Basics of the modelling of the ground deformations produced by an earthquake

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Content

- Earthquakes and faults
- Examples of SAR interferograms of earthquakes
- The earthquake cycle
- Elastic model
- Data needed to constrain the model and the complementarity of seismological, geodetic and geological data
- Example of models
Most earthquakes are located at plates boundaries

Earthquakes M>6 (NEIC) - GPS velocities ITRF2005

Somalia/Nubia Euler poles: ★ Geologic
☆ Geodetic
Earthquakes occur on faults (and faults grow with repeated earthquakes)

The Atalanti fault, Greece
Earthquakes produce ground deformations

Surface rupture produced by the 2010 Edgecumbe earthquake (New Zealand)
Cumulated earthquakes produce topography

The San Andreas fault: cumulated deformation along the fault

Uplifted marine terraces near Wellington (NZ)
Gutenberg – Richter law

Earthquakes per year in a given area = f(Magnitude)
The first interferogram produced by ERS1

Landers earthquake (1992)
1 colour cycle = 28 mm in the satellite line of sight
Radar satellite imagery
Radar images correlation

**Principle:** accurately co-register the amplitude images & compare phase images

Two acquisitions from almost identical orbits at two different epochs
The slip on the fault induces a difference in the phase registered by the satellite.
Izmit, 1999
Boumerdes, $M_w=6.8$, 21/05/2003

Meghraoui et al., 2007
Christchurch, 22/2/2011
Envisat interferograms of the Christchurch (22/2/2011) and Tohoku (11/3/2011) earthquakes
The deformation cycle across a fault
Inter-seismic deformation near an active fault

Between major earthquakes:
• the active faults are « locked »
• the surrounding region deforms in a continuous manner, measurable until a distance of ~50km
• velocity gradient looks like a sigmoid
The co-seismic deformation can be observed:
- by GPS
- by SAR interferometry

Observed displacements:
- up to 5.7 m near the fault
- decreasing to the N and S away from the fault

Reilinger et al., 2001
Strike-slip earthquakes in continental crust occur in the ~15 shallowest kilometres of the crust (the brittle/elastic part of the crust)

Laboratory rock mechanics indicate that the rocks behave:
- elastically above ~15 km, with friction law governing the triggering of slip above a threshold
- in a ductile and mostly aseismic manner below 15 km
Inter-seismic deformation

- Locked fault at shallow depth
- Aseismic creep in the lower crust
- For a infinite fault length:

\[
V_{GPS} = \frac{v}{\pi} \times \tan\left(\frac{d}{p}\right)
\]

\(v\) = relative plates velocity (in the far field)
\(d\) = perpendicular distance to the fault
\(p\) = ‘locking’ depth of the fault

At the surface the deformation cumulates in a broad area, and the deficit near the fault plane will be recovered during the earthquake.
Coseismic deformation

- **$M_w=7.5$ August 17, 1999, Izmit earthquake: strike-slip on the north Anatolian fault**
- Conceptual model:
  - The accumulated elastic strain is released during the rupture
  - The rupture concerns a fraction only of the entire fault (short => low magnitude, long => high magnitude)
Variability of the earthquakes
Dislocation model: rectangular fault within an elastic half-space

Nine parameters:
- 3 coordinates of the centre of the upper edge of the fault
- 2 angles (azimuth, dip)
- length and width
- dip-slip and strike-slip (or slip and rake)

- Okada(1985) BSSA, 75, 1135
- Okada(1992) BSSA, 82, 1018
Data constraining the nine parameters

• Seismological data
  – Seismic moment
  – Source duration \{ (Scale laws)
  – Focal mechanism

• Geodetic data
  – Co-seismic deformations

• Geological data
  – Morphology (cumulated)
  – Direct observation of the fault (and the rupture)
1. Constraints from seismology

- Seismology constrains relatively well the azimuth and dip angles of the fault (most of the time better than geodesy and geology)
- Seismology constrains well the energy released and therefore the product of the fault surface and slip
Seismic moment and the relation between the energy released and the fault and medium parameters

\[ M_o = \mu D S \]

\( \mu \) Medium rigidity
Source duration

Example of the M=7.4 Guatemala earthquake of November 7, 2012
## Scale laws

<table>
<thead>
<tr>
<th>Magnitude ($M_w$)</th>
<th>Moment (Nm)</th>
<th>Length (km)</th>
<th>Duration (s)</th>
<th>Slip (m)</th>
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<td>$10^{24}$</td>
<td>1000?</td>
<td>300?</td>
<td>100?</td>
</tr>
<tr>
<td>9</td>
<td>$3.10^{22}$</td>
<td>300</td>
<td>100</td>
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<td>6</td>
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</tbody>
</table>

Magnitude / Moment relation

$$\log_{10} M_0(Nm) = 1.5M_w + 9.3$$
Focal mechanism (video from IRIS)

Earthquake Focal Mechanisms

These describe the direction of slip in an earthquake & the orientation of the fault on which it occurs.

It's not just a beach ball
2. Constraints from geodesy

• Geodesy gives good constraints of the fault location
• It gives also good constraints on the fault length and width
• It gives good constraints on the slip on fault
• It constrains poorly the fault dip angle
Simulation of a M=6.2 normal faulting earthquake

- Vertical displacements larger than horizontal in the near field, and maximum subsidence ~four times maximum horizontal motion

- Horizontal displacements dominate in the far field (still significant at distances larger than 50km)
3. Constraints from geology

- Geology constrains relatively well the location of the fault
- Often it gives also good constraints on the fault azimuth (and sometimes its dip angle)
Interferogram and model of the Grevena earthquake (Meyer et al., 1996)
Model of the Athens, 1999 earthquake
Model of the Izmit, 1999 earthquake

Interferogram

Synthetic interferogram (assuming a dislocation in an elastic half-space)

Residual interferogram
Model of the Bam, 2003, earthquake