Deformation Measurements for Seismic Hazard Assessment

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Global Positioning System

- Portable Surveying Equipment
- Precision of a few millimeters in 3D
- Repeated surveys measure motion of sites
Measuring the Crust

• GPS surveys repeated over time
• Series of positions records the motion of a point fixed to the crust
  – Plate motion
  – Deformation
  – Measurement noise
• Three Dimensions!
Rates of Motion to Hazard

• Seismic hazard and risk roughly proportional to rates of motion

• All other things being equal, the frequency of earthquakes of a given size on a fault is proportional to the slip rate of the fault
  – Faster slip rate means shorter recurrence time

• Deformation data also help constrain size of seismogenic region on fault → maximum earthquake size
Outline

• Example of measuring motion before, during and after a major earthquake
  – 2002 Denali fault earthquake
• What this illustrates about general properties of faults
• Some examples from other parts of Alaska
Deformation Across Denali Fault

- 8 mm/yr total
- Possibly ~2-3 mm/yr on northern fault
- ~5-6 mm/yr on McKinley strand
Earthquake and Effects
Mainshock and Aftershocks
Coseismic Displacements - Horizontal

Two scales (3:1)
Western Part of Rupture
Coseismic Slip Model

(a) Total Slip

(b) Strike-slip component

(c) Dip-slip component

TAP

Denali - Totschunda fault junction
What is Postseismic Deformation?

- Transient deformation triggered by an earthquake
  - Afterslip on the fault zone
  - Viscoelastic relaxation of the mantle or lower crust
  - Poroelastic deformation associated with earthquake-driven fluid flow (changes elastic constants)
A Sample Postseismic Time Series

- Time series are shown with pre-earthquake trend subtracted (less than ~6 mm/yr relative to North America)
- Post-earthquake rates still >20 mm/yr
- Total 4-year displacement
  - 15 cm east
  - 20 cm north
  - 12 cm vertical
Postseismic Displacements
Postseismic Displacements
Faults
A View of a Fault

Can divide fault zone based on how fault slips
  – Seismogenic Crust exhibits stick slip
  – Transitional Zone may exhibit complex behavior
  – Aseismic Crust exhibits stable sliding

• Crustal earthquakes involve slip of seismogenic crust and possibly transitional zone
A Simple Analogue: Spring Slider

- Block is held in place by force of friction

FORCES
- Friction
- Elastic restoring force
A Simple Analogue: Spring Slider

- Block is held in place by force of friction
- Moving load point increases elastic force
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- Slips when elastic force exceeds friction
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Frictional Instability

- **Velocity-weakening (dynamic < static friction)**
  - $F_e > F_f$; block accelerates
  - Velocity increases, $F_f$ decreases; block accelerates more
  - $F_e$ decreases with slip, in few seconds $F_e < F_f$; block decelerates
  - Velocity decreases, $F_f$ goes up; block decelerates and stops
Alternative: Stable Sliding

• Velocity-strengthening (dynamic > static friction)
  – $F_e > F_f$; block accelerates
  – Velocity increases, $F_f$ increases; acceleration stops
  – But velocity then remains the same
  – Velocity reaches equilibrium with shear stress
A Simple “Earthquake Cycle” Model

• Based on the spring-slider analogue model
• Between earthquakes:
  – Shallow fault is locked
  – Deeper fault is creeping at long-term slip rate
  – Stress builds up: elastic strain energy stored in crust
• During earthquake, shallow fault slips
  – Stress on fault reduced
• Cycle repeats forever
Shallow Locked Fault Causes Deformation Away from the Fault

• Earth deforms as elastic body over short timescales
• Locked shallow fault + slipping deep fault produces elastic strain in vicinity of fault
  – Most important close to fault
  – Far from fault, motion is same as rigid blocks
• Simple numerical models allow us to compute effects of fault slip
• When there are multiple faults, it can be difficult to separate the effects of each one.
Broad-Scale Deformation of Overriding Plate
Southeast Alaska Block Model
Summary

- We can measure rates of motion of Earth’s crust using repeated GPS measurements, and relate these to slip on faults, or models for the motion of crustal blocks.
- Rates of slip on faults are directly related to seismic hazard
- GPS velocities also provide information about the width and extent of the seismogenic region of faults
- The information provided by geodesy is a bit different from the data usually used for hazard estimation
  - Methodology to fully incorporate this information into formal seismic hazard estimates is still being developed
Tectonic and Earthquake Effects in Southern Alaska