Can geodetic strain rate be useful in seismic hazard studies?

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**Basic points**

- Geodetic Strain-Rate measures how fast the lithosphere is deformed due to tectonic plate motion.

- In some places, the crust is brittle enough to produce earthquakes by faulting.

- When earthquakes occur they release the accumulated crustal strain.

**Strain-Rate**

Can be considered as a proxy for **earthquake potential**.
**Current view**

Measured geodetic strain rate is compared to the earthquake activity rate to assess unbalances and provide insights for future seismic activity:

- conceived for long-term assessment of earthquake occurrence

so that

- comparison on limited areas **cannot account** all the strain rate loaded by plate motion
- comparison on a limited time span implicitly assumes a **linear time evolution** of loading rate

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http://www.globalquakemodel.org/what/seismic-hazard/strain-rate-model/
Our view

strain rate must be considered space and time dependent

• strain is built up by plate interactions and is released on faults during the seismic cycle
• in the pre-seismic phase, faults are mostly locked
• strain is maximum when the fault is “ripe”, whereas strain-rate is minimum

Devoti et al., 2011
Our model

Idealized seismic cycle ⇔ history of strain rate near faults

- the tectonic load acts at large scale far from faults
- the strain-rate near active faults is non-linear in time
- the fault is “ripe” when the strain-rate is at minimum
- the slow accumulation of elastic strain ⇔ frictional locking of the fault between eqs

Thatcher, 1993
Geodetic deformation rate is compared to the earthquake activity rate to assess imbalances and provide insights for future seismic activity.

Seismic / geodetic imbalance may be caused by localized non linear strain accumulation.

GEM
http://www.globalquakemodel.org/what/seismic-hazard/strain-rate-model/
**Our Background: GPS observations**

**Time series of GPS coordinates sample the seismic cycle at each station**

**Interseismic:** linear displacement as a function of time => constant velocity.

**Coseismic:** offset of the GPS time series, related to the magnitude and depth of the seismic rupture

**Postseismic:** strain readjustments (afterslip, viscoelastic relaxation, poroelasticity), decay related to the mechanism and the lithospheric rheology
1a- Mapping the strain rate: a snapshot of an evolving deformation field

geodetic strain rate = spatial gradient of a sparse velocity field

\[
\begin{pmatrix}
\dot{\varepsilon}_{11} & \dot{\varepsilon}_{12} \\
\dot{\varepsilon}_{21} & \dot{\varepsilon}_{22}
\end{pmatrix} = \begin{pmatrix}
\frac{\partial v_x}{\partial x} & \frac{1}{2} \left( \frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right) \\
\frac{1}{2} \left( \frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right) & \frac{\partial v_y}{\partial y}
\end{pmatrix}
\]

2D strain rate tensor

Devoti et al., 2011
1b- Mapping the strain rate: a snapshot of an evolving deformation field

SR = total strain-rate
sum of all the 2D tensor components

• velocity interpolation on a regular grid
• smoothing with distance

\[ SR = \sqrt{\varepsilon_{11}^2 + \varepsilon_{22}^2 + 2\varepsilon_{12}^2} \]
1c- Mapping the strain rate: snapshots of pre-seismic locked fault

![Graphs showing shortening and extension rates for Emilia and L’Aquila](image-url)
2a- Magnitude and strain rate

The size of seismic events appears inversely related to strain-rates.

Eqs M\geq 2.2 from 2007 to 2011
Interpolation of the strain rate field at the epicenter coordinates

Riguzzi et al., 2012
2b- Magnitude and strain rate

Which is the occurrence probability of an earthquake of $M$ in a given class of $SR$?

analytical description based on a Bayesian approach

\[
f(M|S) = \frac{f(S|M) f(M)}{f(S)}
\]

probability density of $M$ occurrence from GR law

probability density of $S$ for each $M$ class

normalization constant

\[
f(S) = \int f(S|M) f(M) dM
\]

Riguzzi et al., 2012
2c- Magnitude and strain rate

The probability density of $M$-occurrence in a given class of $S$ is represented by a family of exponential-decay curves, calibrated by $\mu$ (normalized average $M$)

$$f(M|S) = \frac{1}{\mu(M|S)} \cdot e^{-\frac{M}{\mu(M|S)}}$$

Inversely to the interpretation of b-value, according to which a

- high b-value $\iff$ larger proportion of small events

- high $\mu$-value $\iff$ higher probability of large events
2d- Magnitude and strain rate

Example: the probability to have an earthquake with $M \geq 4.0$, the integral of $f(M|S)$ for $M \geq 4.0$) for each $S$ class:

- $0 - 20 \text{ nstrain} (\mu = 0.14)$ is 9.1%
- $20 - 40 \text{ nstrain} (\mu = 0.15)$ is 10.3%
- $40 - 60 \text{ nstrain} (\mu = 0.13)$ is 7.6%
- $60 - 85 \text{ nstrain} (\mu = 0.06)$ is 0.5%

Riguzzi et al., 2012
3a- recurrence time ≥ relaxation time (?)

\[ \tau = \frac{2\eta}{\mu} \]

**Model**
- non-linear time evolution of strain rate due to visco-elastic properties of Earth
- classical process of time exponential decrease

**Assumptions**
- the interseismic SR on different seismogenic sources of the same type behave as a stationary process: their time decaying rate are similar, dependent only on the time elapsed since the last strong earthquake
- the time decaying model parameters can be estimated just sampling the process on different seismogenic sources for which different intervals since the last strong earthquake elapsed
3b- timing the snapshots

- SR map of the Italian area (contour lines every $20 \cdot 10^{-9}$ yr$^{-1}$) from the 2D velocity field

- individual seismogenetic sources reported in the DISS database (black boxes)

- the red (reverse faults) and blue (normal faults) boxes are the last significant seismic events reported in CPT04
3c- timing the snapshots: fault relaxation time

Strain-Rate sampled at the epicentres of the selected events
vs.
elapsed time since the last event

Exponential decay models SR(t) = a \cdot e^{-b \cdot t} \quad \text{with} \quad \tau = b^{-1},
The characteristic times are \( \tau_n = 317 \pm 204 \text{ yr} \) and \( \tau_t = 991 \pm 690 \text{ yr}, \)
for normal faults and thrusts.
Therefore

\[ \tau_t \sim 3 \cdot \tau_n \]

Riguzzi et al., 2013
Conclusions

MAPPING

Strain-Rate maps are *snapshots* of evolving deformations $\rightarrow$ *short term* occurrence studies

Strain-Rate *lows* within deforming areas $\rightarrow$ detection of *locked faults*

TIMING

Strain-Rate time relaxation at faults follows an exponential decay law

Relaxation and recurrence times of *thrusts* 3 times longer than *normal faults*

SIZING

Higher Strain-Rate corresponds to a lower probability of large size events