Reminder/Motivations for Why We Need CFEM

Mark Simons, Caltech
What is driving CFEM development?

Why Now?

Data, data, data, data, data
1. Geodetic (InSAR, GPS, …)
2. Structural (Geology, seismic)
3. Seismicity
4. Laboratory

Why FEM?

1. Geometric complexity
2. Rheologic complexity
Modern Geodesy- The impetus

Temporal and spatial resolution
- GPS networks
- Satellite radar interferometry
Modern data sets highlight geometric complexity
• Explosion of data
• Geometric complexity
• Rheologic complexity
Start with this…
Structure of the forearc
Faults, material, etc.

Bangs et al., 2005
The Meshing Challenge

Bookkeeping Materials + properties + interfaces
slip models from Yamanaka and Kikuchi (2002)
Fault zone rheological complexity
Complexity of slip behavior on a single fault

5 years of continuous rapid after slip under peninsula

1995 Mw 8.1 Earthquake

Aseismic pulse 3 years after
Complexity of slip behavior on a single fault

- Negligible coseismic slip at the hypocenter (Previous/next earthquake? Probably not)
- Centroid at ~ 30-km-depth
- Along strike variability in behavior
- Aftershocks surround the aseismic patch
- Correlation with long-lived geologic Structure

Pritchard & Simons, 2006
The Seismic Cycle

- Where is elastic stress accumulating to be released in future earthquakes?
- What are the mechanics of the fault and surrounding regions?
- What is the connection to permanent inelastic deformation (e.g., topography)?
Issues in Seismic-cycle modeling

Example:

Interseismic Subduction Zones

Invert GPS velocities for the “coupling coefficient”

- $v_{bs} = v_T$: coupled (C=1)
- $v_{bs} = 0$: uncoupled (C=0)

It is time to go beyond purely kinematic models!

Suwa et al., 2006
Stress Shadowing

Not slipping \(\neq\) Coupled

- 2D FEM models
- 2D pinning (a line asperity, not a point) - Caution with stresses
- Zero shear tractions updip of the pin(s)
- Driven motion on the downdip portion of the plate
- A single pin has a dramatic influence

Charles Williams, 2005
Observational Challenges

- Where are the observations usually made? On land, usually X>100km
- Updip resolution very challenging
- We really need both horizontals and verticals, and test rheological hypothesis

Charles Williams, 2005
Apparent variation of coupling through an interseismic period

- Quasi-static 2D or 3D fault slip model (no earthquake rupture dynamics)
- Green Functions: BEM or FEM
- Fault rheology: Linear viscous, non-linear viscous, or R&S frictional

Eric Hetland
Near-trench GPS data provide strong constraints on updip behavior
Slip highly heterogeneous in space (rheologic complexity)
Coseismic and postseismic show little overlap
Log(t) afterslip consistent with velocity strengthening frictional slip on fault
Linear relationship EQ vs Slip implies same functional form
Afterslip appears to control aftershock production
Off fault rheological complexity
2003 Mw 6.6 Bam, Iran
The role of damage (e.g., Jim’s talk)

Fialko et al., 2005
Need high spatial resolution at shallow depths

Deeper depths not clear

How much of the residual is elastic vs inelastic?

Presumably we need highly variable mesh sizes to efficiently capture variations in stress both on and off the fault

1997 Mw 7.6 Manyi, Tibet Earthquake

Residual

Funning et al., 2007
The role of history

- Systems with memory need internally consistent pre-stress (frequently ignored - bad)
- Hard to do for geometrically realistic models
The importance of bridging time scales

From earthquakes (seconds to $10^2$ of yrs) to geology ($10^5$ to $10^6$ yrs)
From interseismic to geologic time scales

Invert for:
• Location of western dislocation ($X_3$, $Z_3$)
• Dip of $S_3$
• Slip on $S_1$, $S_2$, and $S_3$

Hsu et al., 2003
Interseismic  

Hsu et al., 2003
Hsu et al., 2003

Long term

Distance from S01R (km)
TPGA = Trench Parallel Gravity Anomaly

Remove average profile of gravity perpendicular to the subduction zone.

TPGA & Earthquakes
What is the characteristic TPGA for areas with large earthquakes?

Global approach
Trench Parallel Gravity Anomaly (TPGA)

Gravity & Topography

Song & Simons, 2003
Example: TPGA in Nankai, Japan

1946 Mw 8.4 Nankai, Japan

Kodaira et al., 2002
Earthquake “sees” long term structure during fault rupture

Chicken or Egg?

2001 Mw 8.4 Earthquake

Circle area = potency

TPGA where slip is occurring at a given time
2003 Mw 8.3 Tokachi-Oki, Japan

- Negligible slip at hypocenter
- Frictional properties vary rapidly along strike
- Qualitative fit with region of low TPGA

1952, 1968, 2003 coseismic
Yamanaka & Kikuchi, 2004
2003 postseismic,
Miyazaki et al, 2004
See also Baba et al., 2005
Characteristic TPGA During the Evolution of Rupture

2003 Mw 8.3 Tokachi-Oki
WTPGA = -133 mGal

Nucleates at relatively higher TPGA, most potency (moment) at lower TPGA
Challenges

1. Geometric complexity
   • Meshes, BCs,…

2. Rheologic complexity
   • Non-linear viscous
   • Fault zone friction
   • Damage
     • 1 & 2 -> work flow issues

3. Transitioning from kinematic to dynamic realism

4. Mix of time and length scales (seconds - 10^6 years)
   • Efficient (f(t)?) meshes
   • Time stepping
   • Mix of solvers

5. Parameter Estimation
The Workflow Challenge

Brad Aagaard