Earthquake and fault system dynamics – Putting the pieces together

Jim Dieterich
UC Riverside

With Thanks to
Keith Richards-Dinger UC Riverside
Kayla Kroll - LLNL
Jacqui Gilchrist - USC
Debbie Smith - USGS
Outline of topics

- Elements of earthquake and fault system dynamical models
- A few comparisons with observations and results from well-established computation models
- Earthquake rupture similarity
- Interactions between slow slip events and earthquakes
- Earthquake clustering
- Rupture propagation at fault complexities
- Future direction: earthquakes occurring off explicitly modeled faults
Modeling challenges – system dynamics

• **Extreme range of time and length scales** → **New approach to EQ modeling**
  - $10^5$ years and $>10^6$ earthquakes
  - High spatial resolution for range of earthquake magnitudes

• **Space-time clustering of EQs** → **essential element of seismic activity**
  - Added modeling complexity to incorporate time-dependent failure

• **Fractal-like geometry of faults and fault systems** → **Geometric incompatibilities and modeling pathologies**
  - *Uniform remote stressing does not work*
  - *Finite strength requires off-fault failure (seismicity)*
    - Off-fault yielding alters slip processes on modeled faults
    - Introduces additional time-dependencies
Simulation ingredients – 1) Fault model

UCERF3 fault model and slip rates

- ~ 290,000 triangular elements (~1km^2) in simulations with deep fault creep (~ 260,000 no creep)
- Approximate range of magnitudes $M_w = 4$ to $M_w = 8$
- 120,000 years simulated time ~ $16 \times 10^6$ events
- Simulations may be restarted to span $10^6$ years
Loading conditions in systems with geometric incompatibility – fault systems and non-planar faults

Slip in response to an applied uniform stress increment $\Delta\sigma_{xy}$

- Planar fault
- Fractal fault

Dieterich and Smith (2009)
Fault slip and stress changes

Smooth fault  
Fault with self-similar roughness

Geometric incompatibilities form elastic barriers
Barrier stress produces a back-stress that inhibit slip
Back-stress increases with linearly with total slip resulting break-down of slip scaling with rupture length and other pathologies

Yielding required if $\beta \geq 0.01-0.02$

Dieterich and Smith (2009)
Simulation ingredients – 2) Loading conditions

To prevent long-term build-up of stresses resulting from geometric incompatibilities the following condition must be satisfied at each element $i$ in the model:

$$\dot{S}_i^T + \dot{S}_i^R + \dot{S}_i^F = 0$$

- Direct tectonic stressing rate at element $i$
- Average stressing rate from other sources (stress relaxation processes and slip of (unknown faults))
- Long-term average stressing rate from interactions among the simulated fault elements
Simulation ingredients – 2) Loading conditions

External loading of modeled fault elements

Internal interactions

Direct tectonic stressing rate at element $i$

Average stressing rate from other sources (stress relaxation processes and slip of unknown faults)

Long-term average stressing rate from interactions among the simulated fault elements

In the simulations

$$\overline{S}_i^F = K_{ij} \overline{\delta}_j$$

where $\overline{\delta}_j$ is the long-term fault slip rate

Hence, the the long-term average loading rate of the external loading sources is

$$\dot{\overline{S}}_i^T + \overline{\dot{S}}_i^R = -\overline{S}_i^F = K_{ij}(-\overline{\delta}_j)$$

**BACKSLIP LOADING**
Simulation ingredients – 3) Constitutive Law for fault slip

Rate- and state-dependent friction

Coefficient of friction:

\[
\frac{\tau}{\sigma} = \mu = \mu_0 + A \ln\left(\frac{V}{V^*}\right) + B \ln\left(\frac{\theta}{\theta^*}\right)
\]

Evolution law for state:

\[
d\theta = dt - \frac{\theta}{D_c} d\delta - \frac{\alpha \theta}{B \sigma} d\sigma
\]

Stationary contact at constant normal stress, \(d\theta = dt\)

fault strengthens with \(B \ln(\text{time})\)

At steady state, \(d\theta/dt = 0\) and

\[
\theta_{ss} = \frac{D_c}{V} \quad \mu_{ss} = \text{const.} + (A - B) \ln V
\]
Simulation ingredients – 4) Computational engine: RSQSim

- Boundary elements \(\rightarrow\) faults are represented as arrays of rectangular or triangular elements
- Simulations avoid repeated solutions of a large system simultaneous equations \(\rightarrow\) fast computation
- Event driven computations based on changes of fault sliding state. A fault element may be at one of three sliding states
  - 0 – Fault is essentially locked – aging by log time of stationary contact
  - 1 – Nucleating slip: Time- dependent accelerating slip to instability
    Analytic solutions with rate-state friction
  - 2 – Earthquake slip: quasi-dynamic – slip speed is specified as an input based on shear wave impedance.
    \[ \dot{\delta}_{EQ} = \frac{2\beta\Delta S}{G} \] Estimate of EQ stress drop
Simulation ingredients – 4) Computational Inputs

• Fault system model — (e.g. SCEC community fault model)
• Long term slip rates
• Slip rake angles — UCERF deformation model
• Fault-normal stresses acting on fault elements — locally tuned to
given interevent recurrence times consistent with community
paleoearthquake results
• EQ slip speed (We typically use 1m/s, which is appropriate for stress
drops of ~4-5MPa)
• Rate-state friction parameters ($a, b, D_c$) at each element
• Simulation parameters (dynamic overshoot, rupture tip parameters)
DYNA3D – Fully dynamic finite element simulation

Normal Stress on Fault

(Background Stress = 120 MPa)

Along - Strike Distance (Km)

Depth (Km)

145 MPa

140 MPa

130 MPa

135 MPa

125 MPa

150 MPa

128 MPa

138 MPa

Propagation time 14.0 s

RSQsim – Fast simulation

Propagation time 14.3 s

RSQsim – Dynamic finite element comparison
RSQSim – Fully Dynamic Finite Element Comparison

Normal stress on fault
(Background Stress = 120 MPa)

Along - Strike Distance (Km)

Depth (Km)

145 MPa
140 MPa
130 MPa
125 MPa
135 MPa
150 MPa
128 MPa
138 MPa

Stress change and slip

Shear stress (MPa)
Along - Strike Distance (Km)

Slip (m)
Along - Strike Distance (Km)
RSQSim – Foreshocks and aftershocks

UCERF3 fault model
independent mainshocks M≥7

Aftershocks, slope = -0.94
Foreshocks, slope = -0.87

* Background seismicity rate is global average, not local to mainshock
Interevent Waiting Time Distributions

**California Catalog: M5 to M6**
- Probability Density (s) vs. Inter-event Time (s)
- Slope = -0.884

**California Catalog: M6 to M7**
- Probability Density (s) vs. Inter-event Time (s)

**California Catalog: M7+**
- Probability Density (s) vs. Inter-event Time (s)

**RSQSim Catalog: M5–M6**
- Probability Density (s) vs. Inter-event Time (s)
- Slope = -0.882

**RSQSim Catalog: M6–M7**
- Probability Density (s) vs. Inter-event Time (s)
- Slope = -0.998

**RSQSim Catalog: M7+**
- Probability Density (s) vs. Inter-event Time (s)
- Slope = -1
Space – Time Distributions

California Catalog: M5–M6

California Catalog: M6–M7

California Catalog: M7+

RSQSim Catalog: M5–M6

RSQSim Catalog: M6–M7

RSQSim Catalog: M7+
Rupture Branching

Event # 107232; M = 7.8; \( dt^- = 2e+05 \) days; \( dt = 144 \); \( dt^+ = 2e+05 \) days

Origin time (yrs): 761.720  Nucleated on patch 41374 (SanAndreas(Carrizo)rev)  max slip = 5.360 m  full color scale slip = 5.360 m

San Andreas

Garlock

North
Rupture Similarity

Example of 1906-type earthquake on San Andreas Fault
Event similarity – N. section of San Andreas

From an all-California simulation by J. Gilchrist, with cluster analysis on along-strike EQ slip by K. Richards-Dinger.

UCERF fault model and slip rates, tuned to paleoseismic recurrence intervals
Event similarity – N. section of San Andreas
Comparison with 1906 San Francisco earthquake
Event similarity – N. section of San Andreas

90% of all events $L \geq 290\text{km} \ (\sim M \geq 8)$ fall in one of these 3 clusters

205 EQs
Event similarity – N. section of San Andreas
Rupture similarity – Cascadia

McCrory et al. [2012]
Boundary @ 25 km depth contour

Boundary halfway between 350°C and 450°C isotherms of Wang et al. [2003]

Rate weakening (continuous creep)

Rate strengthening (seismogenic)

Rate weakening (continuous creep)

Richards-Dinger, Dieterich, Wells (AGU 2014)
Cascadia mean recurrence interval $M>8$

Paleo-turbidite recurrence [Goldfinger et al., 2012]
Cascadia mean recurrence interval $M>8$

Richards-Dinger and others (AGU 2014)
Cascadia mean recurrence interval M>8

Paleo-turbidite recurrence [Goldfinger et al., 2012]

Tuned simulation by adjusting effective normal stress

Richards-Dinger and others (AGU 2014)
Slip and Coastal Subsidence in Great Cascadia Earthquakes

Richards-Dinger and others (AGU 2014)
Vertical Deformation M>8
Comparison w/ data for the great earthquake of 1700
Leonard et al [2004]
Exploratory model for coupled interactions between slow slip events and earthquakes

Effective normal stress (MPa)
- Seismogenic zone $\sigma = 100$
- SSE zone (high $P_f$) $\sigma = 3$
Slow slip events

Necessary conditions:
1) Slip-rate weakening \((b>a)\) at slow slip speeds
2) Mechanism to quench acceleration of slip before reaching earthquake slip speeds
   - Cut-off of state term in constitutive law \(\rightarrow\) reversal from rate weakening at low slip speeds to rate strengthening at higher speeds

\[
\mu = \mu_0 + a \ln \left( \frac{V}{V^*} \right) + b \ln \left( \frac{\theta}{\theta^*} + c \right)
\]
Range of slip speeds in SSEs

Effective normal stress conditions
Seismogenic sector $\sigma = 100\text{MPa}$
SSE sector $\sigma = 3\text{MPa}$

SSE driven by large EQ

Independent SSE

Friction coefficient

Slip rate in units of $Dc/s$
Space – time plot of SSE

Event 166976

Area slipping in SSE

Seismic

SSEs

Distance (km)

0
20,000
40,000
60,000
80,000
100,000

Time (sec)

0
2
4
6
8
10
SSE triggered by mainshock
Space – time plot of SSE

Event 135761

3 small foreshocks triggered SSE

14 foreshocks

Mainshock

Seismic SSEs
Space – time plot of complex SSE with mainshock

Event 593773:

59 foreshocks

Mainshock

Seismic

SSEs

Distance (km)

Time (sec)
**Summary**

**Definitions**
Large SSE: slip area > 75% of transition zone
Large EQ: slip area > 75% of seismogenic zone

**Simulation times**
- Total simulation time: $4.1 \times 10^{10}$ s (1300 yr)
- Total time in large SSEs: $1.78 \times 10^8$ s (~0.4% of sim time)
- Total time all SSEs: $2.01 \times 10^9$ s (~5% of sim time)

**Numbers of events**
- Large SSEs: 1766
- Large EQs: 33
- Large EQs with SSE before mainshock: 14

- 42% of large EQs were preceded by SSEs
- 0.8% of large SSEs preceded large EQs
Large-earthquake cluster along southern San Andreas Fault

M7.3
43 aftershocks in 18.2 days

Large-earthquake cluster along southern San Andreas Fault

M6.9 Followed by 6 aftershocks in 4.8 minutes

Large-earthquake cluster along southern San Andreas Fault
Clusters of Large Earthquakes

\( F_{\text{cluster}} \) is the fraction of M≥7 events that occur within 4 years of other M≥7 events (in excess of that predicted by a Poisson model)

<table>
<thead>
<tr>
<th>All Cal model – effect of ( a )</th>
<th>( F_{\text{cluster}} ) for M ≥ 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Cal, ( a = 0.008 )</td>
<td>0.124</td>
</tr>
<tr>
<td>All-Cal, ( a = 0.009 )</td>
<td>0.117</td>
</tr>
<tr>
<td>All-Cal, ( a = 0.010 )</td>
<td>0.145</td>
</tr>
<tr>
<td>All-Cal, ( a = 0.012 )</td>
<td>0.171</td>
</tr>
</tbody>
</table>

California Catalog
1911-2010.5, M=6 to M=7

\( F_{\text{cluster}} \) for M ≥ 7

0.14

All Cal Simulation

Rates of M≥7 Earthquakes following M≥7 Earthquakes

slope = -1.1

Seismicity rate relative to background

Time after mainshock (yr)
Aftershocks of Non-Clustered and Clustered $M \geq 7$ Events

Non-Clustered: Blue

Slope=-0.96

Seismicity relative to background

Time after mainshock (yr)
Aftershocks of Non-Clustered and Clustered M≥7 Events

Clustered: Red
Non-Clustered: Blue

Seismicity relative to background

Time after mainshock (yr)

Slope=-0.93
Slope=-0.96
Aftershocks of Clustered and Non-Clustered $M \geq 7$ Events

Red - Aftershocks of Clustered Events
Black - Aftershocks of Non-Clustered Events

Cumulative number of aftershocks vs. Time from mainshock (yr)

- ~5 min
- ~9 hr
- ~1 Month
- 1 year
Probability Additional Earthquake $M \geq 7$ Within 50km of Earthquake $M \geq 7$

Transition from aftershocks of a prior M>7 event to foreshocks of an impending M>7 event

Accelerating Seismicity Prior to Secondary Events

Distance Between Aftershocks and Secondary Events with Time

Stacked data for Large Event Clusters that had 3 to 4 years between them

Simple geometric complexity – fault stepovers

Harris and Day (1993)

Rupture nodes

Dilatational stepover

Compressional stepover
Single event simulations with forced nucleation

- FaultMod – fully dynamic & slip-weakening friction
- RSQSim – quasi-dynamic & rate-state friction $\alpha = 0$
- RSQSim – quasi-dynamic & rate-state friction $\alpha = 0.25$

Kroll and others
Kroll and others

Single event simulations with forced nucleation

- FaultMod – fully dynamic & slip-weakening friction
- RSQSim – quasi-dynamic & rate-state friction $\alpha = 0$
- RSQSim – quasi-dynamic & rate-state friction $\alpha = 0.25$

Stepover width (km)

Re-nucleation position along strike (km)

Delayed rupture jumps
Multi-cycle simulations with evolved stresses and spontaneous nucleation

Kroll and others
Immediate rupture jump probabilities under evolved stress conditions

Kroll, (2016, UCR thesis)
Probability of immediate and delayed rupture jump

probability of delayed jump within 4 years ~40%

Inter-event time
- Immediate
- 1 min
- 1 hour
- 1 day
- 1 month
- 1 year
- 2 years
- 3 years
- 4 years

Kroll, (2016, UCR thesis)
Rupture jump probabilities (instantaneous and delayed)

Kroll, (2016, UCR thesis)
Rupture jump probabilities (instantaneous and delayed)

Kroll, (2016, UCR thesis)
Simulation of a complex fault system between the Elsinore and Laguna Salada faults

Aftershocks of 2010 M7.2 El Mayor Cucapah EQ

Faults from Fletcher et al., (2010) and triggered surface slip of Rymer et al. (2011)

Kroll, (2016, UCR thesis)
Local fault model embedded in regional southern California UCERF3 model
Aftershocks to Laguna Salada mainshock similar to the M7.2 El Mayor-Cucapah earthquake

No through-going ruptures between Laguna-Salada and Elsinores faults
Looking Ahead: Simulations that incorporate off-fault seismicity (as driven by tectonic stressing and on-fault slip history)

\[ R = \frac{r}{\gamma \dot{S}_r}, \quad d\gamma = \frac{1}{a\sigma} \left[ dt - \gamma dS \right] \]

(Dieterich, 1994)

- Background rate \( r \) from recorded seismicity
- \( S(t) \) from assumed tectonic stressing and RSQSim stress

Kroll and others (unpublished)
Comparison of observed and modeled seismicity

- Seismicity between the M7.2 El Mayor-Cucapah earthquake and the M5.7 Ocotillo aftershock ($\Delta t = 71$ days)
- Seismicity after Ocotillo ($\Delta t = 371$ days)
- Seismicity between a simulated Laguna Salada mainshock and a M5.9 aftershock ($\Delta t = 400$ days)
- Seismicity following aftershock ($\Delta t = 730$ days)

Locations:
Hauksson et al., 2012; Kroll et al., 2013
**Incorporating stress relaxation into simulations**

**Concept for stress relaxation:** Assume stresses fluctuate around a steady-state condition where the long-term growth of interaction stresses due to fault slip is balanced by off-fault yielding due to slip on minor fault.

![Change of stress during earthquake](image1)

![Relaxed state (+ tectonic stressing)](image2)

![Elastic response](image3)

![Elastic response + relaxation](image4)
Rate-State off-fault stress relaxation

Assume in the brittle crust that off-fault stress relaxation occurs through earthquakes. Bulk relaxation rate is proportional to earthquake rate, where

\[ R = \frac{r}{\gamma \dot{S}_r}, \quad d\gamma = \frac{1}{a\sigma} \left[ dt - \gamma dS^E \right] \]

Relaxation rate of pressure and deviatoric components of the stress tensor

\[
\dot{P}^R(t) = -\frac{c}{\gamma^P(t)}
\]

\[
d\gamma^P = \frac{1}{a\sigma} \left[ dt - \gamma^P \left( \Lambda^E P^E \right) \right]
\]

where \( \Lambda^E = \text{sign}(\dot{P}^{ss}) \)

\[
\dot{\sigma}^R_{ij}(t) = -\frac{C'_{ij}}{\gamma^D(t)}
\]

\[
d\gamma^D = \frac{1}{a\sigma} \left[ dt - \gamma^D \left( \Lambda^E_{ij} : d\sigma^E_{ij} \right) \right]
\]

where \( \|\Lambda^E_{ij}\| = \sqrt{\Lambda^E_{ij} : \Lambda^E_{ij}} = 1.0 \)

The functions \( \Lambda \) reflect the sign of the stress changes under steady-state slipping conditions, and act to pull the solutions toward an equilibrium stress state

Smith and Dieterich (in prep)
Off-fault stress relaxation for a full earthquake cycle

$t_a=11$ yr, $T=150$ yr

Coulomb stress change

MPa

Coseismic

Aftershocks

Interseismic

Total – all sources

Smith and Dieterich (in prep)