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PhD position

Physics-informed statistical modeling of earthquakes

Context

Earthquakes correspond to the sudden reactivation of shear slip on pre-existing faults or fractures, releasing the elastic energy stored in the upper crust by tectonic plate motion. Stress is then redistributed, possibly triggering other earthquakes (King et. al, 1994). This cascade process results in swarms, or mainshock-aftershock sequences, that from time to time degenerate into catastrophic devastating events, as recently in Turkey (Melgar et al., 2023). However, it is today largely impossible to predict the evolution of such earthquake sequences.

One of the main challenges of seismic hazard assessment is to achieve a better physical understanding of what controls the nucleation and interaction of earthquakes on active faults. This can be done through two main approaches. In the first approach, earthquakes are seen as resulting from slip instabilities on active faults. In the simplest of such models, the slip behavior of the fault is modeled by a spring block system (or arrays of interacting spring blocks) loaded with a prescribed stress and charectrized by dynamic slip-dependent friction law (Burridge & Knopoff, 1967; Carlson et al., 1994; Dieterich, 1994). However, although successful in reproducing statistical properties of earthquake sequences, this approach largely simplifies mechanical interaction in an elastic medium. The second approach, on the other hand, consists in considering a fault as a frictional interface between continuous deformable solids. Initially developed for a single planar fault with homogeneous frictional properties (Rice, 1993), such models have later been extended to simulate the behavior of fault networks (Romanet, 2018; Ozawa & Ando, 2021), rough faults (Heimisson, 2020), or with heterogeneous friction (Dublanchet, 2019). The main outcome of these studies is that geometrical, or frictional heterogeneity needs to be considered to account for the observed earthquake complexity. However, the computational cost and the large number of unknown parameters generally hampers the use of such deterministic models to infer fault mechanical properties given earthquake observations.

Alternatively, stochastic models have been proposed to model earthquake sequences in space and time. In such models, the aspects of the physical phenomenon that are unknown to the observer, may that be the exact process leading to the earthquake nucleation or the noise that might affect the observations, are replaced in the model by a random process (Vere-Jones, 2010). This probabilistic framework allows in turn to quantify the uncertainty one might have on the model and its outputs. One of the most used stochastic models for earthquake sequences is the so-called space-time Epidemic Type Aftershock Sequence ('ETAS') model (Ogata, 1998). In this model, an earthquake occurrence is seen as a point in space and time, marked with the magnitude of the earthquake. The probability of occurrence of a new earthquake with a given magnitude and at a given location in space time is then modeled by a function with two components: a background intensity which models the spontaneous appearance of new points, and a trigger intensity (also called interaction kernel) which locally increases the probability of occurrence of a new point around the location of past events (thus modeling aftershock phenomena). Both these components are usually parametrized with a small number of parameters, which can be inferred from data using Bayesian methods, hence allowing to quantify the uncertainties of the estimates (Ross, 2021). The ETAS model has been successfully fitted on many earthquake datasets and is often used in risk assessment applications (Darzi, 2023; Harte, 2017; Molkenthin et al., 2022). However, it may lack the interpretability of the physical model, and explicit ways of incorporating prior knowledge on the physics of earthquake formations (Vere-Jones, 2010).

Several studies attempt to incorporate physical considerations about earthquake nucleation and stress redistribution in ETAS models (Console, 2007), improving the physical interpretability of earthquake sequences. However, interaction kernels are generally inspired from the Dieterich model (Dieterich, 1994), which simplifies earthquake interaction, and does not predict earthquake magnitude. Here we propose to take advantage of more recent earthquake cycle model developments to propose a new physics-based formulation of ETAS model.

Research goals of the thesis

Seismic activity (the occurrence and magnitude of earthquakes) is generally modeled either with stochastic or deterministic (driven by physics) approaches. Although physics-based models allow realistic earthquake nucleation and interaction, their computational cost and the number of involved and unknown parameters prevent any practical use for earthquake hazard assessment. Stochastic models usually rely on a limited number of parameters, which allows tractable parameter inference and uncertainty quantification. Although congenial, stochastic models miss relevant features of earthquake triggering, resulting in unrealistic predictions.

This project aims at bridging the gap between statistical and mechanical approaches, by proposing new point process models for earthquake modeling, driven by physics-based models explaining the nucleation and interaction of earthquakes on a planar fault (asperity model). A refined formulation of the widely used ETAS model will be developed: the parameters of this model will be directly inherited from the asperity model (friction heterogeneity, stress state, loading rate), and their inference will be tackled using efficient Bayesian algorithms. The models developed will be tested against natural earthquake sequences, observed in several active regions worldwide (California, Italy, Corinth rift…), and also on earthquake swarms induced by the exploitation of georesources.

Expected profile of the candidate

The candidate should have a background in statistics and/or applied probability, and a taste for interdisciplinary applications. They should show an interest for physical modeling and computational methods. Competences in spatial statistics and/or solid mechanics are a plus. They should have programming skills in R and/or Python.

Practical information

The thesis is funded for three years (start date 1st of October 2023), at the Geosciences and Geoengineering department of Mines Paris – PSL loacted in Fontainebleau (77), France. It will be supervised by Mike Pereira (Geostatistics Research Group) and Pierre Dublanchet (Geophysical Research Group).

How to apply

Send a CV, a letter of motivation (in English or in French), and reference letters (or people to be contacted) to Mike Pereira (mike.pereira@minesparis.psl.eu) and Pierre Dublanchet (pierre.dublanchet@minesparis.psl.eu).

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