Earthquake simulation by Fiber Bundle Model and Machine Learning techniques

Marisol Monterrubio-Velasco*, José Carlos Carrasco-Jiménez*, Armando Aguilar-Meléndez*, Octavio Castillo*, Josep De la Puente*
* Barcelona Supercomputing Center, Barcelona, Spain
E-mail: {marisol.monterrubio, jose.carrasco, armando.aguilar, octavio.castillo, josep.delapuente}@bsc.es

Key words – Seismic rupture processes, Fiber Bundle model, Machine Learning.

I. EXTENDED ABSTRACT

The rupture processes of any heterogeneous material constitute a complex physical problem. Earthquakes are the result of rupture in the Earth's crust. This process is difficult to model deterministically due to the number of parameters and physical conditions, which are largely unknown. Computational physics offers alternative ways to study the rupture process in the Earth's crust by generating synthetic seismic data using physical and statistical models. The Fiber Bundle model (FBM), describes the complex rupture processes in heterogeneous materials in a wide range of phenomena. It has shown the capacity to generate data that depicts the main statistical characteristics of real seismicity. High-performance computing (HPC) combined with Machine Learning (ML) techniques provide a good ground base to perform and improve the simulations, the data management process and data analysis. In this study we show the FBM model versions applied to simulate two stages in the seismic cycle: the rupture stage related with the so-called mainshock and the stress relaxation stage which produces the aftershocks.

A. Introduction

Although we have knowledge about the occurrence of certain major earthquakes, our observational span is still too short to be able to draw strong (predictive) conclusions about when, where and how big the next earthquake will be. Earthquakes can be studied from either a physical or a statistical point of view. The statistical approach considers earthquakes as stochastic point processes [1–3]. Seismic catalogs are the tool that allows study the statistical characteristics of earthquakes. In these catalogs is register the seismic activity occurred in a particular time. It contains at least the information of: the epicentral and hipocentral coordinates, the originate time and the magnitude.

The Fiber Bundle Model (FBM) [4], is an agent-based model that describes the interactions of individual cells, featuring particular transfer load rules and a probability distribution function describing the intrinsic cells properties. Its simplicity offers many advantages and an adaptability to describe a wide range of phenomena. The objective is to study the rupture seismic phenomena via numerical simulations using the FBM. These simulations allow the analysis of natural systems that can not be studied in a laboratory due to their large energetic scale and complexity. Through numerical simulation, we look for example the most important mechanisms related to the seismic migration after a mainshock. In this work our objective is shown the application of the FBM to simulate seismic rupture scenarios, in particular the asperity ruptures and the aftershocks.

The FBM model has been capable to generated seismic synthetic catalogs which reproduces many statistical features of real events [5-7]. At present we developed two different model versions to simulate:

1) the rupture stage (10^0 s-10^2 s) of the faults, due to the excess in the accumulated strain. This stage culminates in the so-called mainshock.

2) The stress relaxation stage (10^1-10^3 days) in the area affected by the mainshock. This stage produces the so-called aftershocks, and it culminates when the background seismic rate is achieved [8-9].

These two stages are those that have a higher risk in our society and can cause major disasters when they occur in highly populated areas.

In our work Machine Learning ML techniques are used to classify and cluster data via training of models of data series which help to find the characteristics that generate patterns, thus making predictions on data [10]. For example, the favorable mechanical properties to produce aftershocks, the geometry pattern and/or number of fractures, among others.

B. Background: FBM applied to earthquake simulation

At the present the development of the FBM versions to simulates seismic scenarios has been divided in two main modules. In chronological order they are:

1) The aftershocks simulator in which the main statistical patterns in time, magnitude and space domains have been studied via parametric and statistical analysis [6]

2) the mainshock simulator developed to study the dynamical rupture and the magnitude's behavior [7]. With this model we use few input parameters coming from observational source inversion, to model dynamic characteristics.

Both versions modelize from simple assumptions and self-evolve in complex patterns similar to the real. Our goal has been the parametric study in order to learn how model behaves and which are the most important variables.

C. Methdology

The two major challenges of this research work are: the generation of a large number of simulations required to gain statistically accurate results and the optimization of simulation parameters. In order to deal with the first major challenge, we use High Performance Computing (HPC) to produce a large number of simulations in a reduced period of time. To deal with HPC we require to adapted the algorithm to be executed in a distributed environment.

Furthermore, to solve the second major challenge, we exploit state-of-the-art ML techniques to analyze and extract patterns from data generated by the simulations to estimate optimal parameters that approximate synthetic events that are similar to real seismic events.

To analyze the synthetic seismic series generated with the FBM we applied supervised learning methods in order to:
1) determine the minimum grid size using machine learning methods such as Random Forest, Flexible Discriminant Analysis, and Support Vector Machines [10].
2) identify the most relevant input parameters of the simulation (i.e. percentage of conserve load, initial organization probability) using statistical analysis and machine learning methods.
Once optimal input parameters are estimated, we validate the model using real seismic sequences and the corresponding spatial distribution of their faults systems.

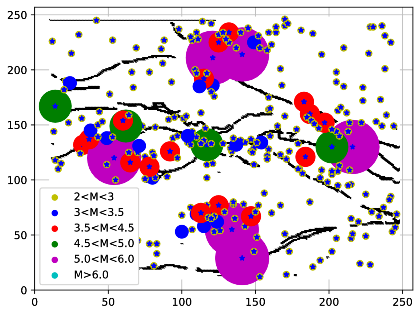

Fig. 1 Example of a simulated aftershocks sequences in space and magnitude domain

D. Conclusion

The novelty of this work lies in the study of the Earth dynamical rupture processes by using an agent-based model which describes the general rupture of heterogeneous materials. This stochastic model requires a large amount of numerical experiments to reduce uncertainties and consequently give robustness to the model. We exploit HPC to increase the number of numerical experiments. Also we introduce ML techniques to better estimates model parameters that better approximates to describes real Earthquakes statistical characteristics.

II. Acknowledgment

Authors thanks to Mexican National Council for Science and Technology (CONACYT) and Barcelona Supercomputing Center (BSC).

References

[1] B. Gutenberg and C.F. Richter, “Earthquake magnitude, intensity, energy and acceleration”. *Bull. Seis. Soc. Am.*, vol.46(2), pp. 105–145,1956.
[2] T. Utsu, Y. Ogata and R.S. Matsu’ura, “The centenary of the Omori formula for a decay law of aftershock activity”. *J. Phys. Earth*, vol. 43(1), pp. 1–33, 1995.
[3] G. King, S. Ross and J. Lin. “Static stress changes and the triggering of earthquakes”. *Bull. Seis. Soc. Am*., vol.84(3), pp. 935–953, 1994.
[4] F. Peirce, “The Weakest Link. Theorems on the Strength of Long and of Composite Specimens”. *J. Textile Inst. Trans*, vol.17(7), pp. T355.
[5] M. Monterrubio-Velasco, X. Lana and M.D. Martínez, “Aftershock sequences of three seismic crises at Southern California simulated by a Cellular automata model based on self-organized criticality”. *Geosciences Journal*, vol.19, pp. 81 – 95, 2014.
[6] M. Monterrubio-Velasco, F.R. Zúñiga, V.H. Márquez-Ramírez and A. Figueroa-Soto, “Simulation of spatial and temporal properties of aftershocks by means of the fiber bundle model”. *Journal of Seismology*, vol.21, pp. 1623 – 1639, 2017.
[7] M. Monterrubio-Velasco, Q. Rodríguiez-Pérez and F.R. Zúñiga, “Simulates Asperities by means of the Fiber Bundle model”. (In review process *Geophysical Journal International* GJI-18-0140).
[8] R. Shcherbakov, D.L. Turcotte and J.B. Rundle, “Aftershock statis-tics”. *Pure and Applied Geophysics.* vol.162(6), pp. 1051–1076, 2005
[9] A. Fereidoni and G.M. Atkinson, “Aftershock statistics for earthquakes in the St. Lawrence Valley”. *Seismological Research Letters*, vol. 85(5), pp.1125-1136, 2014.
[10] R. Kohavi and F. Provost, “Guest editors' introduction: On applied research in machine learning”. *Machine Learning*, vol.30, pp.271-274, 1998.

Marisol Monterrubio-Velasco received her PhD in computational physics by University Politécnica de Catalunya. She was post-doctoral researcher in the Geosciences center at Universidad Nacional Autónoma de México. At present she is postdoctoral researcher in the Barcelona Supercomputing Center thanks to Mexican National Council for Science and Technology. Her research interests focus on computational physics, statistical analysis and numerical simulation applied to the Earthquakes.