Imperial College London

Earthquake Forecasting Using Machine Learning

PhD project 2025

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Aim: Use Machine Learning (ML) methods to build earthquake forecasting models, initially trained and validated on induced seismicity data.

Motivation:

Despite our comprehensive understanding of the main mechanisms of earthquake triggering, our current knowledge of subsurface structure and stresses has precluded forecasting magnitudes and locations of seismic activity that may follow the extraction or injection of fluids. This incomplete knowledge has led to exploring alternative approaches to standard physical and statistical modelling, such as machine learning (ML). ML methods can identify complex non-linear associations between seismicity and candidate triggering factors that may constrain subsurface properties and stress levels.

However, previous machine learning studies have often identified different key drivers of induced seismicity, even within the same study region. Although the models derived from these studies may offer equivalent predictive performance, their underlying decision-making process must be better understood to allow a proper interpretation of their performance and reliability. Previous studies mainly use standard interpretation methods, which are known to carry the risk of providing misleading explanations and an illusory sense of understanding. This motivates new directions of research into more theoretically informed models and a better understanding of the decision-making process underlying inscrutable ML models.

This project:

Our team has tackled the challenge of deciphering the opacity of machine learning (ML) models by exploring their decision-making processes. This has led to the development of an interpretable ML method recently applied to the Delaware Basin (Texas, USA) [1]. By condensing the complexity of ML models into human-understandable descriptions of how they work and make decisions, we have demonstrated the potential of this method for constructing a physics-based earthquake forecasting model. In this PhD project, you will follow this innovative and cutting-edge line of research by building on existing work in the following ways:

(1) Test the interpretable ML method on more recent earthquake data for the Delaware Basin, and if needed, further refine the models to forecast patterns of seismic activity (probabilities of occurrence of events of a given size and location) in response to fluid injection and extraction histories.

(2) Tailor and apply similar methods to understand the variability in seismic responses to subsurface operations in other parts of the central and eastern US where industrial activity has led to enhanced earthquake activity. We expect to find further variability in the key factors that make regions more or less prone to induced seismic activity.

(3) Depending on progress on these first two objectives, we would like to turn our attention to California, where there is evidence that industrial activity modifies patterns of seismicity. Our physics-based method will be particularly important in distinguishing between natural and induced seismicity. Learning more about similarities and differences between induced and tectonic processes ultimately helps to enhance the forecasting of both types of events.

Our Team:
The work would be supervised by a team with diverse backgrounds, including postdoctoral researchers Dr. Alexandra Renouard (who developed the methods for the Delaware Basin) and Lior Suchoy (with broad expertise in numerical modelling of tectonic processes and faulting) and experienced supervisors: Prof. Saskia Goes, Prof. Peter Stafford and Dr. Alex Whittaker who together have worked on seismic hazard assessment from geophysical, engineering and geological perspectives. The student would join an active research community in the Department of Earth Science and Engineering, working on natural hazards and various applications of advanced machine learning and data science techniques.

Student Profile:
We are seeking a highly motivated individual with a background in geophysics, physics, or geology with a solid quantitative foundation, experience in programming and, optimally, previous background in machine learning techniques. The successful candidate will be able to work independently and have a keen interest in doing interdisciplinary work on applying machine learning methods to earth science data with their challenges of sparsity, incompleteness and uncertainty. For more information on this project, please contact Saskia Goes (s.goes@imperial.ac.uk), Peter Stafford (p.stafford@imperial.ac.uk), Alex Whittaker (a.whittaker@imperial.ac.uk) or Alexandra Renouard (alexandra.renouard@gmail.com).

[1] Renouard, A., Stafford, P., Goes, S., Whittaker, A. (2025). Decoding Machine Learning Decisions to Illuminate the Physical Mechanisms of Induced Seismicity in the Delaware Basin, New Mexico-Texas. *Submitted to JGR: Solid Earth*.

Renouard, A., Stafford, P., Goes, S., Whittaker, A., & Hicks, S. (2024). *How to Limit the Epistemic Failure of Machine Learning Models?* (No. EGU24-16930). Copernicus Meetings

Renouard, A., Stafford, P., Hicks, S. P., Whittaker, A. C., & Goes, S. D. (2022, December). Can Probabilistic Machine Learning Extract the Physical Mechanism of Induced Earthquakes in the Delaware Basin, West Texas?. In *AGU Fall Meeting Abstracts* (Vol. 2022, pp. S33A-08).