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Improving long-term seismic parameters estimates from earthquake catalogs

A new approach for long-term seismicity estimation

By Cyrielle Colin – Stéphanie Durand – Thomas Bodin – Marine Laporte –
Guillaume Daniel – Pierre Arroucau and David Marsan

Earthquake catalogs are an essential source of information for assessing seismic hazards. However, using catalogs that cover long periods of time is not straightforward: historical and instrumental data are of very different quality and detectability levels. In particular, smaller earthquakes are less likely to be detected in older records, and magnitude estimates can be subject to significant uncertainties.

In this work, we develop a new approach that better accounts for these limitations when estimating long-term seismicity parameters. The method jointly estimates the **b-value** and seismic rate, while describing how the earthquake detection changes over time using a **detection function**. It also explicitly **accounts for magnitude uncertainties**, which are often neglected in classical approaches.

The aim is to make better use of the information contained in the full earthquake catalog (i.e. historical and instrumental), while quantifying parameter uncertainties and trade-offs.

This approach can be applied to various contexts, ranging from national-scale for seismic hazard assessment purposes to specific contexts of **induced seismicity**. It is currently being applied to France and Finland historical and instrumental catalogs, as well as to **induced seismicity**, where the ability to detect earthquakes can vary significantly over time.

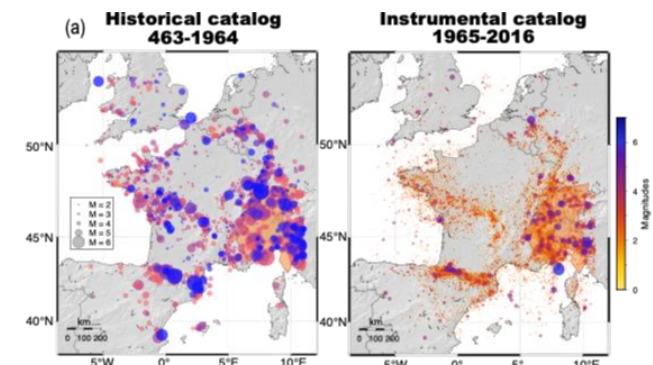


Figure 1: Historical and instrumental catalogs of metropolitan France spanning the time period from 463 to 2016. The catalog is divided in two sub-catalogs, historical (left) and instrumental (right), highlighting the variations of detection over time.

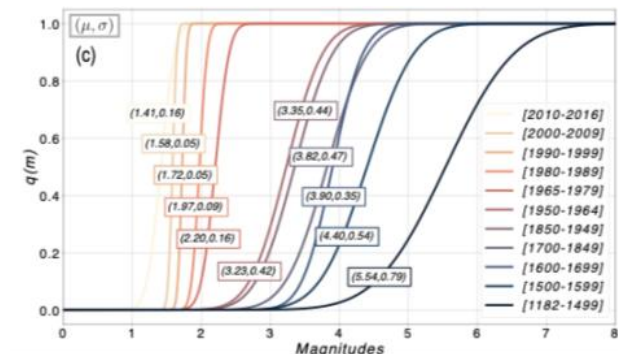


Figure 2: Variations over time of the detection functions of eleven sub-catalogs for the Alpine region (France). Mean parameters are obtained from the posterior distribution.



The Swedish Radiation Safety Authority and Uppsala University join SIGMA3

Towards a new PSHA framework for Sweden

By Carl-Henrik Pettersson (SSM), Margaux Buscetti(UU), Björn Lund (UU)

Focus on contributions to SIGMA3

The first action will use a **Generalized Inversion Technique (GIT)** to estimate **moment magnitudes and their uncertainties** for earthquakes recorded by the Swedish National Seismic Network since the year 2000, accounting for **attenuation and site effects** using the GIT results.

The second action will use the moment magnitude results to derive **new recurrence parameters** for the area sources in the hazard model, and then **update the seismic hazard estimates**. Based on the updated hazard model and the GIT-derived attenuation and site characteristics, the action will also investigate what further data and models would be needed to extend the hazard model to a **site-specific seismic hazard estimate for nuclear facilities in Sweden**.

The historic report "**Project Seismic Safety**" (SKI 1992:3), which laid the foundation for how Swedish nuclear power plants are analyzed against earthquakes, is today **over 30 years old**. The report was originally written to meet the increasing safety requirements of the time and to develop new calculation methods for Sweden's older reactors, as previous models provided an overly conservative picture. Since the publication of the report, however, methodological developments have taken place in the field, and the availability of both geological and seismological data has increased over the past decades. As the report itself states that **continuous methodological development is a necessity to maintain a complete risk profile**, demands for a comprehensive update are now growing. For this reason, the **Swedish Radiation Safety Authority (SSM)** is financing a project at Uppsala University aimed at laying the foundation for an improved PSHA methodology for nuclear facilities in Sweden.

The main focus of the project is on the source, with a **reassessment of moment magnitudes and accompanying recurrence relations** for the small to moderate earthquakes in Sweden. The results will feed into an **update of the recent probabilistic seismic hazard model for Sweden** and an assessment of what further work is needed for future site-specific hazard assessments. We have therefore proposed **two research actions within the SIGMA3 research program**.



QuakeT – A shared platform to simulate, test and compare

Where SIGMA3 research becomes an open toolbox

By Luis ALVAREZ (EDF)

WHY QUAKET?

Within Work Package 5 of the SIGMA3 project, a simulation platform named QuakeT is being developed by GEM Foundation. Its purpose is to gather, in a single and consistent environment, a set of tools for building the components of a probabilistic seismic hazard model, generating synthetic datasets, and checking the compatibility between observations and models. In other words, QuakeT aims to give the community a common ground to test modelling assumptions before they become hazard estimates.

BUILT ON THE OPENQUAKE ECOSYSTEM

QuakeT is developed in **close connection with the OpenQuake engine** and the other toolkits maintained by the GEM Foundation. This choice guarantees that the developments carried out within SIGMA3 remain interoperable and reproducible, and, as for the other GEM developments, **the platform will be released in open access** so that it can be used and further improved by the wider scientific and engineering community.

FOUR COMPLEMENTARY MODULES AND SET OF TUTORIALS FOR USE-CASES

01 Auxiliary module

Corollary functions that support the core capabilities of the platform

02 Ground motion module

Computation of ground motion intensity measures (ImS)

03 Seismic source module

Codes for evaluating source-related models

04 Site & site-effects module

modelling of site response



QuakeT – A shared platform to simulate, test and compare

A FIRST APPLICATION: ARE DECLUSTERING AND SMOOTHING CONSISTENT?

A recent study carried out with the platform illustrates the kind of question it is designed to address. Distributed seismicity is commonly modelled by **declustering** an earthquake catalogue with time-space windows, then redistributing the remaining mainshocks in space with a **smoothing kernel**. But are the spatial assumptions of these two successive steps consistent with one another? Using earthquake catalogues from **France and Peninsular Italy**, three declustering algorithms and two spatial smoothing techniques were evaluated. Synthetic earthquake catalogues spanning **10,000 years** were generated using the **OpenQuake Engine** and subsequently compared with the observed seismicity. The figure illustrates the declustering results and corresponding smoothed seismicity obtained using two of the methodologies tested in this study.

The results show that smoothing partly **re-injects the clustering that declustering had removed**: the synthetic catalogues behave as a stationary Poisson process in time, as required for PSHA, but not in space. A useful reminder that methodological choices made at one step of a hazard model propagate to the next.

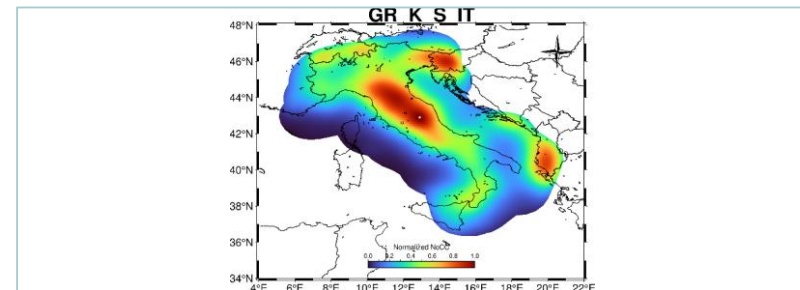
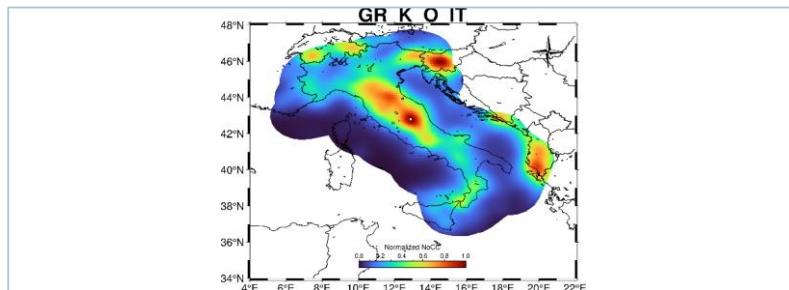


Figure 1. Sensitivity analysis conducted to characterize the seismicity of the Italian peninsula, considering different declustering and spatial smoothing methods.

WHERE WE STAND

Development is progressing steadily: **the auxiliary and seismic source modules are now complete and under final review before entering the testing phase**. The remaining modules will follow, and further announcements will be released as they reach maturity.

HOW TO JOIN

A **first online training session dedicated to these two modules will be held on December 11th**. It will guide participants through the installation of the platform and through hands-on examples drawn from the tutorials. **If you are interested in taking part, do not hesitate to contact Luis!** More information will be shared soon — stay tuned through the SIGMA3 website and LinkedIn page. luis-guillermo.alvarez-sanchez@edf.fr



COSMIC Benchmark

Work Package 4



Work Package 4 topics

01 PSHA METHODOLOGY AND TOOLS

Improved modelling and to develop **new approaches** to better treat **uncertainty propagation efficiently**

02 PSHA TESTING

Validation and updating of PSHA results through the **confrontation to observations**.

03 GROUND MOTION FOR ENGINEERING

Definition of target spectra, time-history selection & generation procedures, and impact on structural response, fragility curves and risk estimates

In nuclear engineering, the UHS (Uniform Hazard Spectrum) is generally used to define the target spectral content for ground motion selection and simulation. The Conditional Spectra (CS) approach allows for the decomposition of the UHS into a series of conditional scenario spectra. Today the CS approach is increasingly being incorporated in codes and standards and performance-based earthquake engineering procedures worldwide. Despite these developments, adoption within the nuclear sector remains limited.

Nevertheless, the potential benefits for nuclear safety assessments are significant:

- **More physical target ground motion spectra**, avoids the conservatism built into the UHS and allows the use of ground-motion records without excessive spectral matching
- **Hazard consistent ground motion input**, minimizes the sensitivity to the selection of the conditioning frequency
- **Improved margin assessment capabilities**, particularly for multimodal and nonlinear structures where conventional approaches may mask available safety margins

To address these questions, we invite scientists, researchers, and engineers interested in the probabilistic definition of seismic input motions and nuclear facility responses to participate in the COSMIC Benchmark Studies. The benchmark will compare modern ground motion simulation, generation and spectral matching procedures considering both horizontal and the vertical component, assess the number of time histories required for both hazard consistency and robust estimates of structural response and fragility.

INTERESTED IN JOINING THE COSMIC BENCHMARK?

Contact us : irmela.zentner@edf.fr | alain.alsokhon@edf.fr



SEISMaster Ground motion toolbox



SEISMaster – Ground motion toolbox

This tool provides a **practical implementation of the conditional spectra approach** for **three-component ground motion**. It can **read Openquake hazard output files** and uses **Openquake GMM modules**. The main functionalities that SEISMaster offers are :

Spectrum Generator

Computes deterministic and probabilistic target spectra (CMS, CS exact and simplified approaches) using the greedy approach

Hazard Consistency

Verification of hazard consistency with respect to the target spectra

Signal Matcher

Selection of 3 component time histories according to filtering criteria (M, D, soil type, SMD, scaling factor) using the ESM database

Site Response

Integrated tool to introduce 1D LEQ site response for ground motion on rock

Within SIGMA3, SEISMaster is being updated to improve current features and implement new ones.



Aftershocks in Probabilistic Seismic Hazard Analysis

Assessing hazard beyond the mainshock

By Zainab Asaad (IUSS Pavia) and Marco Pagani (GEM Foundation)

Seismicity is a physical process characterised by complex sequences and swarms, as observed in almost every earthquake-prone region of the world. Recent events showing this complexity include the 2016 Kaikoura earthquake in New Zealand, the 2019 Ridgecrest sequence in California, and the 2023 Kahramanmaraş earthquake sequence in Turkey-Syria.

In conventional seismic hazard analysis, earthquake occurrences are frequently modelled as a Poisson process, implying independence and stationarity in time and space. Aftershocks sequences are inconsistent with these assumptions because their occurrence in space and time depends on the mainshock's occurrence. This aspect, coupled with the common assumption that most earthquake-induced damage is produced by the mainshock, has historically motivated the practice of declustering earthquake catalogues. In fact, in conventional PSHA, aftershocks are filtered out of the earthquake catalogue used to characterise earthquake occurrence, allowing the remaining seismicity to be modelled approximately as a Poisson process.

Despite significant progress in characterising aftershock behaviour, important challenges remain in accurately modelling their occurrence and hazard potential. In particular, reliable estimates of aftershock productivity parameters, spatial distributions, and ground-motion characteristics are necessary to construct realistic aftershock source models.

Within SIGMA3, two complementary approaches have been investigated to assess aftershock hazard.

A methodology was developed to account for the contribution of aftershocks into long-term probabilistic seismic hazard analysis. It starts from a traditional mainshock seismic source model and **adds aftershock occurrence rates derived from empirical relationships** describing aftershock productivity, temporal decay, magnitude distribution, and spatial distribution. The tests so far have used **distributed seismicity sources**, but the methodology can be extended to fault sources. This approach is not rigorous but **supports relatively fast calculations**.

The **conditional aftershock hazard analysis framework** is a more rigorous approach that computes the hazard posed by an aftershock sequence following the mainshock rupture. **Introduced within the METIS** project to assess the impact of aftershocks on nuclear-facility risk, the method has been **further investigated within SIGMA3** through sensitivity analyses of modelling assumptions.



Recent publications

Seismicity, Catalogs & PSHA methods and Tools

Long-Term b Value and Seismic Rate from Earthquake Catalogs with Time-Varying Completeness and Uncertain Magnitudes

C. Colin et al.

Key take-away : Joint estimation of long-term seismicity parameters (b-value and activity rates) by explicitly accounting for time-varying catalog completeness and magnitude uncertainties

[BSSA Access DOI](#)



Evaluation of PSHA logic trees considering the Pólya distribution to model the spatial correlation between observation sites

L. Alvarez-Sanchez et al.

Key take-away : Analysis of spatial consistency between declustering algorithms and smoothing methods to consolidate probabilistic seismic hazard assessment (PSHA) models

[Springer Nature Access DOI](#)



Wave propagation and attenuation

Separation of Source, Site, and Path Effects Based on Elastic Radiative Transfer Theory. Part 1: Mapping of Scattering and Absorption Properties and Application to Metropolitan France

G. Heller et al.

Key take-away : A new methodology to isolate and independently characterize seismic source, path attenuation, and local site response effects

[BSSA Access DOI](#)



Separation of Source, Site, and Path Effects Based on Elastic Radiative Transfer Theory, Part 2: Generalized Inversion of Source and Site Parameters and Application to Metropolitan France

G. Heller et al.

Key take-away : Concrete application of this separation method to significantly reduce uncertainties in physical ground-motion modeling

[BSSA Access DOI](#)



GMM and Site Response

Ground-Motion Model for Reference Hard-Rock Conditions in the Euro Mediterranean Context by GIT-Based Site-Response Deconvolution

H. Shible et al.

Key take-away : Definition of a new reference hard-rock ground-motion model (GMM) for the Euro-Mediterranean region, derived from GIT-based site-response deconvolution

[BSSA Access DOI](#)



3D numerical simulation of ambient seismic noise for arbitrary surface source distributions: application to the study of horizontal-to-vertical spectral ratios and their variability

D. Gregor et al.

Key take-away : New advances in geophysical characterization and site-response modeling for regional ground-motion prediction

[GJI Access DOI](#)





STAY TUNED!

Newsletter #4 in 2027