao, 2017):

- Roughness favors buried SS transients
- Smoothness favors shallow, sustained SS ruptures

Yao, 2017 (SDSU PhD Thesis)
Based on flat_s, $\alpha=10^{-3.0}$

**Flat boundary and sharp stopping phase exists**

**Spontaneous stopping no sharp stopping phase**

**Based on flat_s, $\alpha=10^{-3.0}$**

$2D$ Cho and Dunham, 2010 (AGU annual meeting)

$3D$ Wang, Day and Shearer, 2014 (AGU annual meeting)
Fault normal/parallel GM ratios vs frequency in kinematic simulations of *Graves and Pitarka (2016)*

Graves/Pitarka model reproduces Imperial Valley (1979) FN/FP ratios

RotD100/RotD50 Ratios vs Period *(Withers et al., 2018)*

Rough fault + CVM

Empirical *(Shahi & Baker)*

Rough fault + CVM + scattering
Co-seismic Surface Slip

1992 Landers Rupture
(Milliner et al. 2015)

$H \sim 0.44$

Surface-rupturing Rough-fault simulations
(Yao, 2017)

$H \sim 0.6$ (ensemble range 0.5-0.8)
Effect of Undrained Gouge Deformation

- Moderates rupture complexity

- Roles of “releasing” and “restraining” orientations are reversed (as in Harris & Day, 1993)

- Rupture velocity fluctuations very similar to constant-pore-pressure case

Hirakawa & Ma (2018)
SUMMARY

- Contributes to high-frequency GM (may be the principal source)
  ~10 Hz @ ~100 km is now calculable

- Contributes to GM statistical variability
  But random heterogeneities are at least equally important

- Modifies kinematic parameter correlations
  Reduces rupture coherence

- Promotes transient, buried supershear bursts
  Most are small and probably undetectable

- Suppresses sustained, shallow SS events
  Consistent with observed association of SS with smooth fault segments

- Creates frequency-dependent radiation patterns
  Fills nodes at frequencies > ~3 Hz and improves FN/FP ratio predictions

- Produces power-law co-seismic surface-slip fluctuations
  May be partial (but incomplete) explanation of coseismic slip maps

- Model with undrained gouge compaction has mostly similar GM implications
  Roles of restraining and releasing features are reversed.
  Would have big effect on prediction of, e.g., rupture termination points.