Data analysis of recordings of slow earthquakes: Tectonic tremor, low-frequency earthquakes and slow slip events

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Slow earthquakes

Slow slip

Slow slip

Tectonic tremor

- Long (several seconds to many minutes)
- Low amplitude
- Emergent onsets
- Absence of clear impulsive phases

Tectonic tremor

Low-frequency earthquakes (LFEs)

- Small magnitude earthquakes (M $\sim$ 1)
- Frequency content (1-10 Hz) lower than for ordinary earthquakes (up to 20 Hz)
- Source located on the plate boundary,
- Focal mechanism: Shear slip on a low-angle thrust fault dipping in the same direction as the plate interface

Low-frequency earthquakes (LFEs)

Episodic Tremor and Slip (ETS)

- Tectonic tremor observations spatially and temporally correlated with slow slip observations (Nankai, Cascadia)
- Only biggest tremor episode associated with slow slip
- No spatial or temporal correlation in other regions like New Zealand

Depth of the source of the tectonic tremor in the eastern Olympic Peninsula

- Lack of impulsive phases → Difficult to determine the depth of the source of the tremor
- Tectonic tremor is at least partly made of a swarm of LFEs
- LFEs are located on the plate boundary

→ Research question: Is the source of the tectonic tremor located on the plate boundary? What is the depth extent of the location of the source of the tremor?

A low-frequency earthquake catalog for Northern California

- LFEs grouped into families of events
- All the earthquakes of a given family originate from the same small patch on the plate interface
- LFEs recur more or less episodically in a bursty manner
- Wide range of recurrence behavior between seismic regions, and within the same seismic region

LFEs in Washington State

LFEs on the San Andreas Fault

A low-frequency earthquakes catalog for southern Cascadia

- LFE families in southern Cascadia:
  - 34 LFE families on the subduction zone
  - 3 LFE families on two strike-slip faults from the San Andreas Fault system
- Wide range of recurrence behavior between Washington State and the San Andreas Fault, and within the San Andreas Fault zone

→ Do low-frequency earthquakes families behave similarly or differently in southern Cascadia, compared to Washington State and the San Andreas Fault?

Detection of slow slip events in New Zealand

- Small (M $\sim$ 5) or long (several months) slow slip events are harder to detect
- In Cascadia, Mexico, tremor used as a proxy to study slow slip events
- Different pattern in northern new Zealand:
    - Tremor source located downdip of the slow slip on the plate boundary
    - Tremor activity does not seem to increase during slow slip events

$\rightarrow$ Can we detect smaller and / or longer slow slip events in the absence of spatially and temporally correlated tectonic tremor?

Array of Arrays

Current catalog

Current catalog

- Subduction zone families
  - 34 families
  - Period covered: April 2008
  - One burst of LFEs lasting a fay days and propagating from south to north
- Strike-slip fault families
  - 3 families
  - Period covered: march and April 2008
  - Active all the time, several bursts of LFEs

Creating templates

Creating templates

Finding new LFEs

Finding new LFEs

Comparison with existing catalog

Extension of the catalog

Extension of the catalog

Detection of LFEs with permanent networks

Comparison FAME - permanent networks

Comparison FAME - permanent networks

Future work

- Two-year-long catalog for all LFE families
- Computation of new templates for the permanent networks
- Whenever possible, extension of the LFE catalog to 2009-2019

Effect of nearby earthquakes

Effect of nearby earthquakes

Effect of nearby earthquakes

Future work:

- Event rate before the earthquake
- Event rate after the earthquake
- Comparison between two event rates: Computation of likelihood ratio

Homogeneous Poisson process

Number of events recorded during one day $\rightarrow$ Variance over X values = Y

Homogeneous Poisson process

Number of events recorded during 3 day $\rightarrow$ Variance over X values $=$ Y

Homogeneous Poisson process

Number of events recorded during 9 day $\rightarrow$ Variance over X values $=$ Y

Homogeneous Poisson process

Number of events recorded during 27 day $\rightarrow$ Variance over X values = Y

Homogeneous Poisson process

Number of events recorded during 81 day $\rightarrow$ Variance over X values = Y

Homogeneous Poisson process

Number of events recorded during 243 day $\rightarrow$ Variance over X values $=$ Y

Variance vsLlength of time window

V = Variance m = Sample size V behaves as $m^{2d-1} \rightarrow d = 0$

ETAS model

Epidemic-Type Aftershock Sequence (ETAS) model:

- Magnitude frequency distribution law of Gutemberg and Richter
- Omori-Utsu law of aftershock decay
- Each event, irrespective of whether it is a small or a big event, can trigger its own offspring

$$\lambda = \mu + A \sum_{t_i < t} e^{\alpha(M_i - M_0)} \left(1 + \frac{t - t_i}{c}\right)^{-p} \tag{1}$$

ETAS model

Number of events recorded during 1 day $\rightarrow$ Variance over X values $=$ Y

ETAS model

Number of events recorded during 3 day $\rightarrow$ Variance over X values $=$ Y

ETAS model

Number of events recorded during 9 day $\rightarrow$ Variance over X values $= \mathrm{Y}$

ETAS model

Number of events recorded during 27 day $\rightarrow$ Variance over X values = Y

ETAS model

Number of events recorded during 81 day $\rightarrow$ Variance over X values $=$ Y

ETAS model

Number of events recorded during 243 day $\rightarrow$ Variance over X values = Y

Variance vs Length of time window

V = Variance m = Sample size V behaves as $m^{2d-1} \rightarrow d = 0.23$

Long-range dependence

- Relates to the slow rate of decay of the statistical dependence between two points with increasing time interval between the points
- The fractional index d represents how fast the variance in the number of LFEs in a time window of a given length increases with the length of the time window considered
- $0 < d < 0.5$ is characteristic of long-range dependence

Northern Cascadia

Guerrero, Mexico

San Andreas Fault

Future work

- Computation of fractional index d for the southern Cascadia catalog
- Fit ETAS model on existing LFE families

Tremor as proxy for slow slip

Episodic Tremor and Slip in Cascadia

- Tremor occurrence rate $\rightarrow$ Moment of slow slip events not detectable in the GPS data (Aguiar, 2009)
- Stacking of GPS data when LFEs are detected (Frank, 2016)

$\rightarrow$ What do we do when tremor is not correlated with slow slip?

Northern New Zealand

Tremor during deep slow slip events

Tremor during deep slow slip events

Tremor with no detected slow slip event

Possible questions

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- Detecting longer term slow slip events
- Better measuring of the vertical displacement at the Earths surface during slow slip events

Detecting smaller, currently undetected slow slip events

Detecting longer term slow slip events

Better measuring of the vertical displacement at the Earths surface during slow slip events

GPS stations in New Zealand

Denoising of GPS data

Denoising of GPS data

Questions?