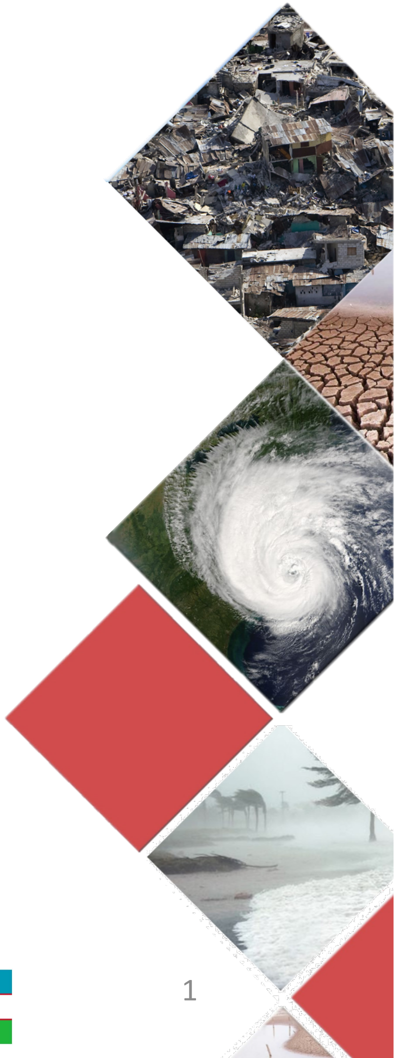
Methodologies for Earthquake Hazard Assessment

SFRARR Central Asia disaster risk assessment

18th January 2022



This project is funded by the European Union

Get to know the Lecturer

Valerio Poggi

Bsc+Msc Geology

UNIVERSITÀ DEGLI STUDI DI MILANO

PhD Geophysics

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Researcher/Lecturer

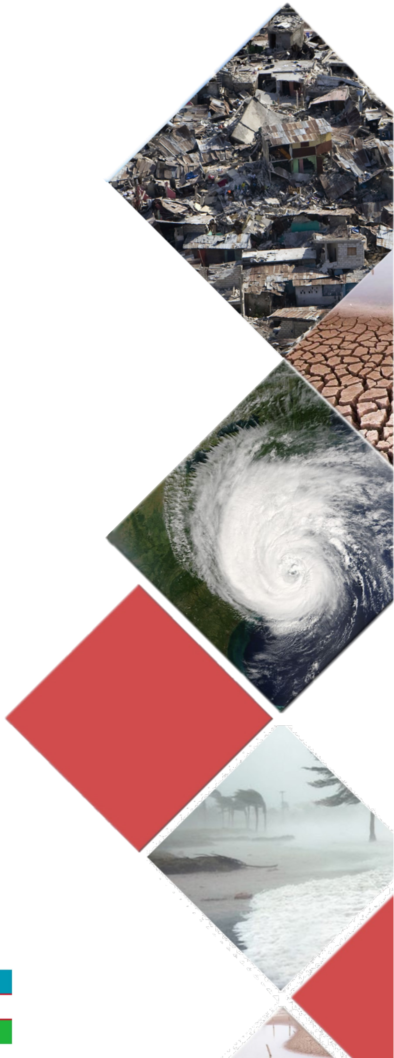
Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

Hazard Scientist

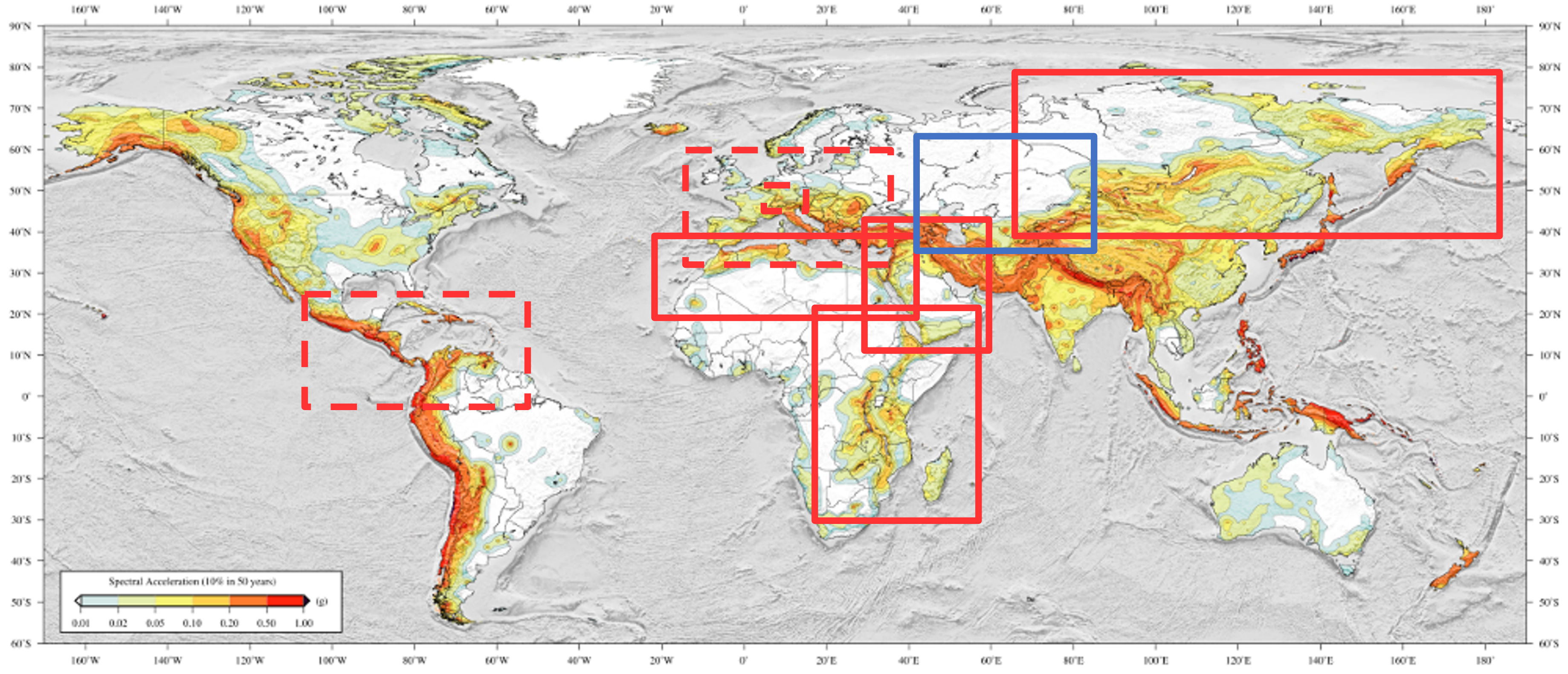
GEM
GLOBAL EARTHQUAKE MODEL
working together to assess risk

Researcher

OGS



Participation to Earthquake Hazard Projects



This project is funded by the European Union

Resources

These lectures wouldn't have been available without the contribution of many people and the numerous resources from textbooks and online material.

A special acknowledgment (and a personal thanks) goes to the following people for their supporting material:

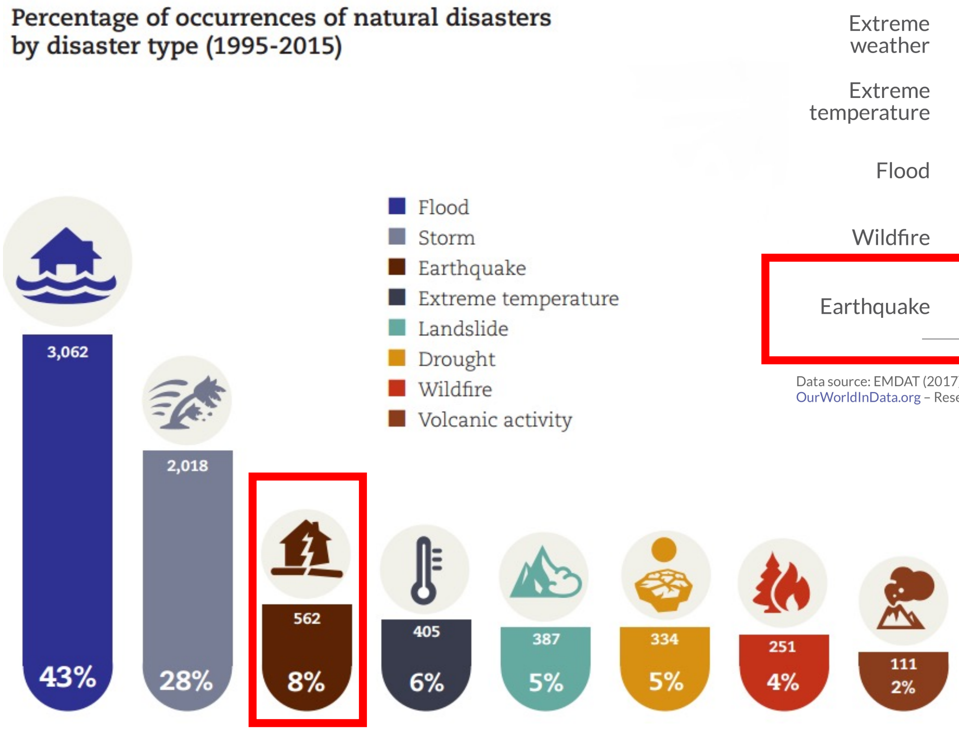
Dr. Dario Slejko – OGS, Trieste, Italy
Dr. Laurentiu Danciu – Swiss Seismological Service, ETH, Zurich, Switzerland
Dr. Marco Pagani – GEM Foundation
Dr. Donat Faeh – Swiss Seismological Service, ETH, Zurich, Switzerland
Dr. Elisa Zuccolo – EUCENTRE Pavia
Dr. John Douglas - University of Strathclyde, UK
Dr. Dave Boore - USGS

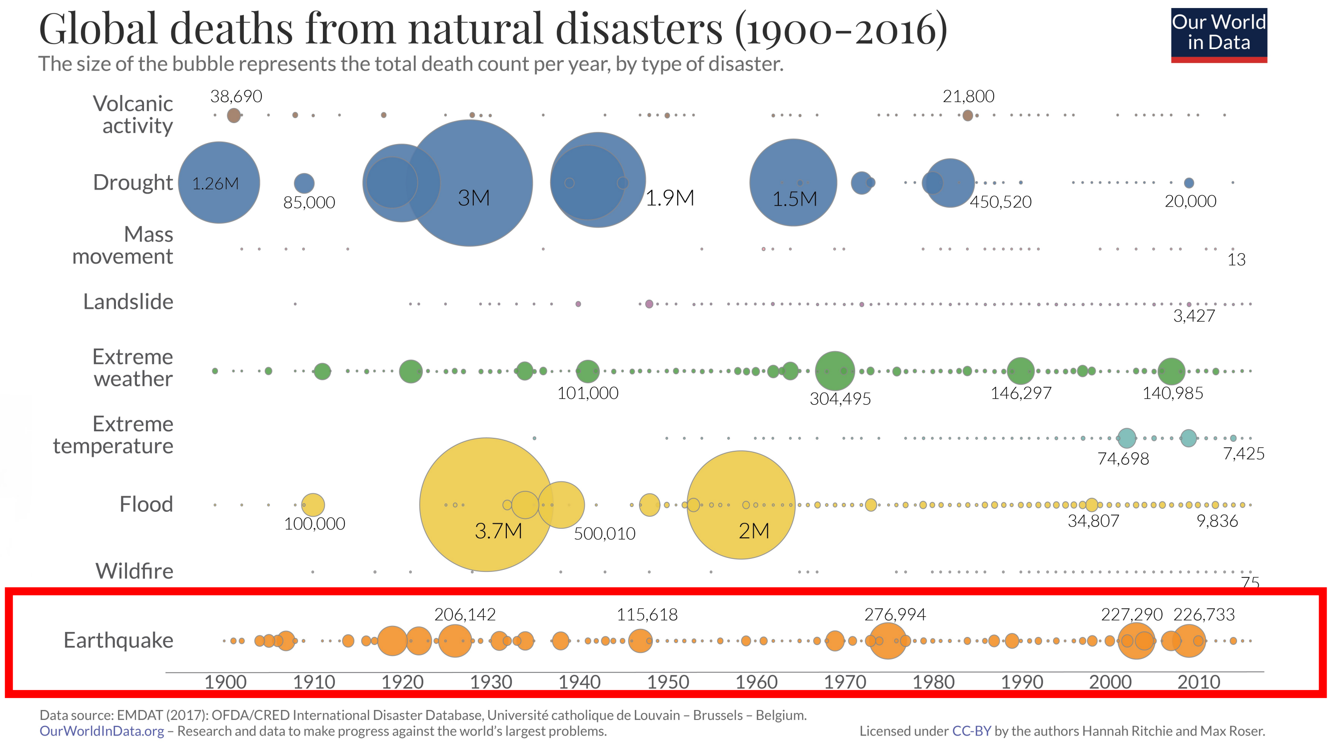
(I hope I did not forget anyone….)

This project is funded by the European Union

Earthquakes: a widespread danger

Earthquakes are one of the most frequent and costly natural hazards worldwide.





The Earthquake Impact

The earthquake main threat is related to the impossibility of structures (buildings, bridges, etc.) to withstand **extreme ground shaking**, and to a lesser extend to the occurrence of secondary phenomena (ground failure, tsunamis, etc.)

M6.5 Taiwan earthquake in 2016

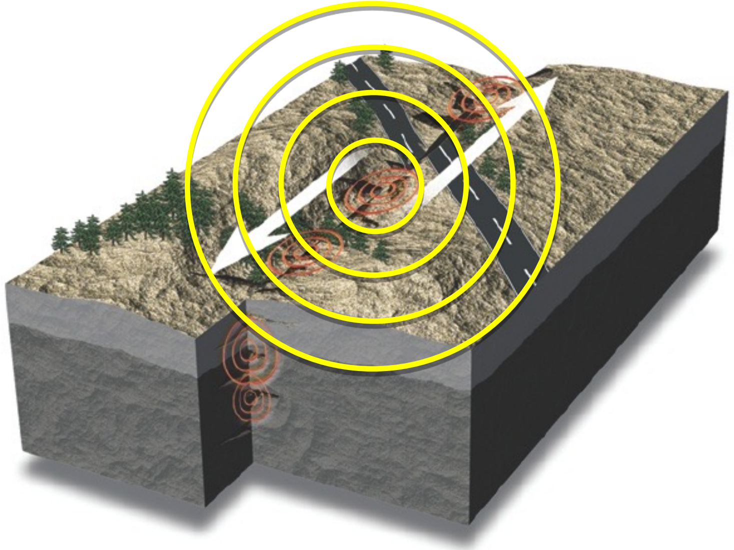
"Earthquakes don't kill people, collapsed buildings do so"

This project is funded by the European Union

Defining the Expected Shaking Level

Reduction of losses should then be properly done by preemptive design and reinforcement of new and existing building and infrastructures.

This requires, however, a proper estimation of the **ground shaking level likely expected at a site, within a given interval of time**



http://www.howitworksdaily.com/

Question is: how and how precisely this level can be defined, given the (little) knowledge we have of the earthquake process?

This is the task of Seismic Hazard Analysis (SHA)….

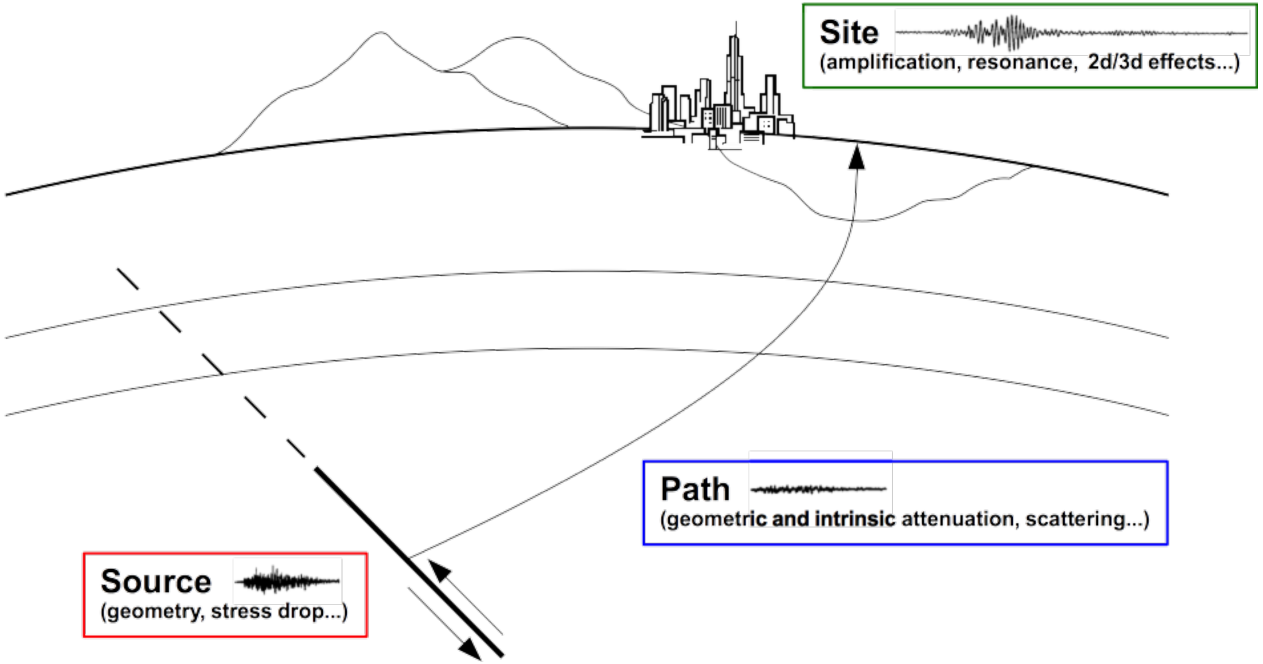
Akua Capital

This project is funded by the European Union

SHA Requirements

To assess the earthquake hazard associated to a region is essential to know:

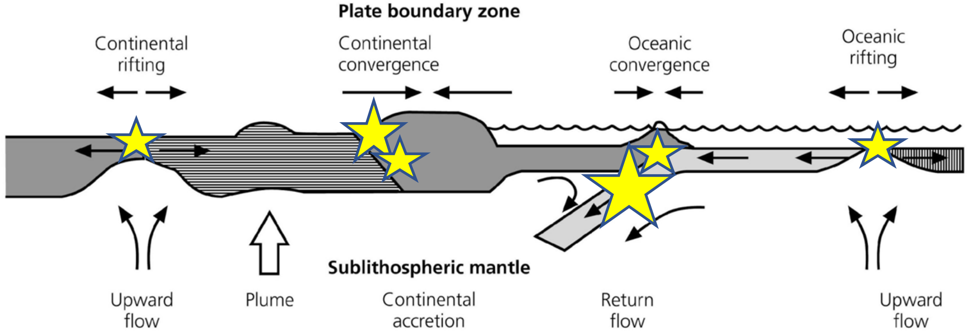
- **Where** the earthquakes occur and the geometry of the seismic sources
- **When** (How often) earthquakes of given size occur at each seismic source
- **How** earthquakes propagate within the crust due to mechanical properties of geological materials (including surface geology)

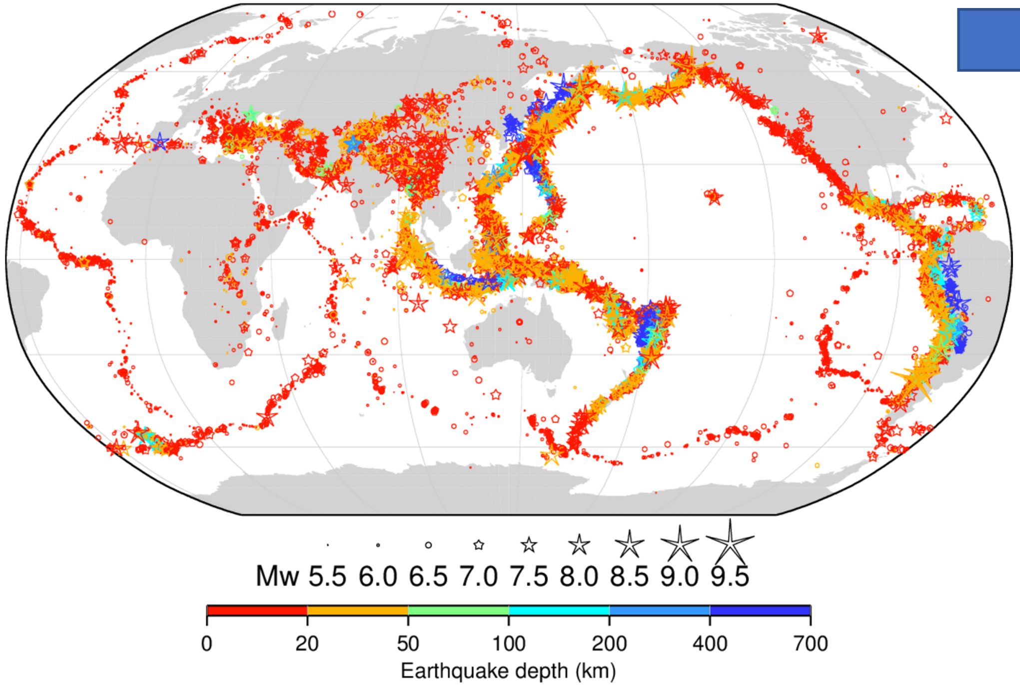


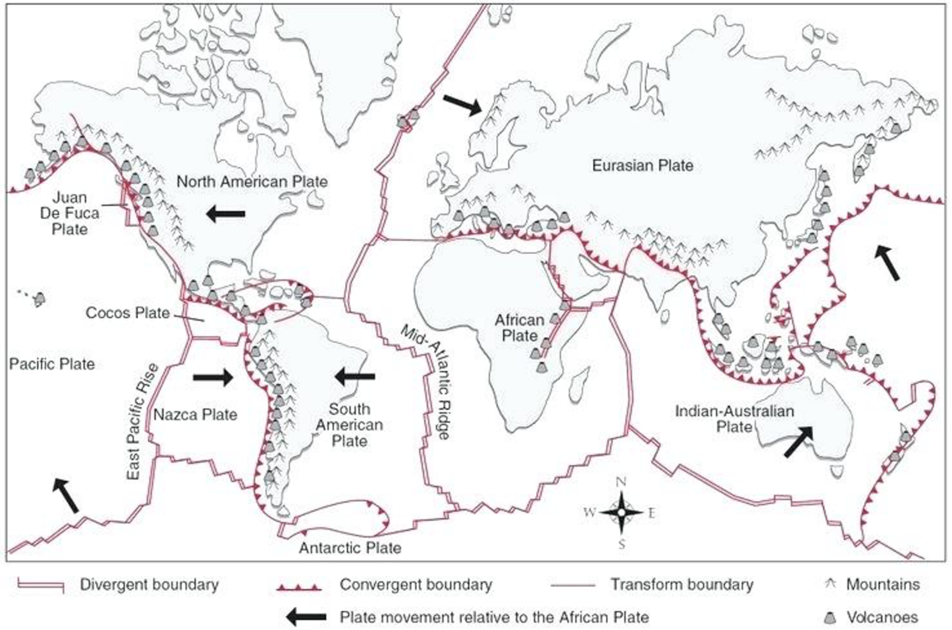
This project is funded by the European Union

Where do Earthquakes Occur?

Earthquake activity is not distributed uniformly around the world. It is mainly confined to relatively narrow bands of intense seismicity on **"active" tectonic margins**.



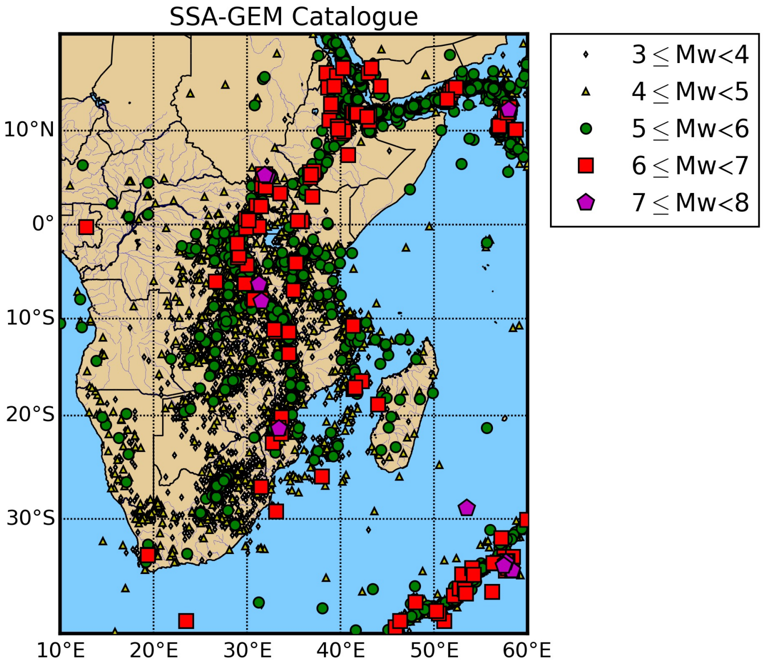


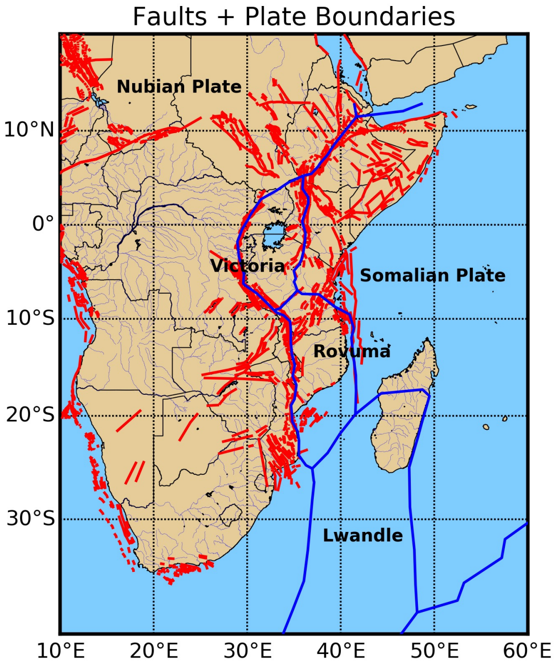


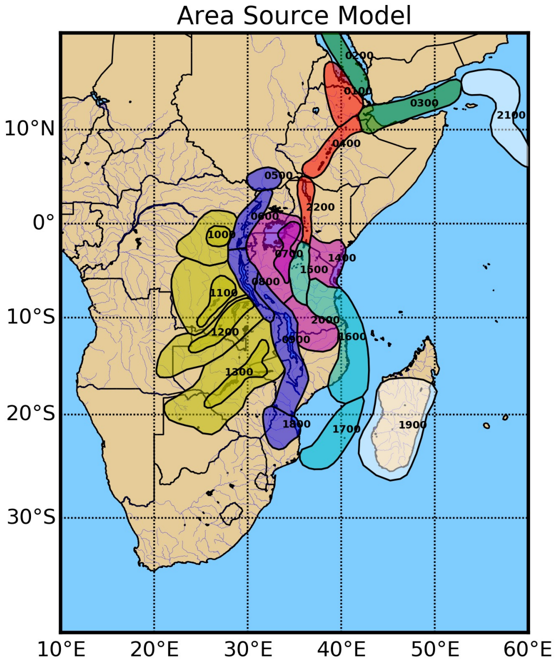
This project is funded by the European Union

Where do Earthquakes Occur?

On a smaller spatial scale, earthquake seismicity is organized often in patterns, so that areas of different "productivity" can be discriminated on the base of the historical earthquake log (**the seismic catalogue**).





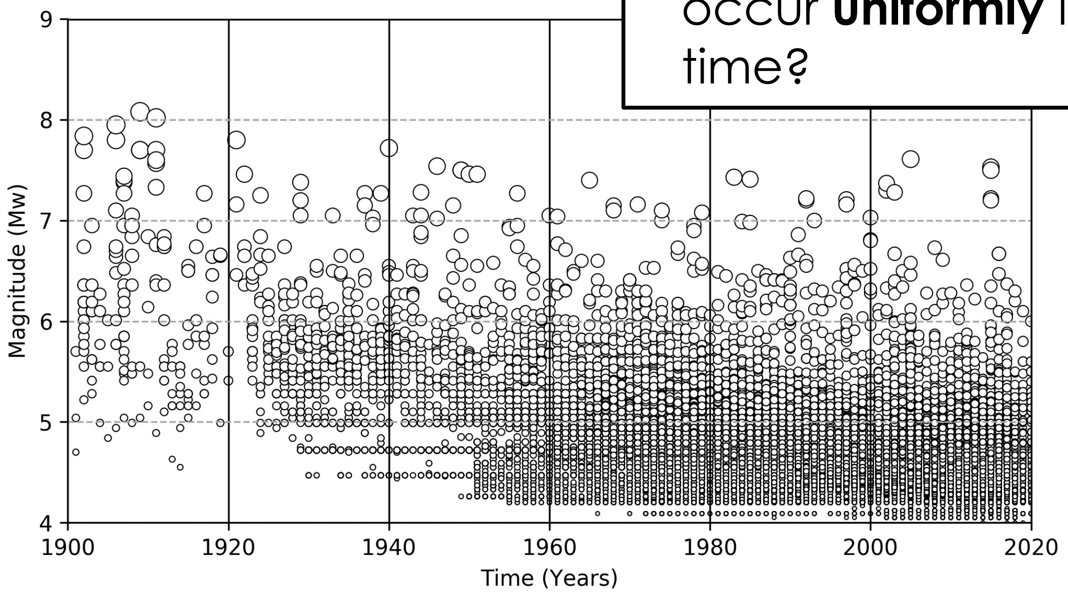


Akua Capital
This project is funded by the European Union

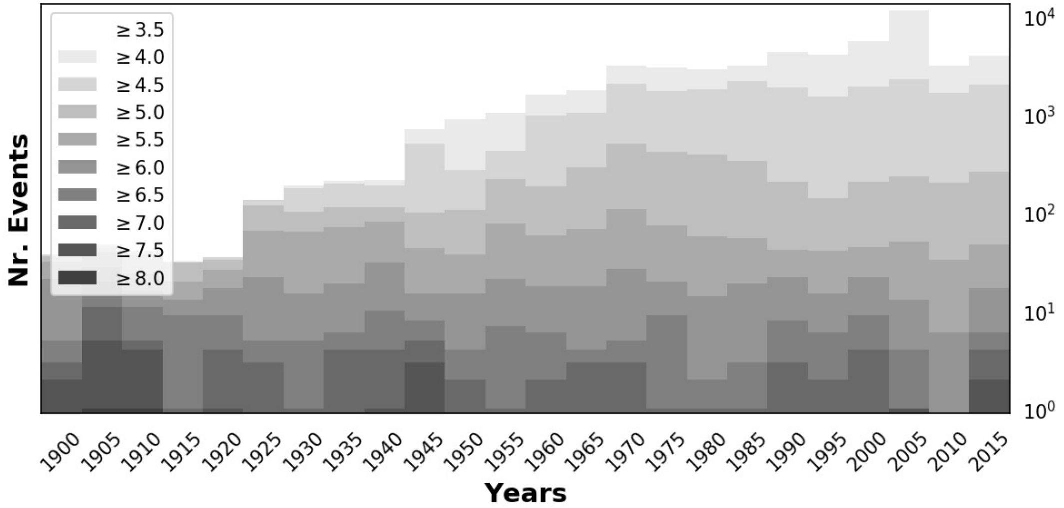
How often do Earthquakes occur?

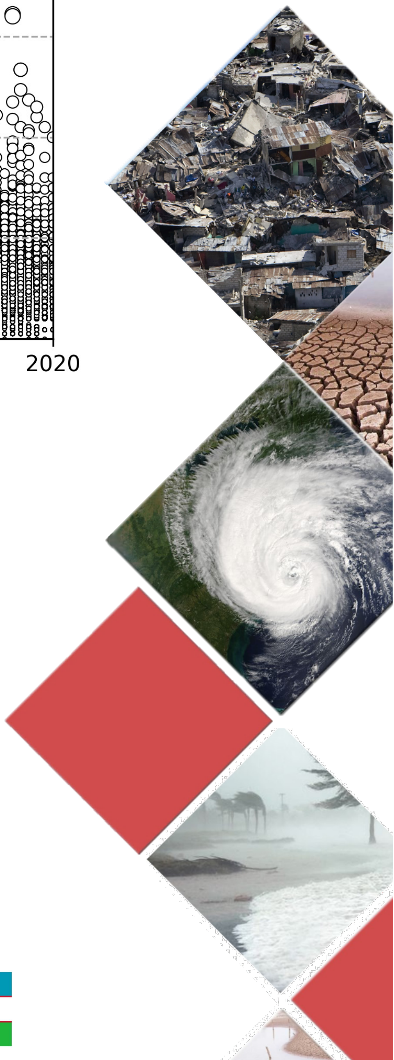
Earthquake generation is not a predictable process. Earthquakes occur randomly in time, however:

- On average, earthquake rate is quite stable (at specific locations);
- The proportion between events of different magnitude (large vs small) is preserved over time.



Do earthquakes occur **uniformly** in time?





Akua Capital

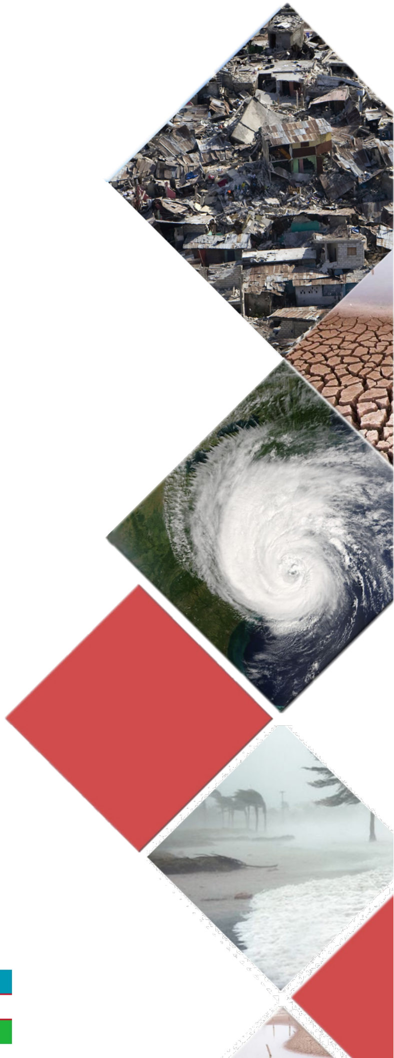
This project is funded by the European Union

Occurrence in Numbers

Large magnitude destructive earthquakes are rather infrequent, although small (mostly non damaging) earthquakes occur every day.

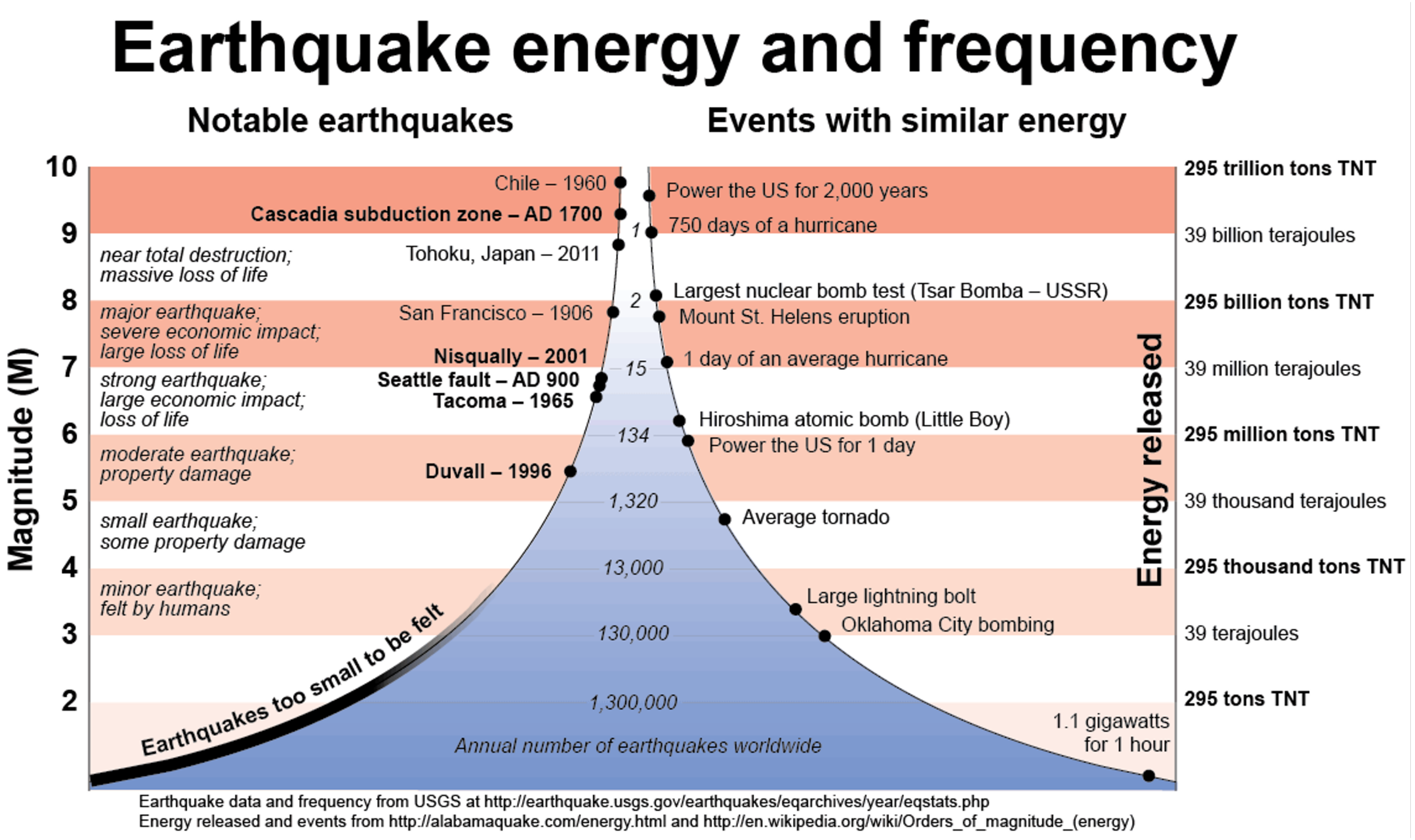
Magnitude	Description	Number in 1 Year	One Quake Every
8+	Great	< 1	1−−2 years
7.0–7.9	Major	17	every 20days
6.0–6.9	Large	135	3 days
5.0–5.9	Strong	1320	9 hours
4.0–4.9	Moderate	13000	90 minutes
3.0–3.9	Mild	130000	11 minutes
2.0–2.9	Small	1300000	2 minutes

Occurrence rate



This project is funded by the European Union

Energy and Occurrence



This project is funded by the European Union

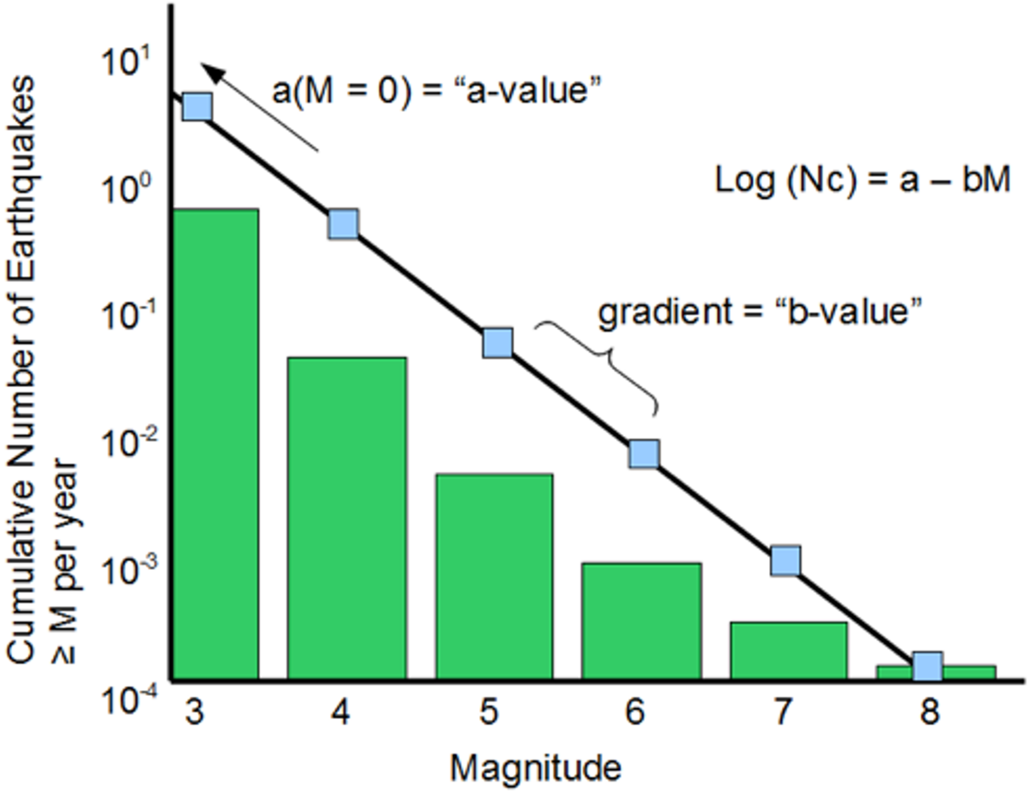
Gutenberg-Richter Occurrence Relation

Gutenberg and Richter observed in 1944 that the **cumulative number of earthquakes** (per unit time) usually scales linearly with magnitude (ML), according to the law:

$$\log_{10}(N_c) = a - bM_L$$

a = intercept, represents the seismic productivity of the region (at M=0)

b = slope, represents the relative proportion between small and large event



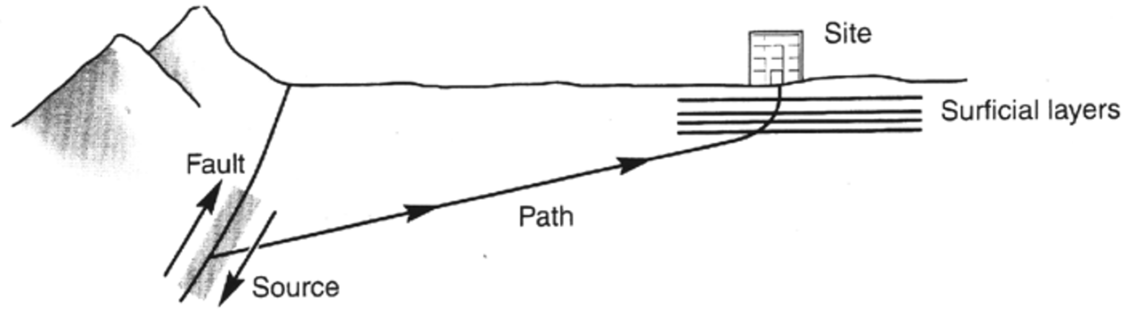
This project is funded by the European Union

Predicting Ground Motion

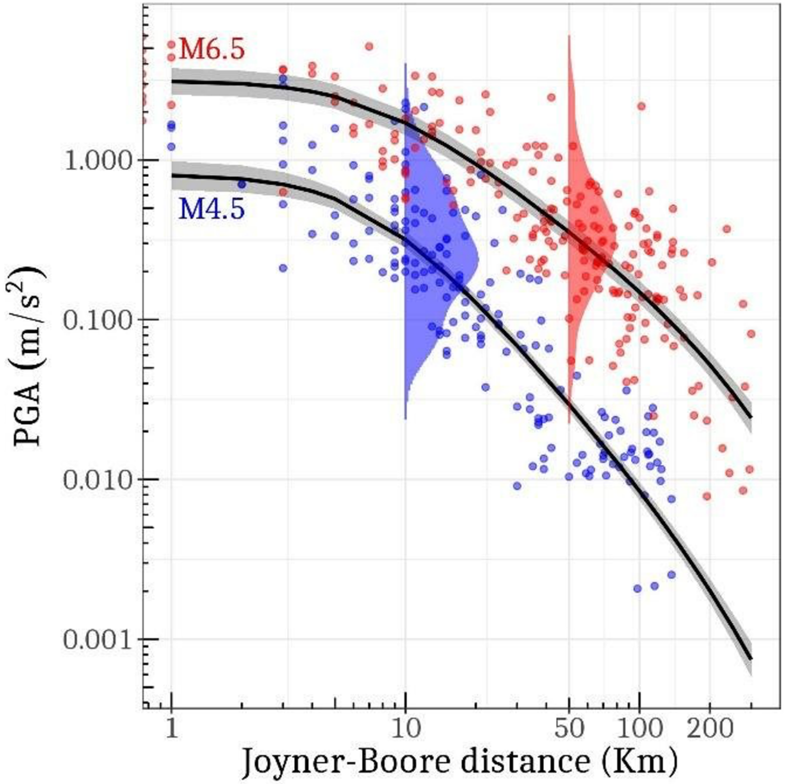
Ground Motion Prediction Equations (GMPEs) are the simplest **empirical** (and in few cases analytical) answer to the following question:

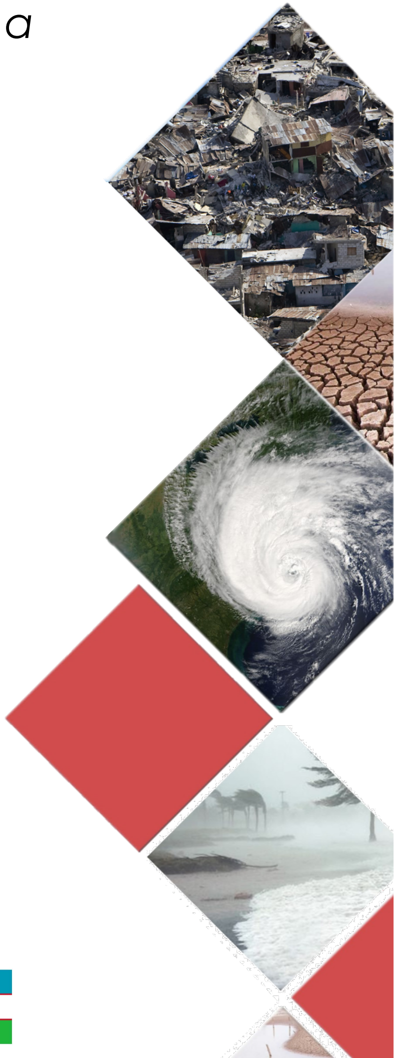
"If we know where a major earthquake is likely to occur, how large will the ground motion be at a particular site?"

GM Amplitude = **Source term** * **Path term** * **Site term**



$$\log(Y) = f(M, \Delta, \ldots) + E$$





This project is funded by the European Union

GMPE Functional Form

The functional form of empirical ground motion model is created following physical principles i.e. trying to reproduce the basic physics of the process.

Here is an "simple" example:

$$\log(Y) = c_0 + c_1 M + c_2 M^2 + c_3 \log\left(\sqrt{(R^2 + h^2)}\right) + \sigma$$

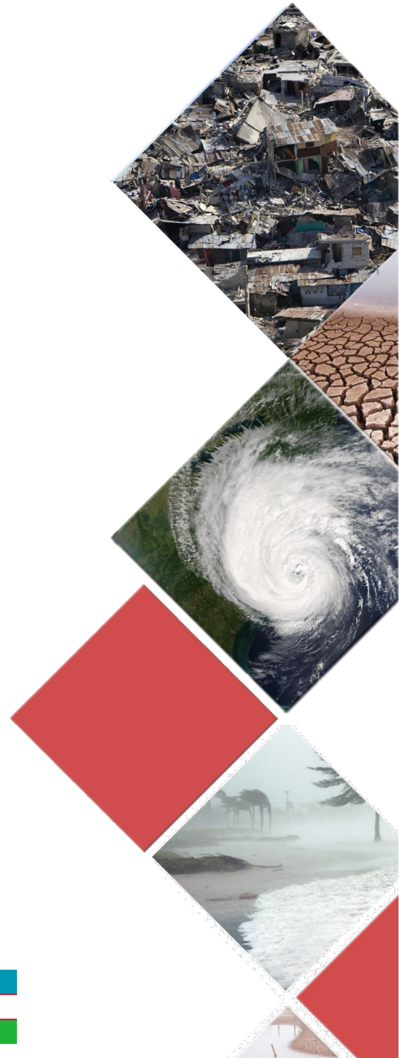
$$\sigma = \sqrt{\tau^2 + \phi^2}$$

Different set of coefficients are defined for each ground motion measure type (PGA, SA…).

Table 2
Coefficients of Equation (1)

PSA at Frequency	c_0	c_1	c_2	c_3	σ-intra	σ-inter	σ-total
0.2	−4.374	1.134	0.0038	−1.426	0.26	0.17	0.31
0.33	−3.869	1.110	0.0039	−1.447	0.25	0.21	0.33
0.5	−4.503	1.532	−0.0430	−1.404	0.25	0.22	0.33
1	−2.009	1.890	−0.1248	−1.828	0.27	0.21	0.34
2	−4.128	1.792	−0.0791	−1.526	0.30	0.19	0.35
3.33	−2.076	1.889	−0.1257	−1.886	0.31	0.18	0.36
5	−3.918	2.112	−0.1266	−1.591	0.31	0.20	0.37
10	−2.839	1.905	−0.1134	−1.658	0.30	0.25	0.39
20	−2.337	1.902	−0.1252	−1.838	0.29	0.29	0.41
33	−2.313	1.840	−0.1119	−1.708	0.29	0.26	0.39
PGA	−2.427	1.877	−0.1214	−1.806	0.29	0.24	0.37
PGV	−4.198	1.818	−0.1009	−1.721	0.28	0.18	0.33

Equation (1) predicts 5% damped horizontal-component pseudospectral acceleration (PSA, in cm/s^2) for B/C site conditions, peak ground acceleration (PGA, in cm/s^2), and peak ground velocity (PGV, in cm/s). The standard deviation of residuals (σ-total) and its intraevent and interevent components are also given.

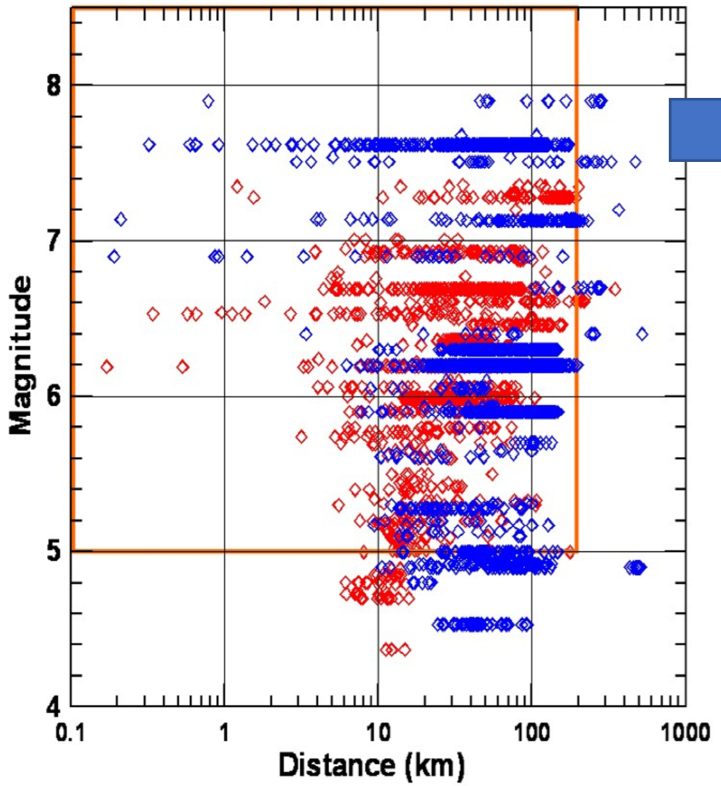


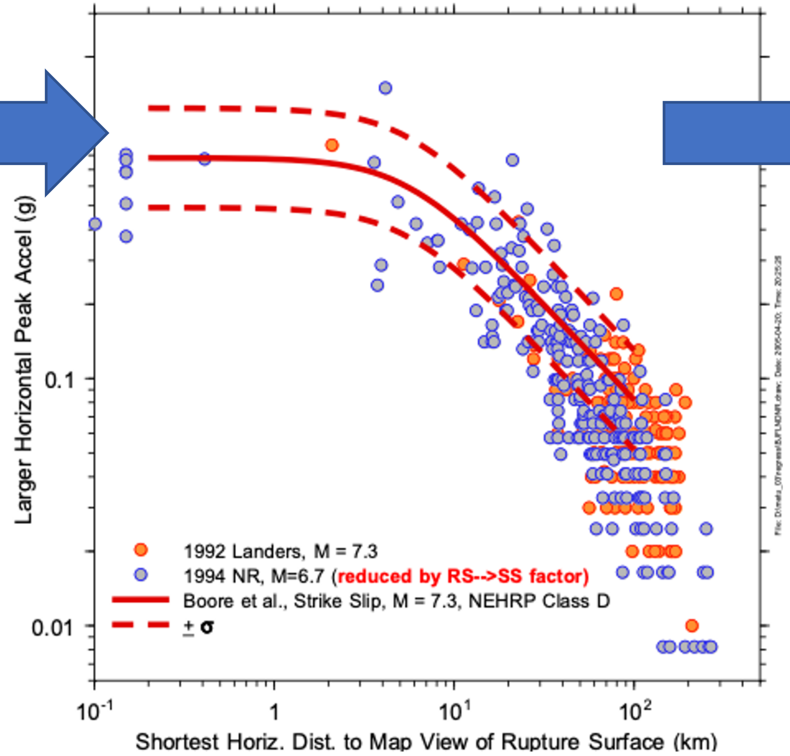
Akua Capital

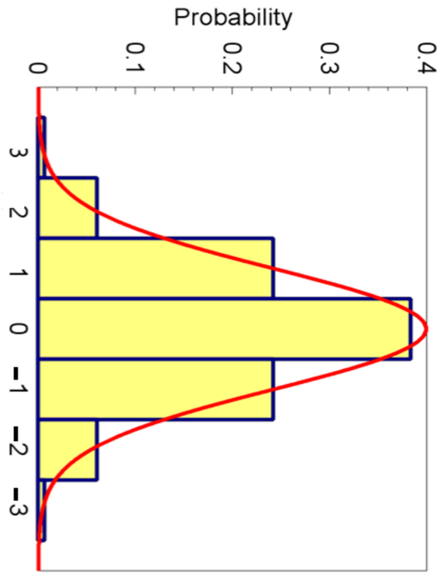
This project is funded by the European Union

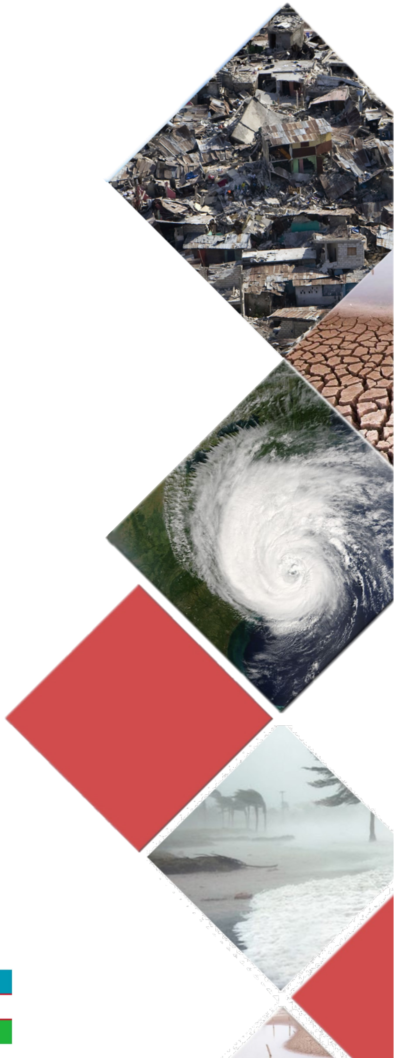
GMPE Calibration and Uncertainty

Relation calibration is done on large datasets of earthquake waveforms covering sufficient magnitude and distance ranges. Uncertainty is assumed log-normally distributed.









This project is funded by the European Union

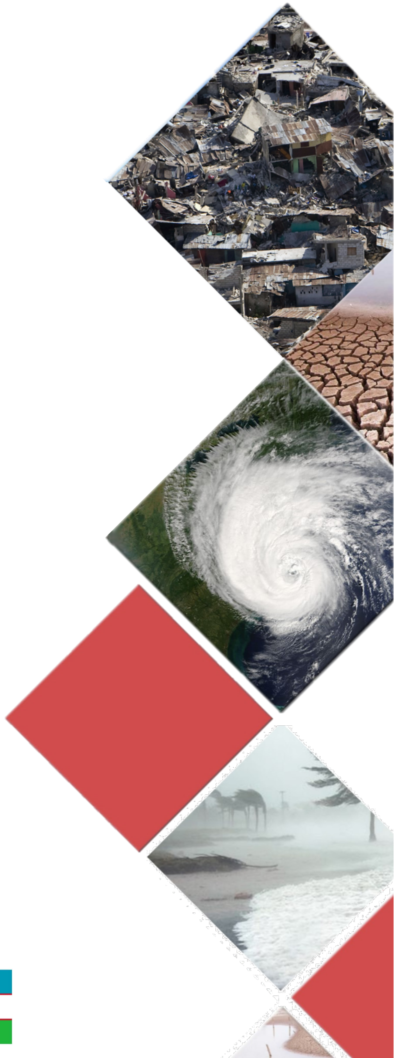
Deterministic vs Probabilistic

Two are the main methodologies currently adopted for seismic hazard analysis:

Deterministic. Also called the **“Worst Case Scenario”**

One or a few earthquake potential scenarios are selected, and the corresponding ground motion computed assuming a level of uncertainty on ground motion (i.e., a number of standard deviations above the median value predicted by a Ground Motion Prediction Equation - GMPE).

Probabilistic: **All possible scenarios** of engineering relevance for the investigated site are considered in the analysis, considering their probability of occurrence i.e., all ruptures (magnitude + distance) and levels of uncertainty on ground motion.



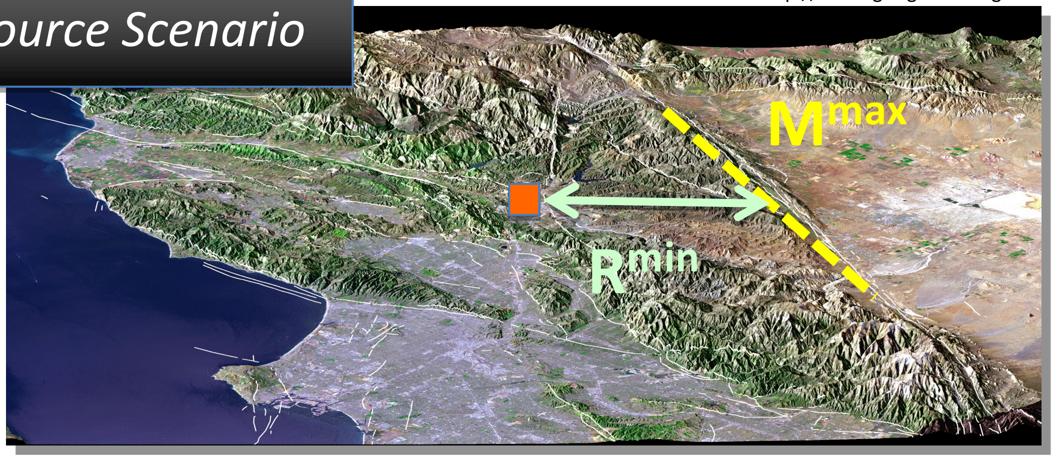
This project is funded by the European Union

Scenario Based Approach

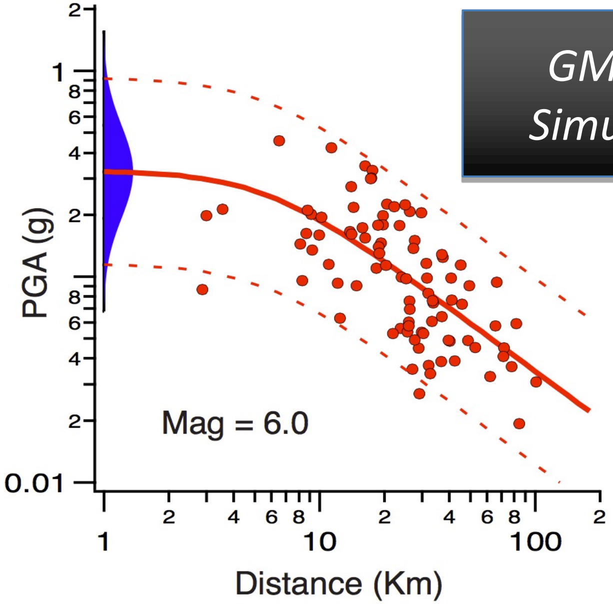
1) Select one or more sources through specific magnitude and distance combinations
2) Compute expected ground motion (accounting for variability)

Source Scenario

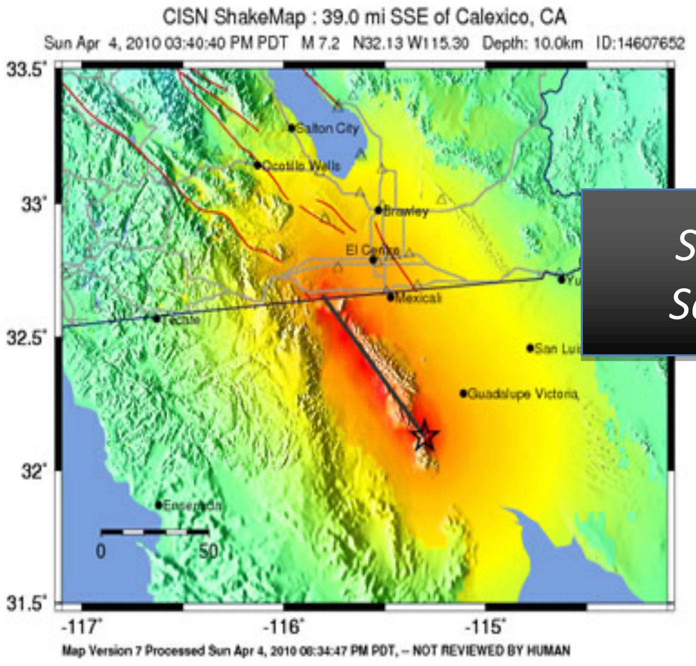
http://eoimages.gsfc.nasa.gov



Modified from Field (USGS)

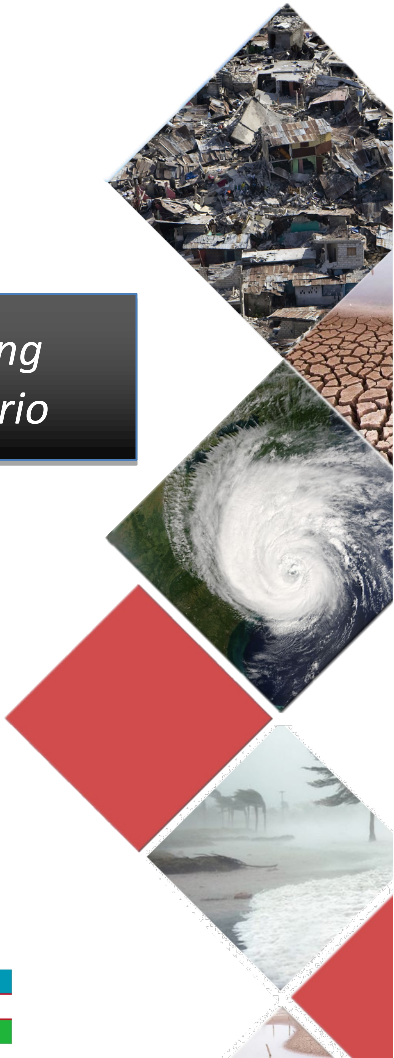


GMPE or Simulation



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Shaking Scenario



Akua Capital

This project is funded by the European Union

Defining a Reasonable Scenario… ?

Note that worst-case ground motion is generally **NOT** selected in deterministic approach.

Combing largest earthquake with the worst-case ground motion is too unlikely a case:

→ The occurrence of the maximum earthquake is **rare**, so it is not "reasonable" to use a worst-case ground motion for this earthquake. Chose something smaller than the worst-case ground motion that is "reasonable", but reasonable is of difficult quantification.

→ What if several sources are present? Is the closest source always the most dangerous?

→ **There is clear need to account for spatial-temporal variability and to evaluate ground motion exceedance!**

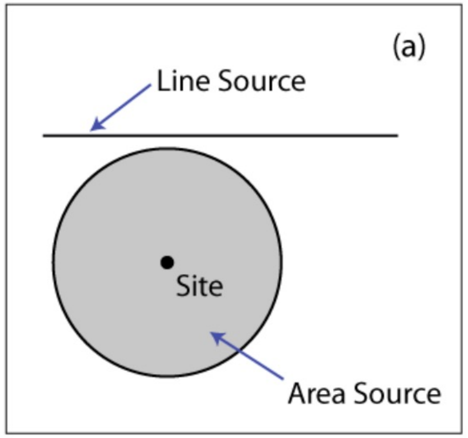
This is done in Probabilistic Seismic Hazard Analysis (PSHA)….

This project is funded by the European Union

Probabilistic Seismic Hazard Analysis

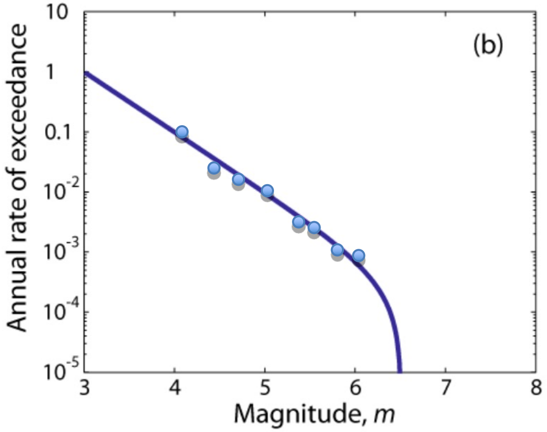
The probability that a certain ground motion level will be exceeded in a given time interval is computed by considering the earthquake scenarios generated by all potential sources within a certain distance range from the investigated site.

Where
Seismogenic Models

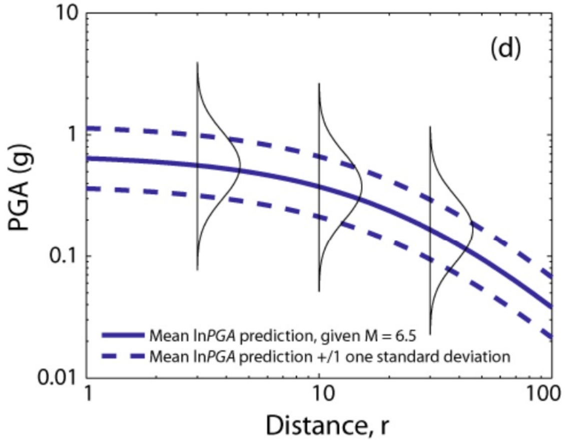


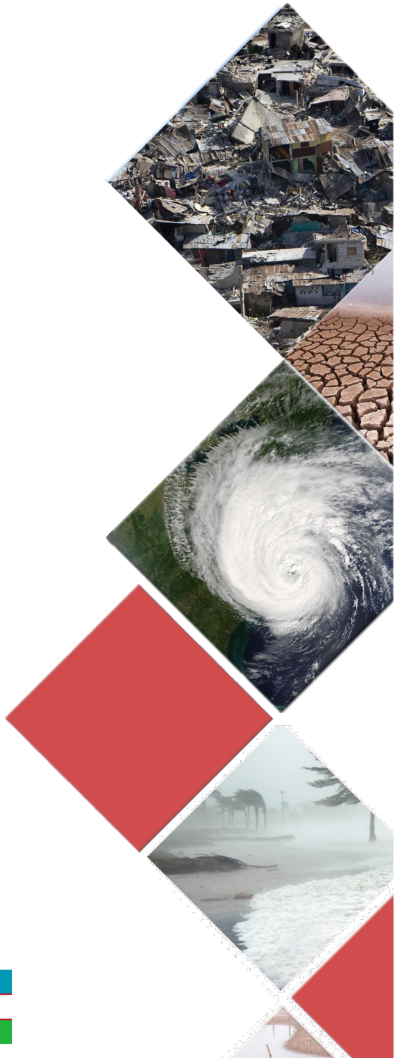
Modified from Baker (2008)

When (how often)
Recurrence Models



How (strong)
Ground Motion Models





This project is funded by the European Union

The Earthquake Hazard Integral

The rate λ of events with intensity (IM) larger than a value x experienced at a given site from the contribution of all sources can be formalized as:

$$\lambda(\text{IM} \geq x) = \sum_{i=1}^{n_{sources}} \lambda\left(m_i \geq m_{min}\right) \int_{m_{min}}^{m_{max}} \int_{r_{min}}^{r_{max}} P(\text{IM} \geq x|m,r) f_{M_i}(m) f_{R_i}(r|m)\, dm\, dr$$

Loop over distances

Loop over magnitudes

Loop over sources

$\lambda(m_i \geq min_{min})$ = the rate of occurrence greater than m_{min}

$f_{M_i}(m)$ = the PDF of the magnitude distribution

$f_{R_i}(r|m)$ = the PDF of distance, conditional to magnitude m

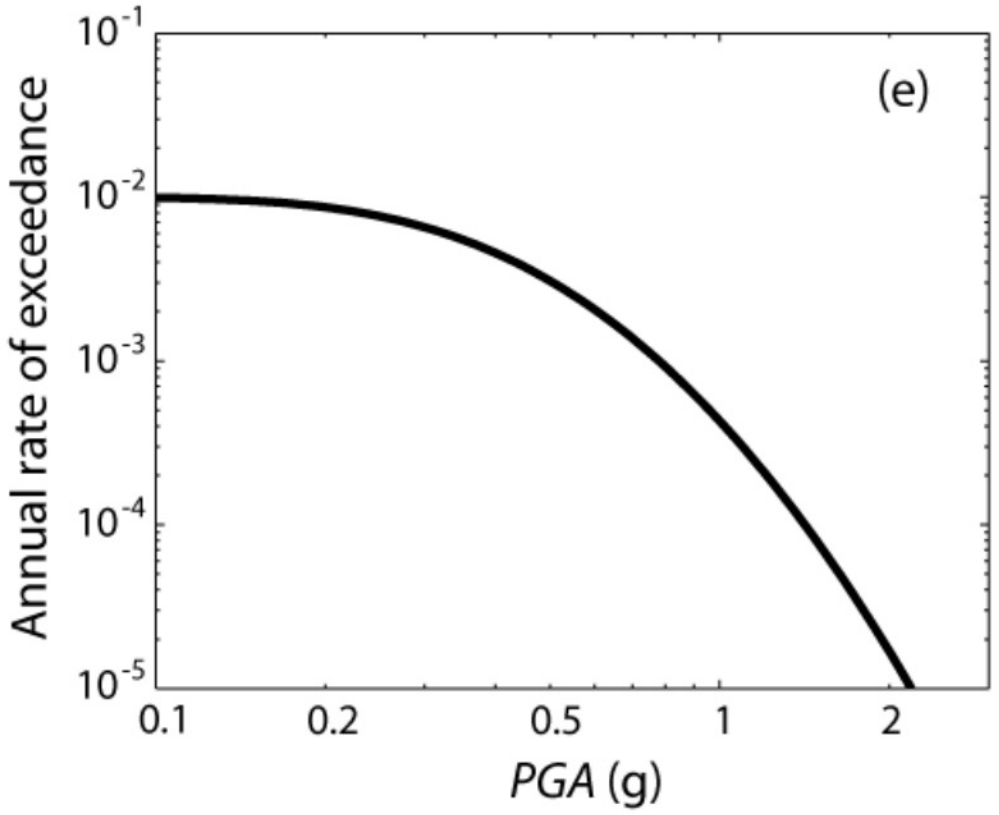
$P(\text{IM} \geq x|m,r)$ = the probability of exceeding an IM level, given m and r

This project is funded by the European Union

PSHA Output: Hazard Curves

Using this equation, the annual rate λ of exceedance is computed for a range of intensity measures (IM) to produce hazard curves. Inverse of λ is defined the average return period.

The hazard curves are subsequently translated into probability by using a **Poisson recurrence model** (assuming independent events)



Poisson Process

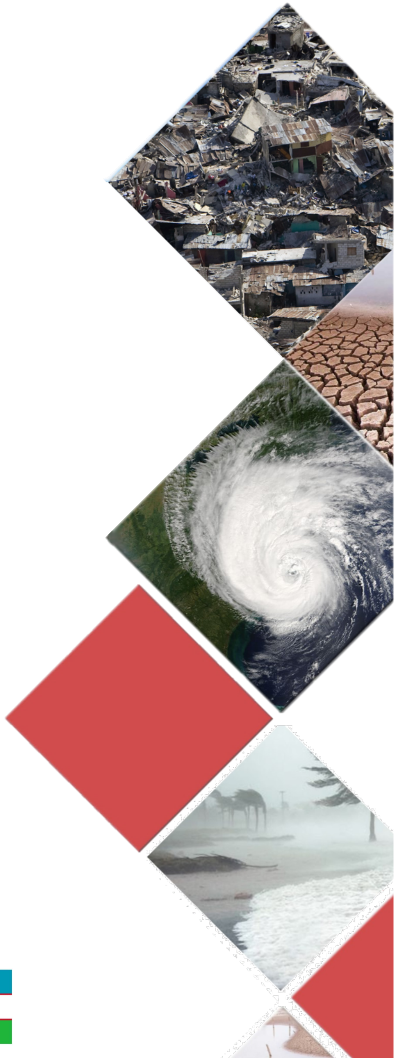
Poisson process - describes the probability that a given number of events (n) with a known constant mean rate (λ) will occur in a given time interval (t), assuming that:

- The number of occurrences in one time interval are independent of the number that occur in any other time interval;
- Probability of occurrence in a very short time interval is proportional to length of interval;
- Probability of more than one occurrence in a very short time interval is negligible.

$$P(N = n|t) = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

The probability of "at-least" one occurrence in time t (**observation time**) is then expressed as the total probability (1) minus the probability of no successful events (0):

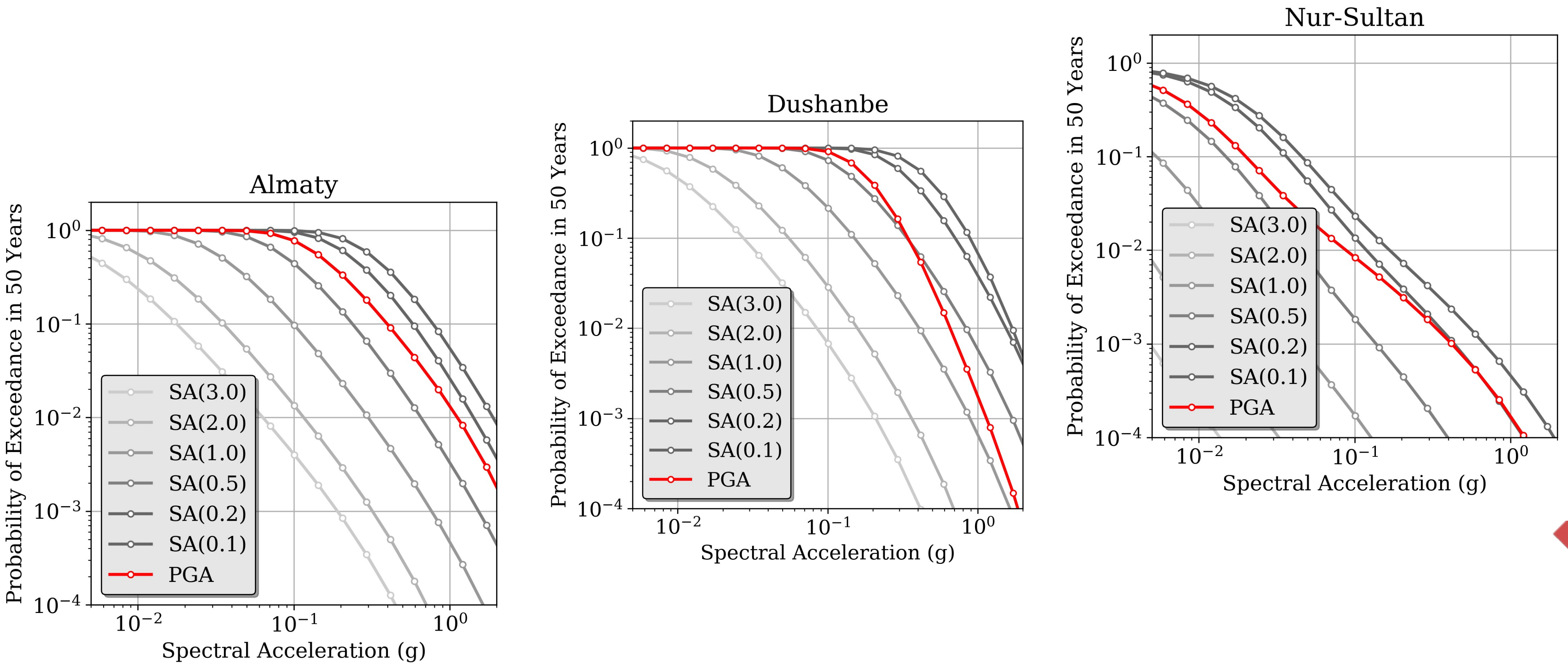
$$P(N \geq 1|t) = 1 - P(0) = 1 - e^{-\lambda t}$$

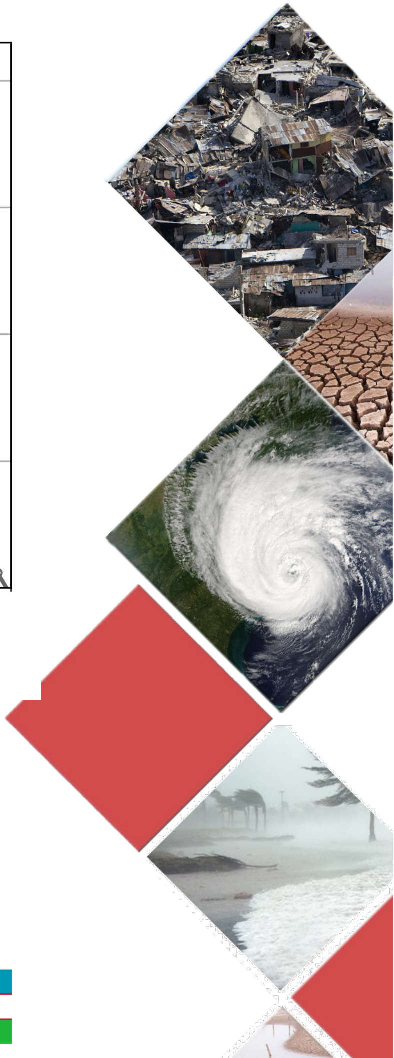


This project is funded by the European Union

Hazard Curves in Probability of Exceedance

The Poisson assumption is used to convert the output of the hazard integral from rate λ of events to probability.



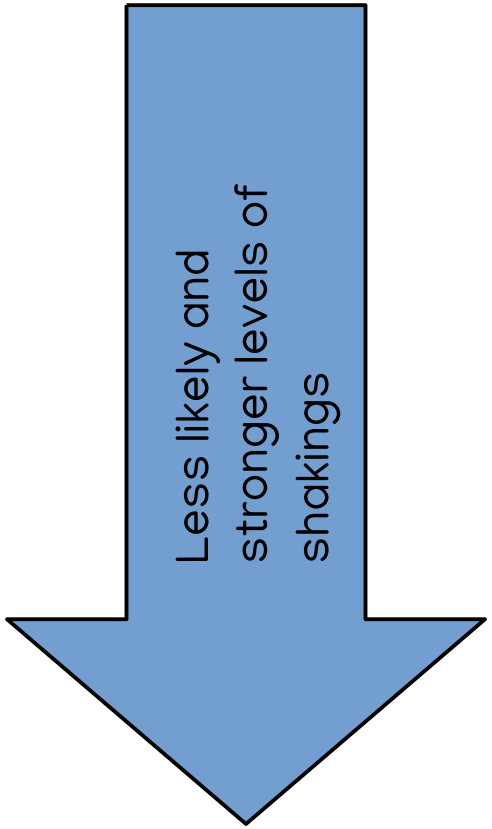


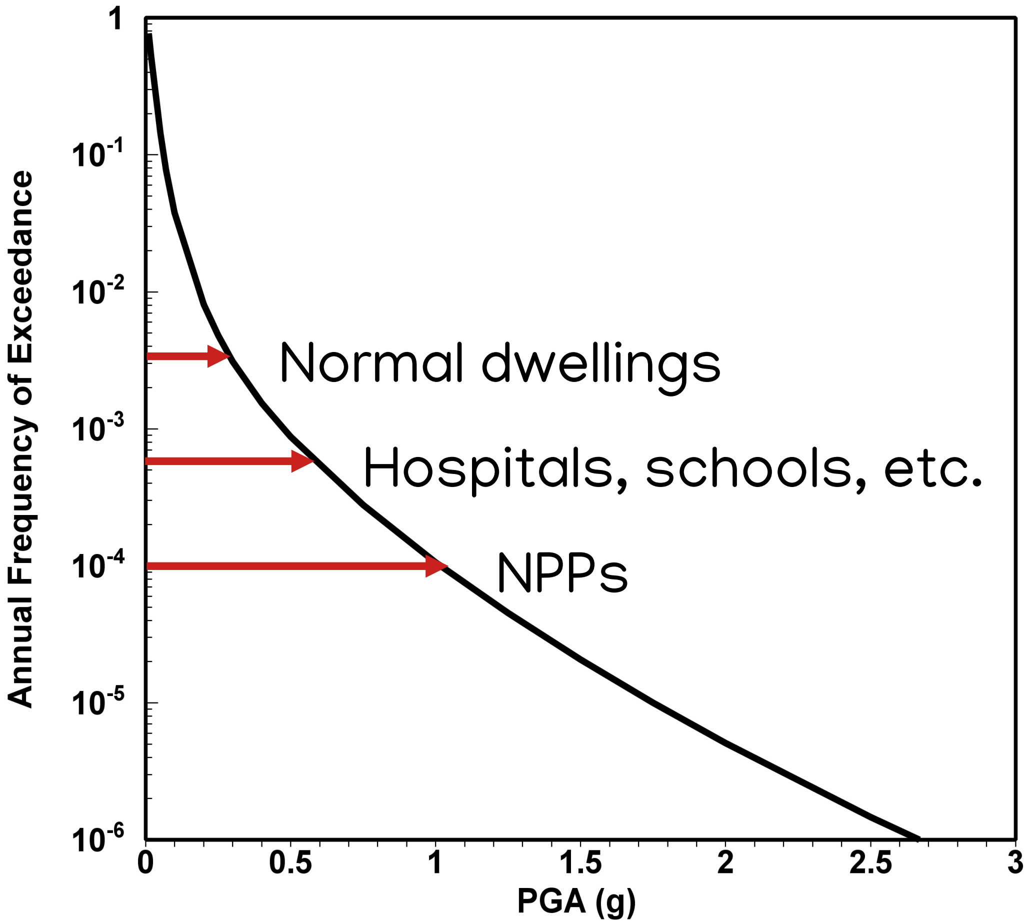
Akua Capital

This project is funded by the European Union

Which Probability of Exceedance?

Normative and building codes usually consider a selected number of probability of exceedance (PoE), which is representative of the ground shaking potentially hazardous for different structure typologies.

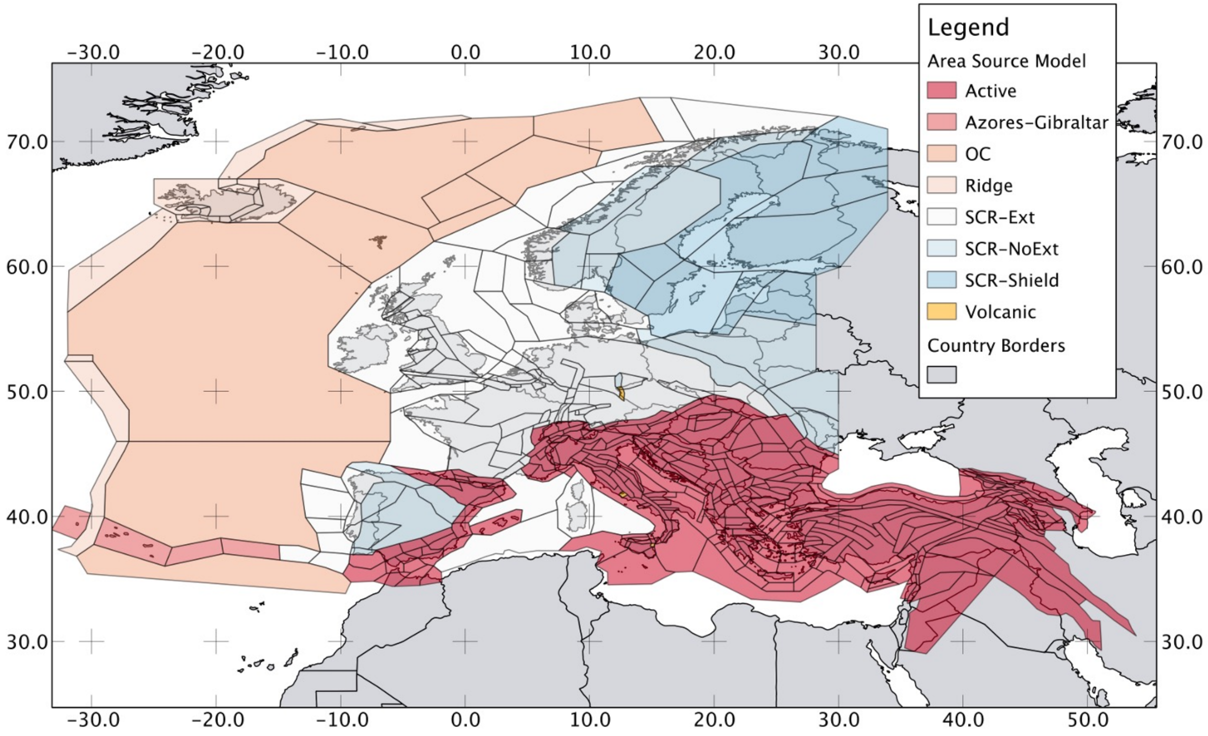


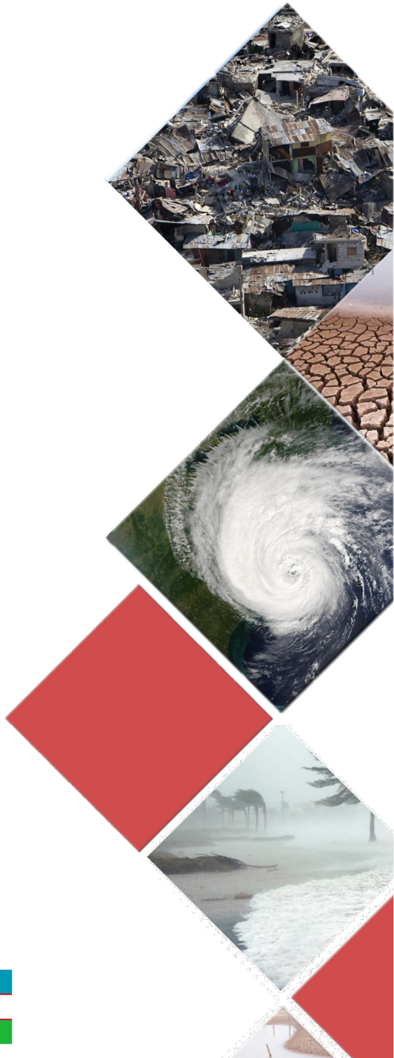


This project is funded by the European Union

Seismogenic Source Model

Distributed Seismicity:
- Single points
- Line sources
- Grid representations (e.g., smoothed seismicity)
- Polygon of Uniform Seismicity (so far, the most widely used approach)

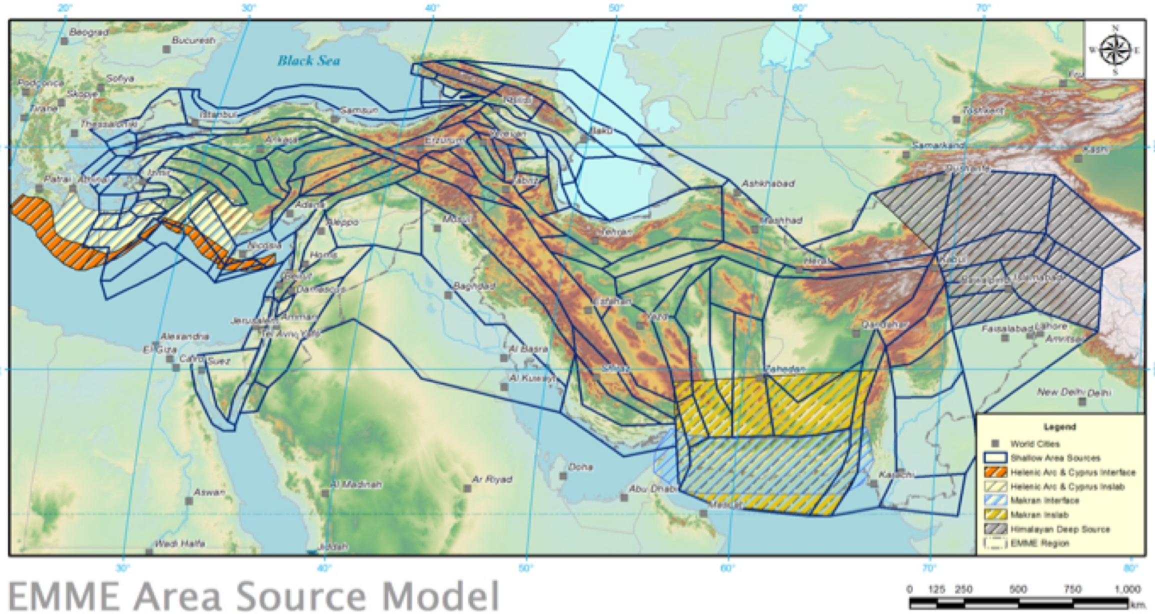




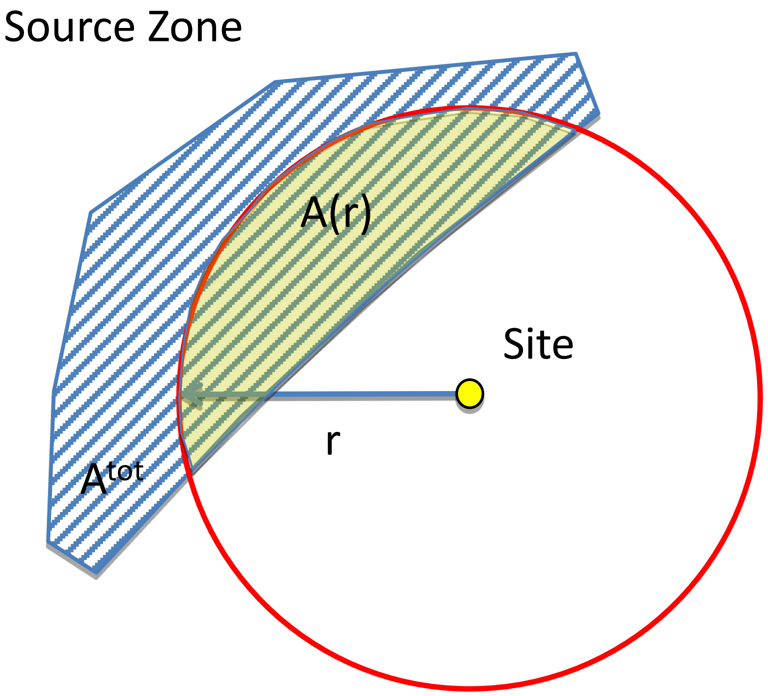
Akua Capital
This project is funded by the European Union

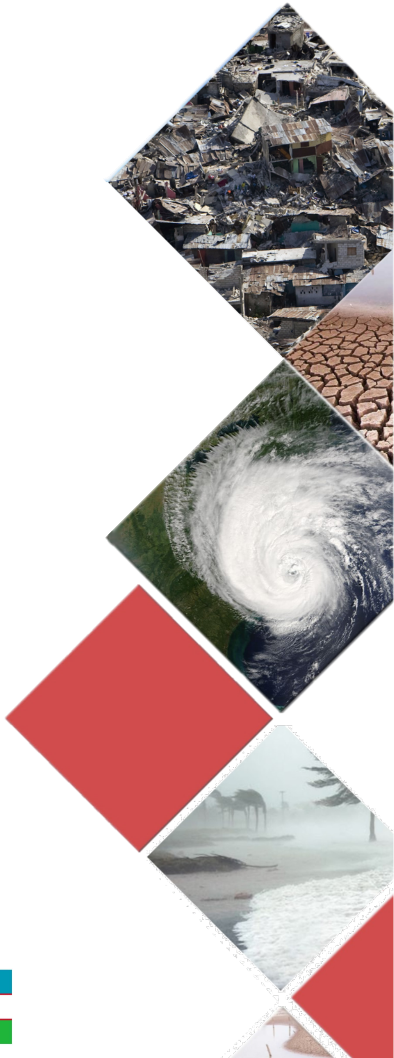
The Homogenous Area Source Zonation

In **homogenous area source zonation**, observed seismicity is assumed to have equal probability to occur anywhere within the area.



EMME Area Source Model

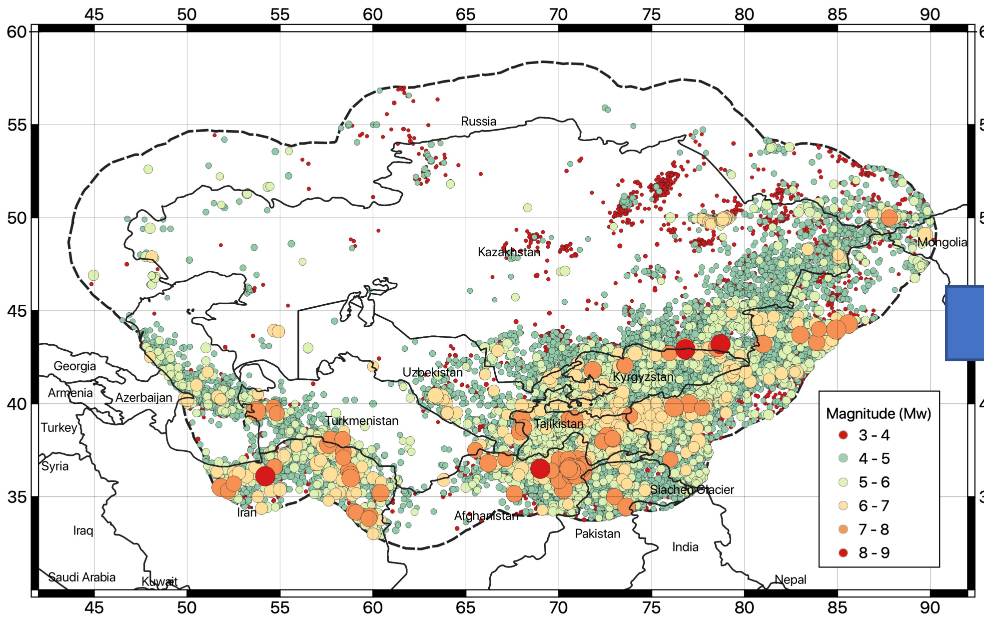


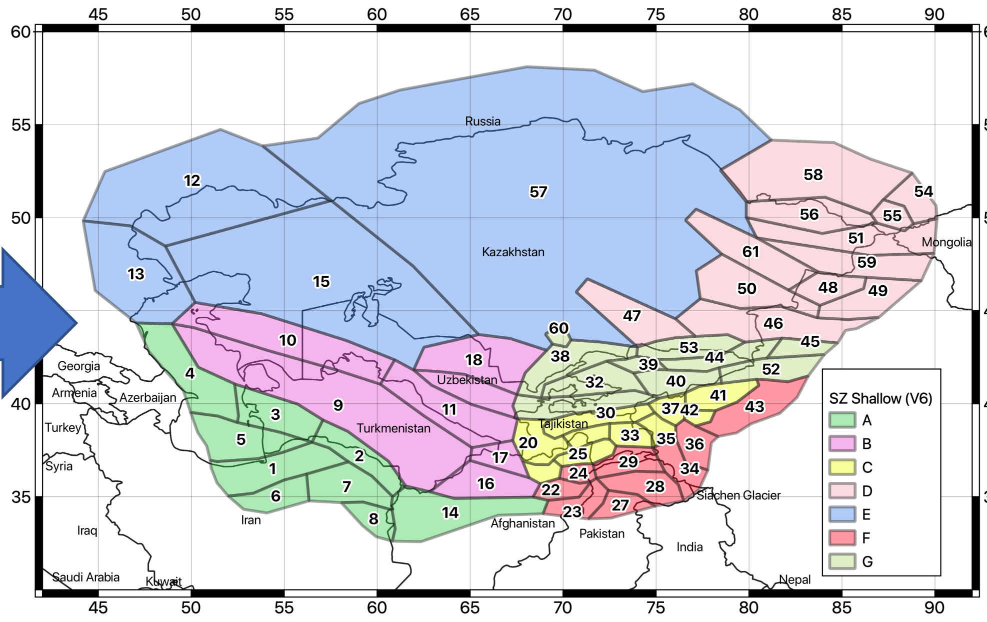


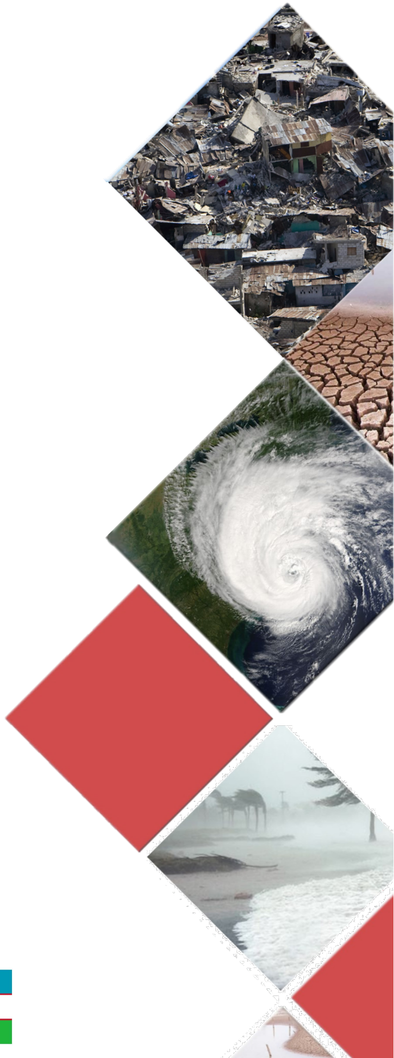
This project is funded by the European Union

The Homogenous Area Source Zonation

Zones are defined on the base of the observed seismicity and the available geological and seismotectonic information for the area.





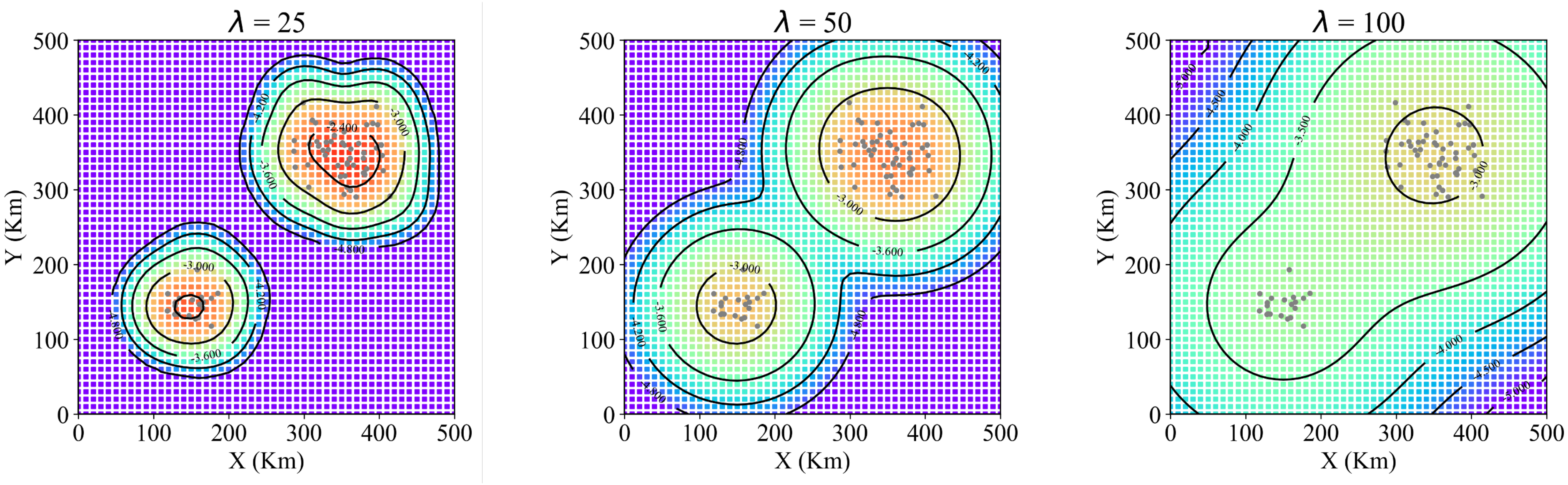


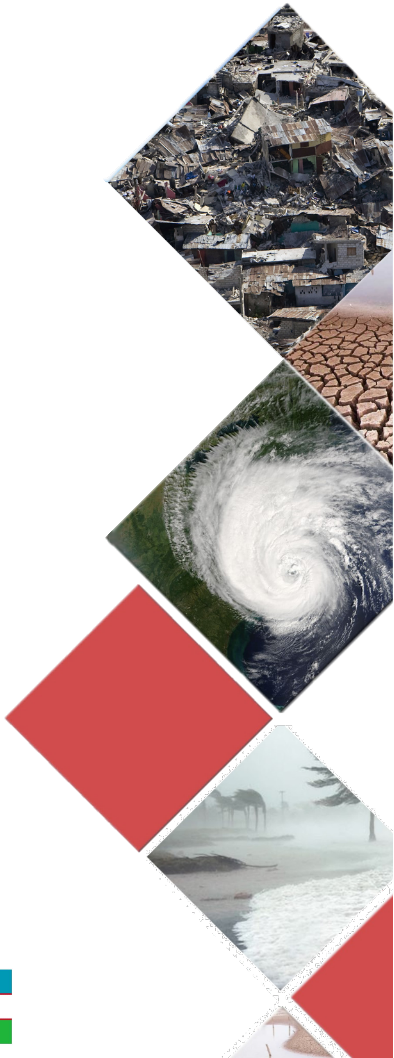
This project is funded by the European Union

Smoothed Seismicity Model

The homogenous area source zonation approach may not be appropriate for regions where seismicity is known to be spatially localized.

A smoothed source model can be used instead, where occurrence rates of each homogenous zone are spatially reorganized on a grid of point sources, weighted according to the spatial density of nearby events.

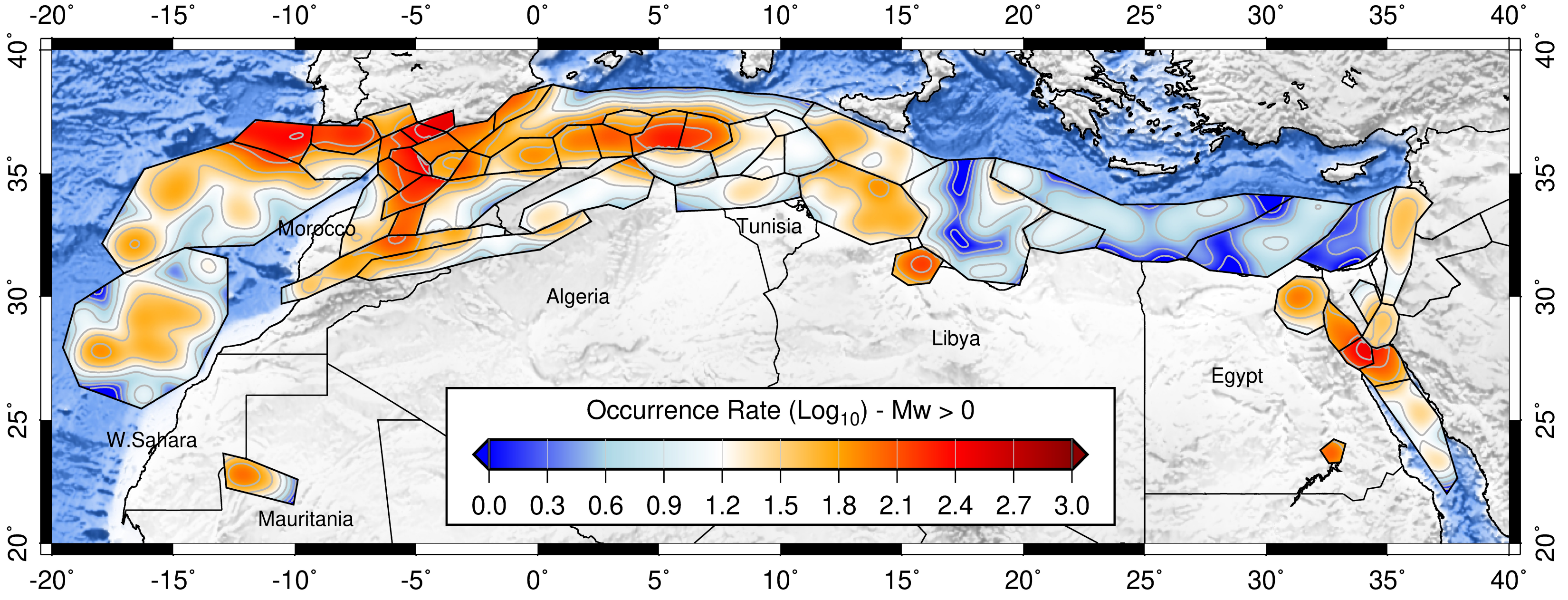


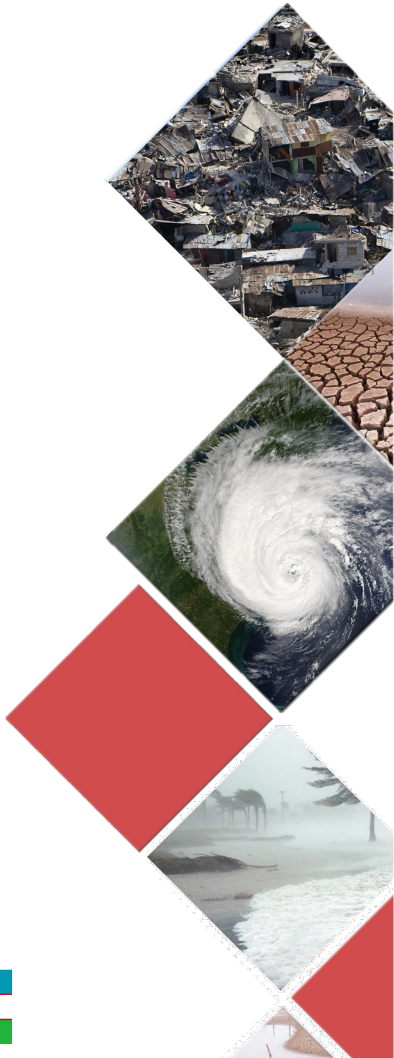


This project is funded by the European Union

Smoothed Seismicity Model

The smoothing approach produces a more realistic spatial source pattern but, heavily relying on the location of past known events, is on the contrary less effective in depicting future events happening in mismatching locations.



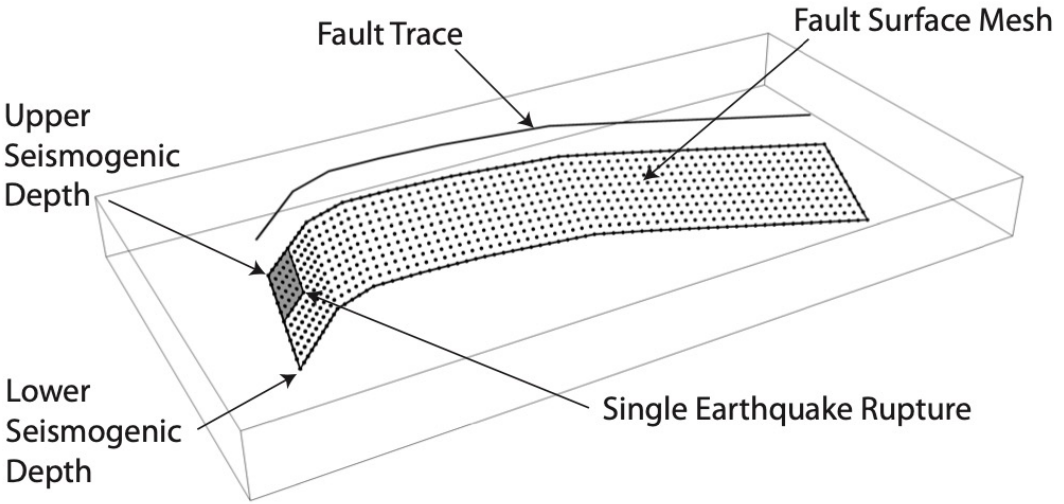


This project is funded by the European Union

Finite Fault Model

Complementary to the distributed seismicity, the **direct modelling of finite faults** has the advantage of better representing ground motion in the source near field.

However, this is possible if enough information (fault geometry, kinematic parameters, displacement rates) is available for the investigated area with sufficient reliability.

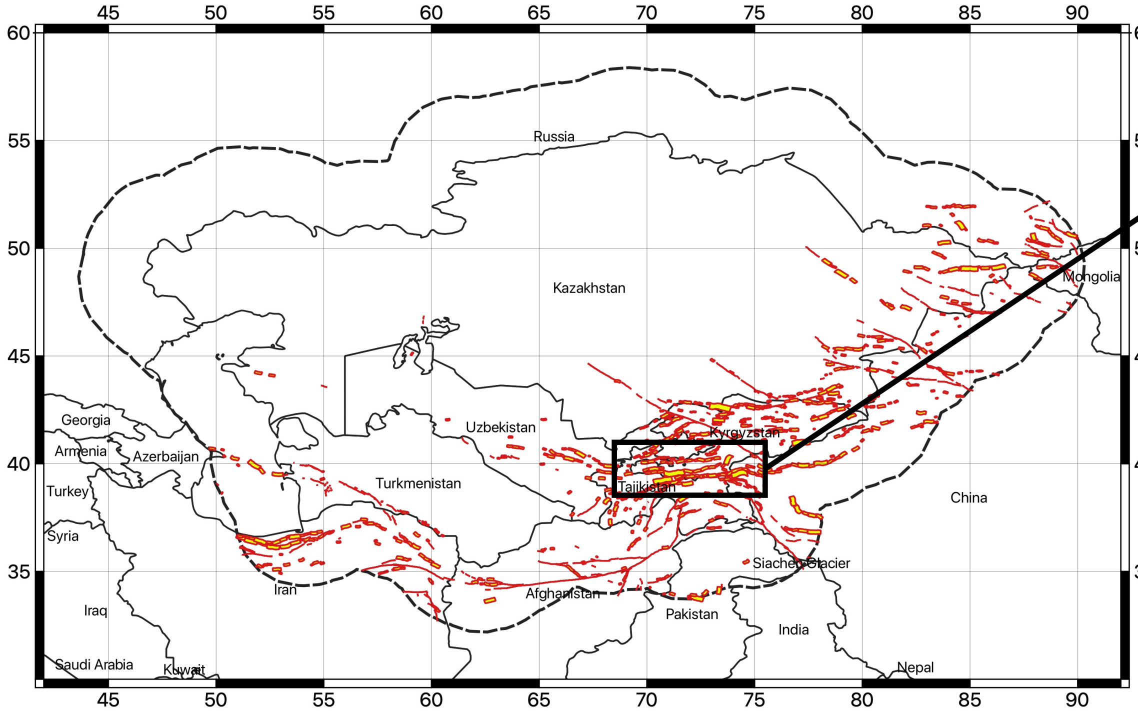


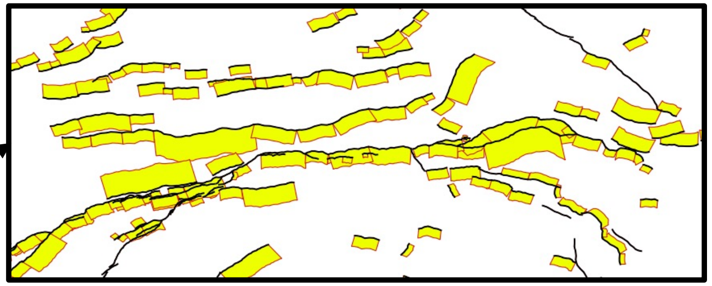
modified from "the OpenQuake-engine book: underlying hazard science"

This project is funded by the European Union

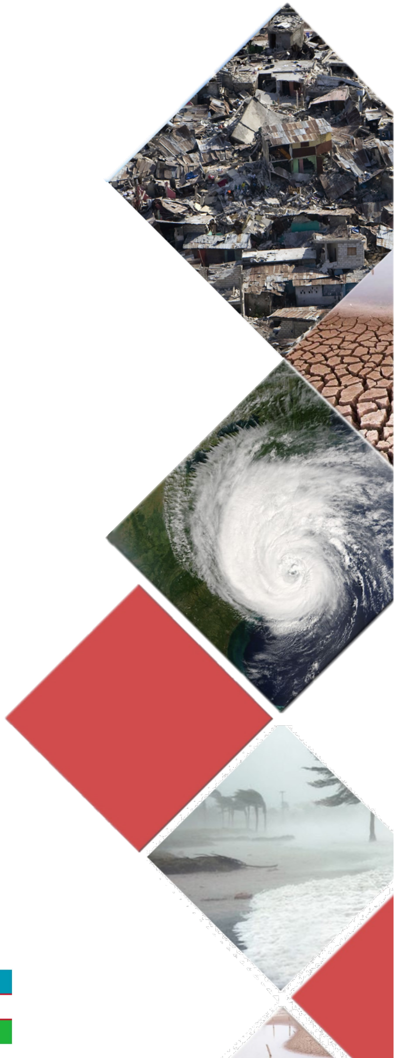
The Fault Source Model

Occurrence rates of each fault can be derived from observed seismicity or from **slip rate estimates**, by balancing the scalar seismic moment accumulation from the integral of the incremental MFD through a direct fitting procedure.





This provides a complementary mean of evaluating source productivity for the very low return periods.



This project is funded by the European Union

Akua Capital

Variability and Uncertainty

Uncertainty and variability are concepts tightly linked with seismic hazard analysis

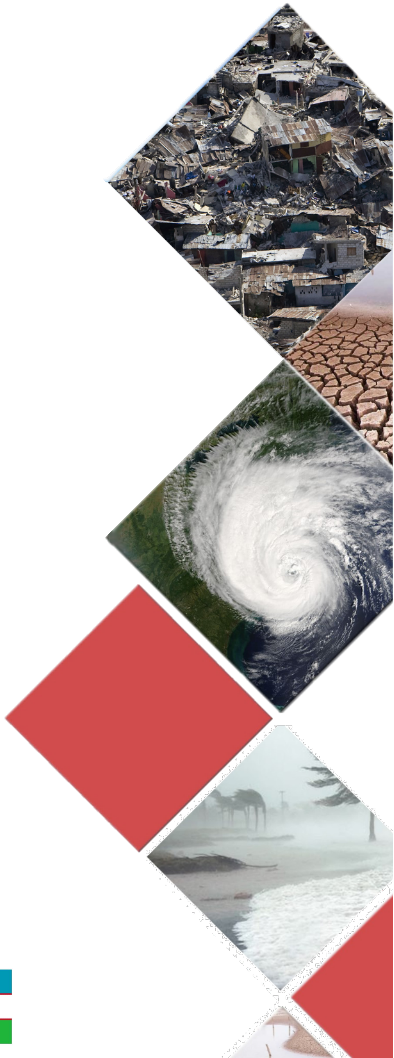
Two are the typologies of uncertainty considered:

- *Aleatory*
- *Epistemic*

Aleatory uncertainty relates to the intrinsic randomness and the nature of the earthquake process

Epistemic uncertainty on the contrary depends on our limited knowledge the phenomenon (e.g., lack of observation data)

This means that: <u>aleatory uncertainty is irreducible whereas epistemic uncertainty can be potentially reduced</u>



This project is funded by the European Union

Variability and Uncertainty

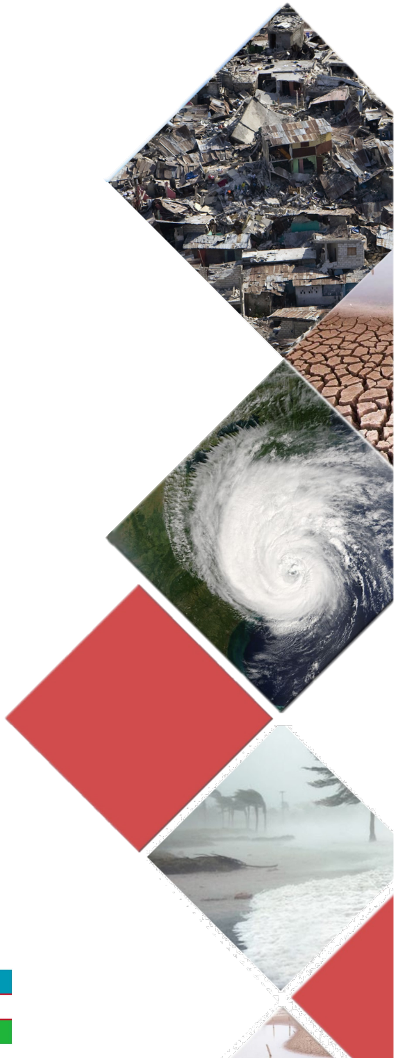
Epistemic and aleatory variability are nonetheless handled separately into the hazard analysis process:

1) Aleatory uncertainty is usually incorporated in the PSHA integrals

Examples: Earthquake location, uncertainty on ground motion estimates

2) Epistemic uncertainty is formally considered by using alternative models (or parameterizations) within a **logic-tree** structure

Examples: ground motion models, recurrence parameters (b-value, maximum magnitude), style of faulting….

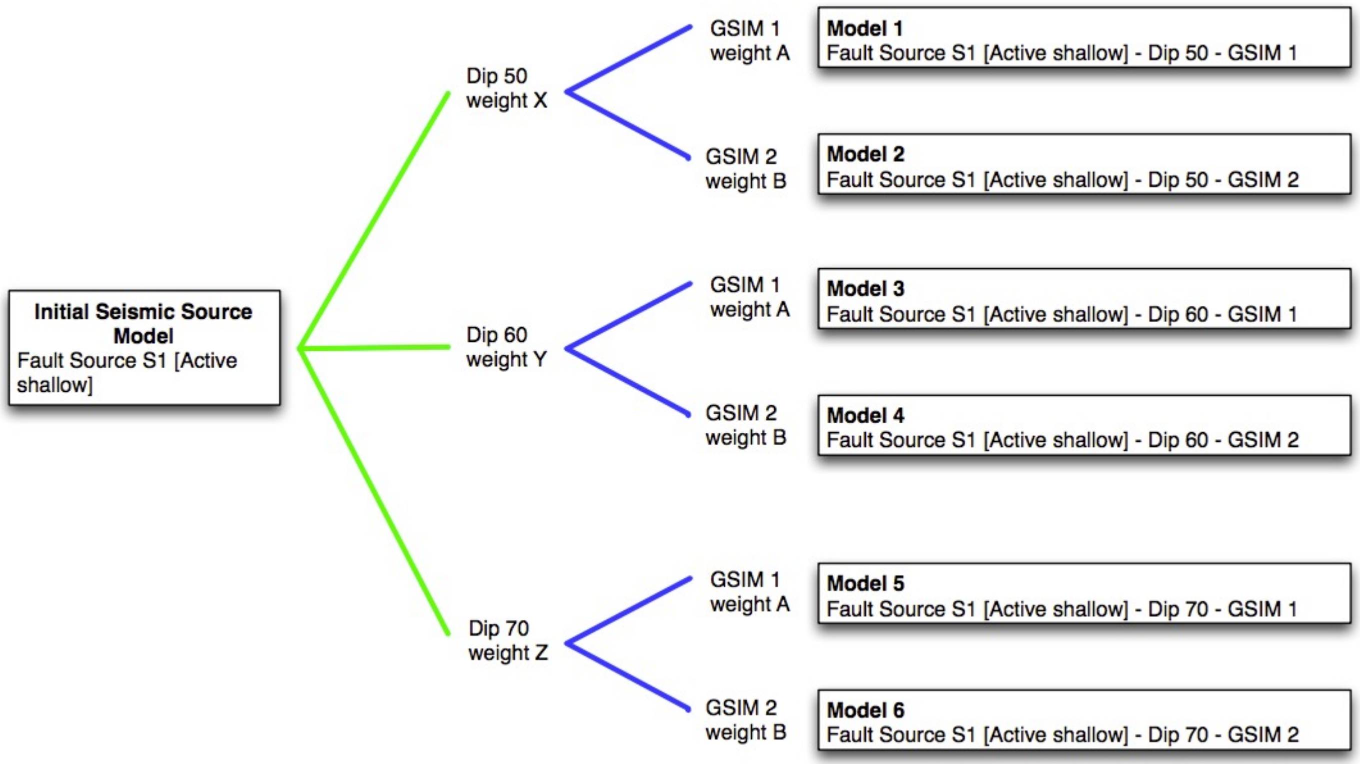


This project is funded by the European Union

Logic-Tree Strategy

A **logic-tree** consists of branches, which are **independent, mutually exclusive and collectively exhaustive** representations of the source and ground motion variability.

Commonly, several **branching levels** are used to combine uncertainties of different type.

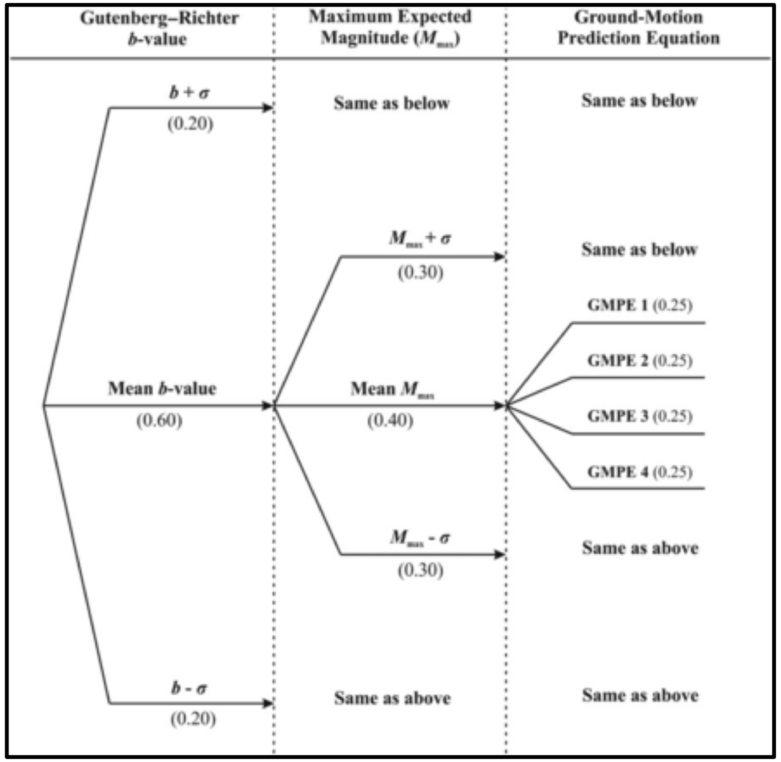


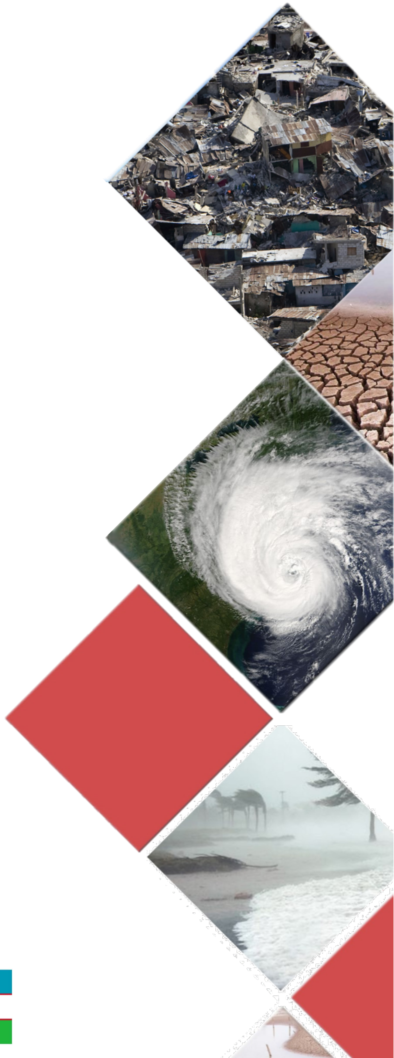
This project is funded by the European Union

Assigning Weights

Each model is assigned **weights**, which express the degree of belief on that model. But how to assign weights?

- Based on fits to observed data? (**Empirical approach**)
- Based on theoretical representation of the physics of the process? (**Physical approach**)
- Weights assignment could be (actually, often is) a subjective process based **expert judgement**.

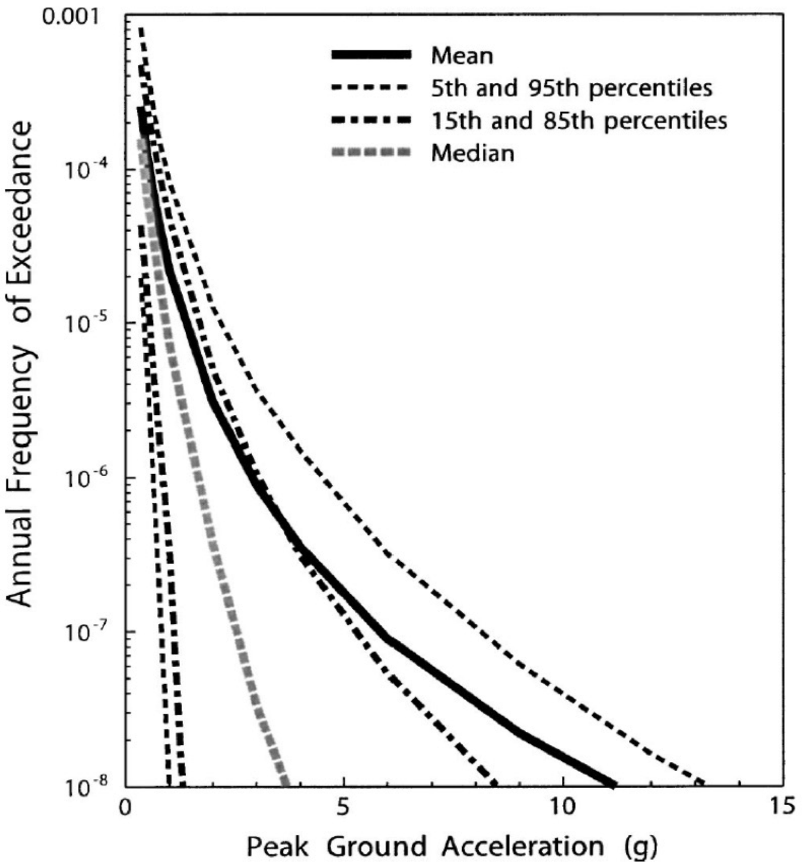




This project is funded by the European Union

A Posteriori Statistic

From the ensemble of all hazard curves from each log-tree realization, **mean** and **percentile curves** can be computed

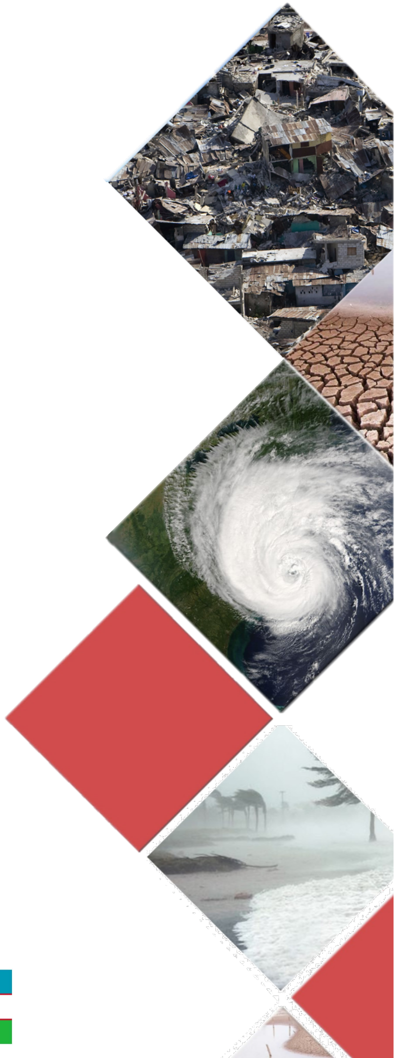


Note: Less data or knowledge should imply greater epistemic uncertainty

HOWEVER

Use of additional “conflicting” models (from newly available data) can increase epistemic uncertainty

Epistemic uncertainty might be (paradoxically) lower in regions with less data!



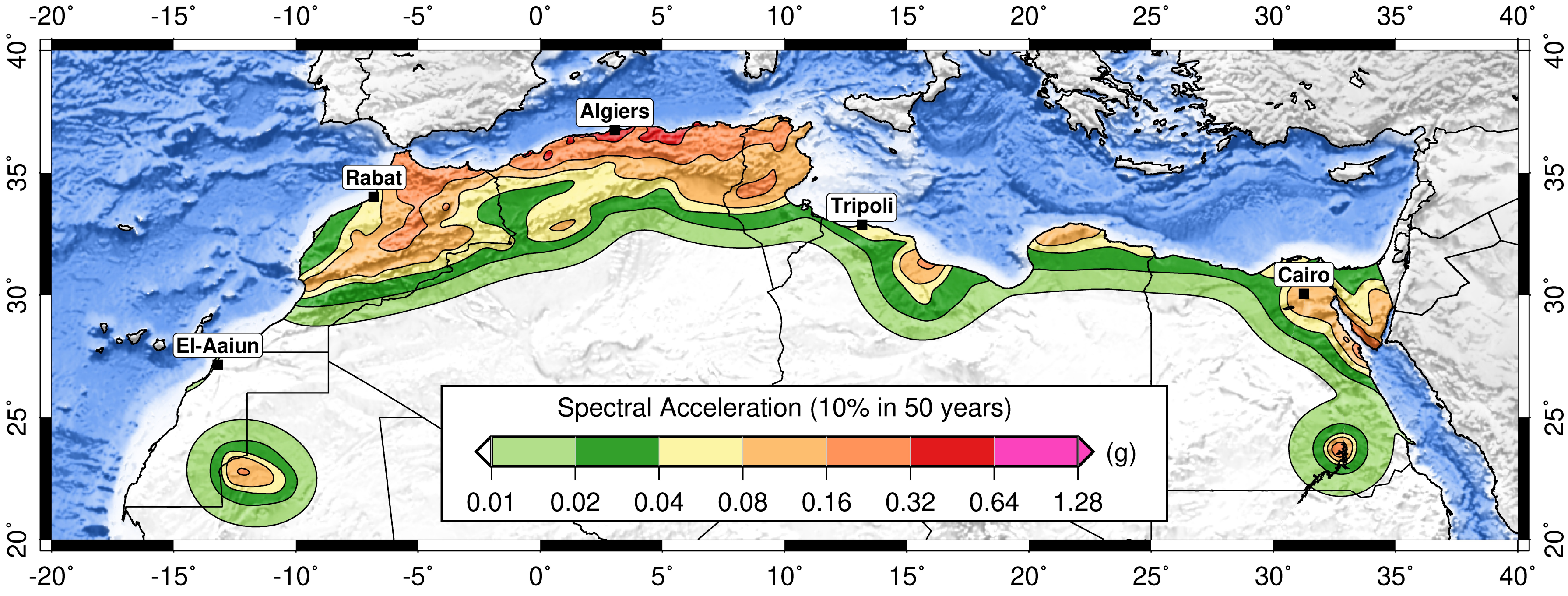
Akua Capital

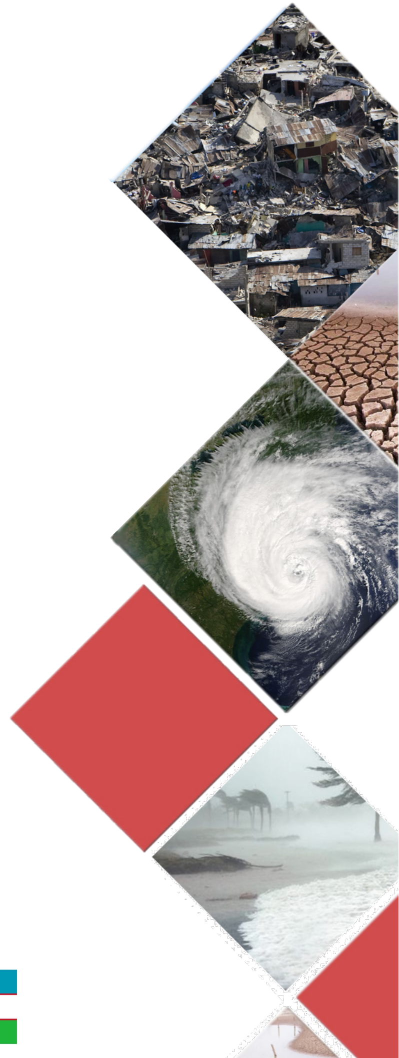
This project is funded by the European Union

PSHA Output: Hazard Maps

Hazard maps are used to show how <u>uniform probability of exceedance</u> of a given ground motion measure for a given observation period distributes over the area.

PGA @ 10% Probability in 50 years

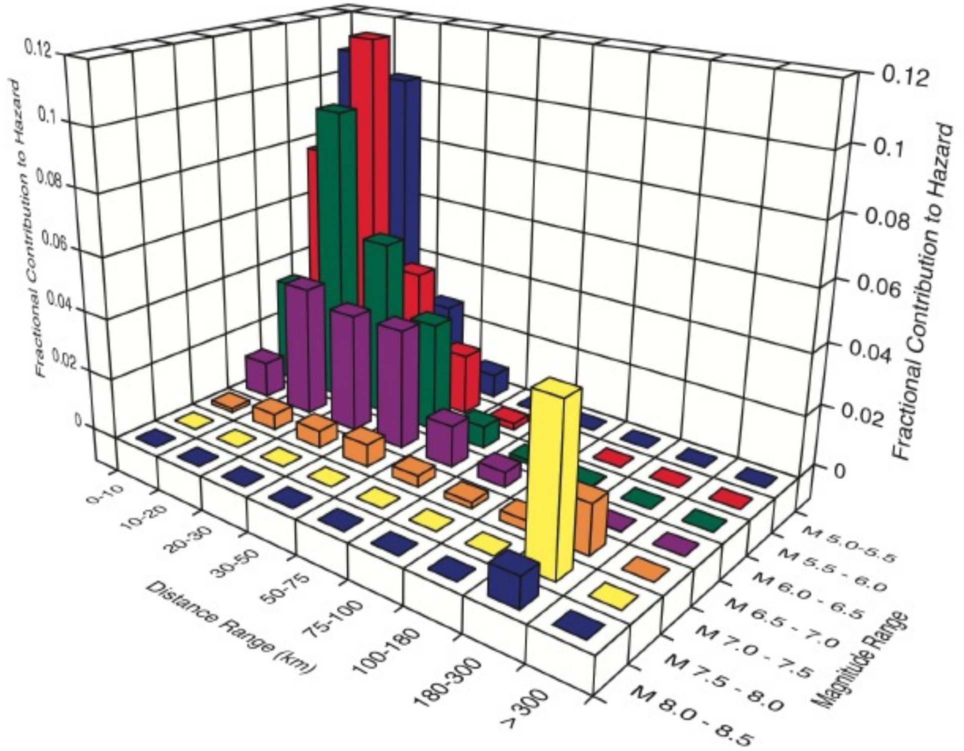




This project is funded by the European Union

Hazard Disaggregation

For a given site, ground motion intensity measure and return period, the fractional contribution of specific scenarios to the hazard can be extracted from the hazard analysis via disaggregation.



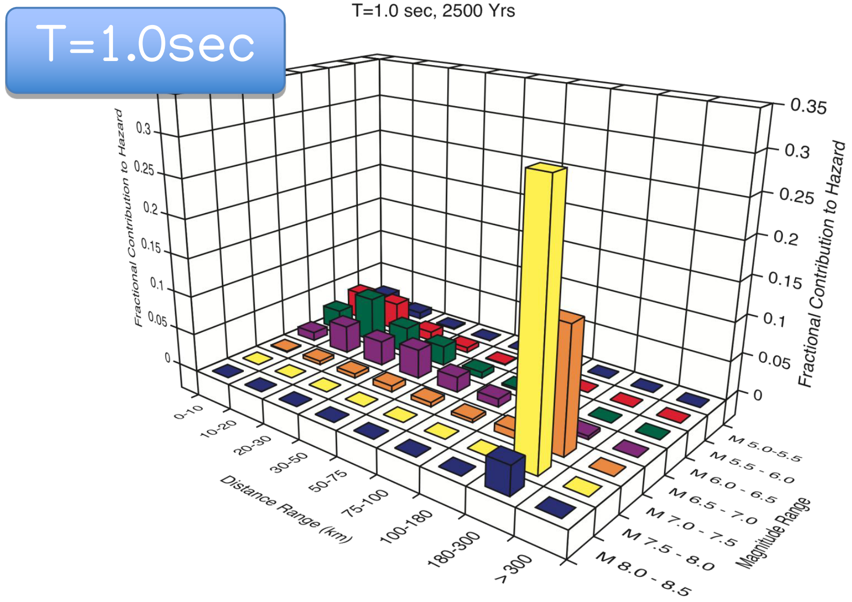
The most common form of disaggregation is a two-dimensional disaggregation in **magnitude** and **distance** bins (formally, it is the conditional probability of the ground motion being generated by an earthquake with magnitude in the range M1-M2 and distance in the range R1-R2).

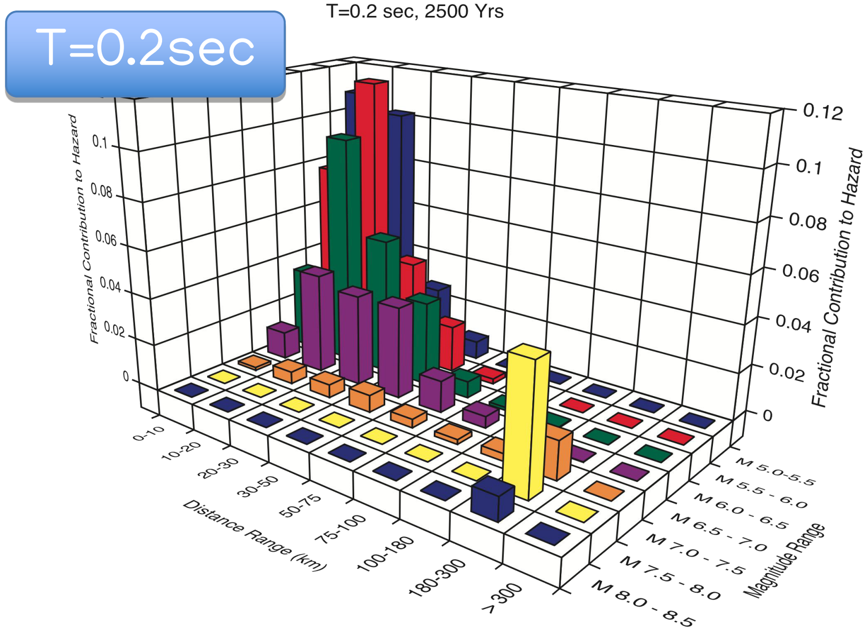
This project is funded by the European Union

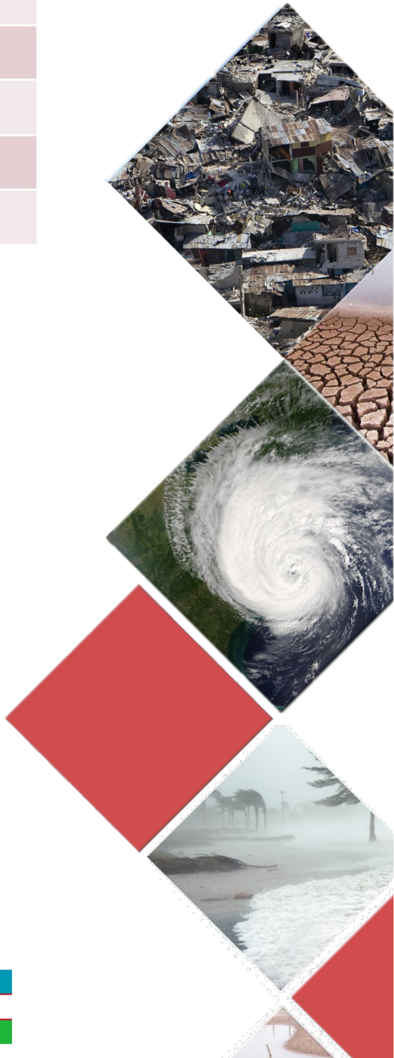
Controlling Scenario

Disaggregation can be used to identify the controlling earthquake scenario driving the hazard, which can be different for different return periods and ground motion parameters.

	T_0=0.2s		T_0=1.0s	
Return Period	Mag	Distance (km)	Mag	Distance (km)
100 yr	6.0	130	6.3	250
250 Yr	6.3	106	6.7	220
500 Yr	6.3	85	7.2	200
1,000 Yr	6.2	60	7.4	200
2,500 Yr	6.1	30	7.5	200
5,000 Yr	6.0	20	7.5	200
10,000 Yr	6.0	15	7.5	200







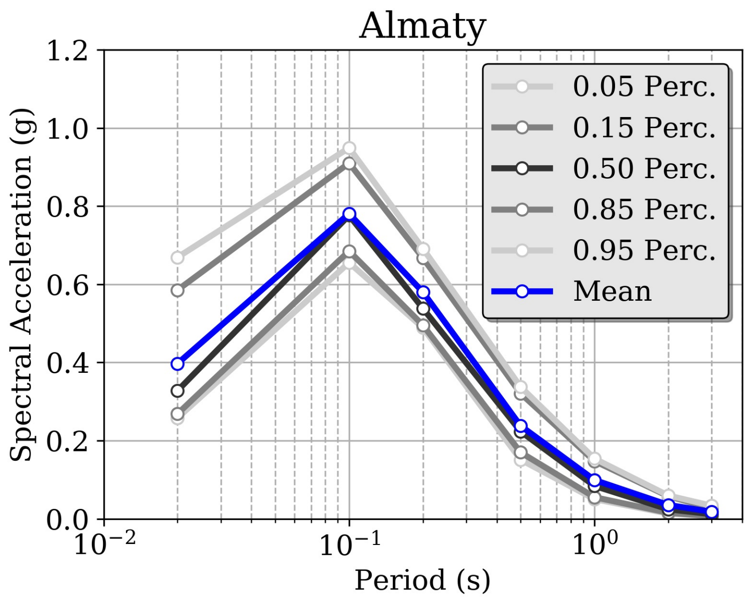
Akua Capital

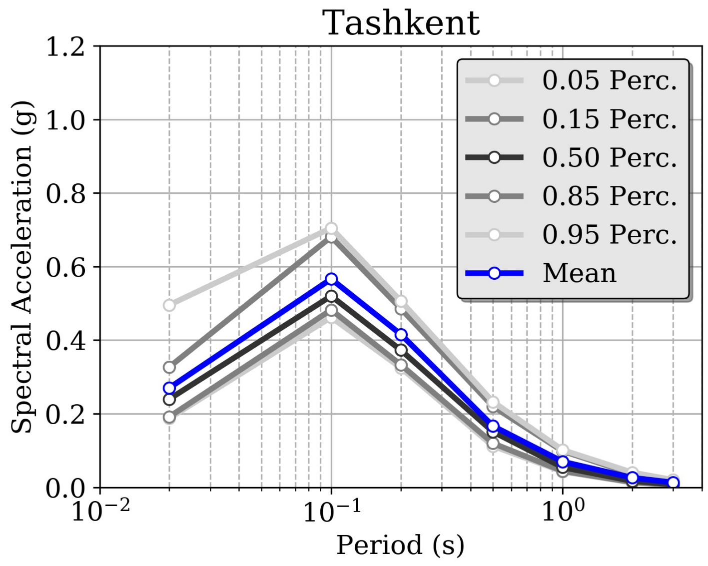
This project is funded by
the European Union

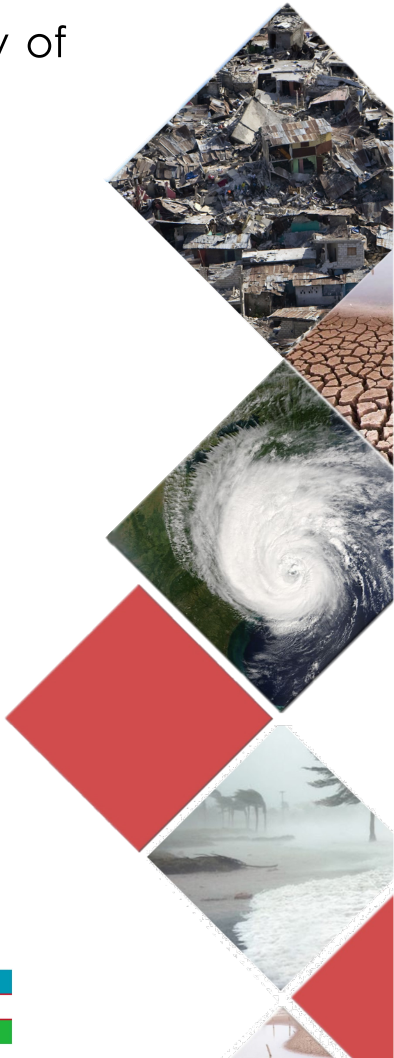
Uniform Hazard Spectra

A common goal of PSHA is to identify a design response spectrum to be used for both structural and geotechnical analysis.

Uniform **hazard spectra (UHS)** is used to represent ground motion that have an equal probability of being exceeded in a fixed time span.







Akua Capital
This project is funded by the European Union

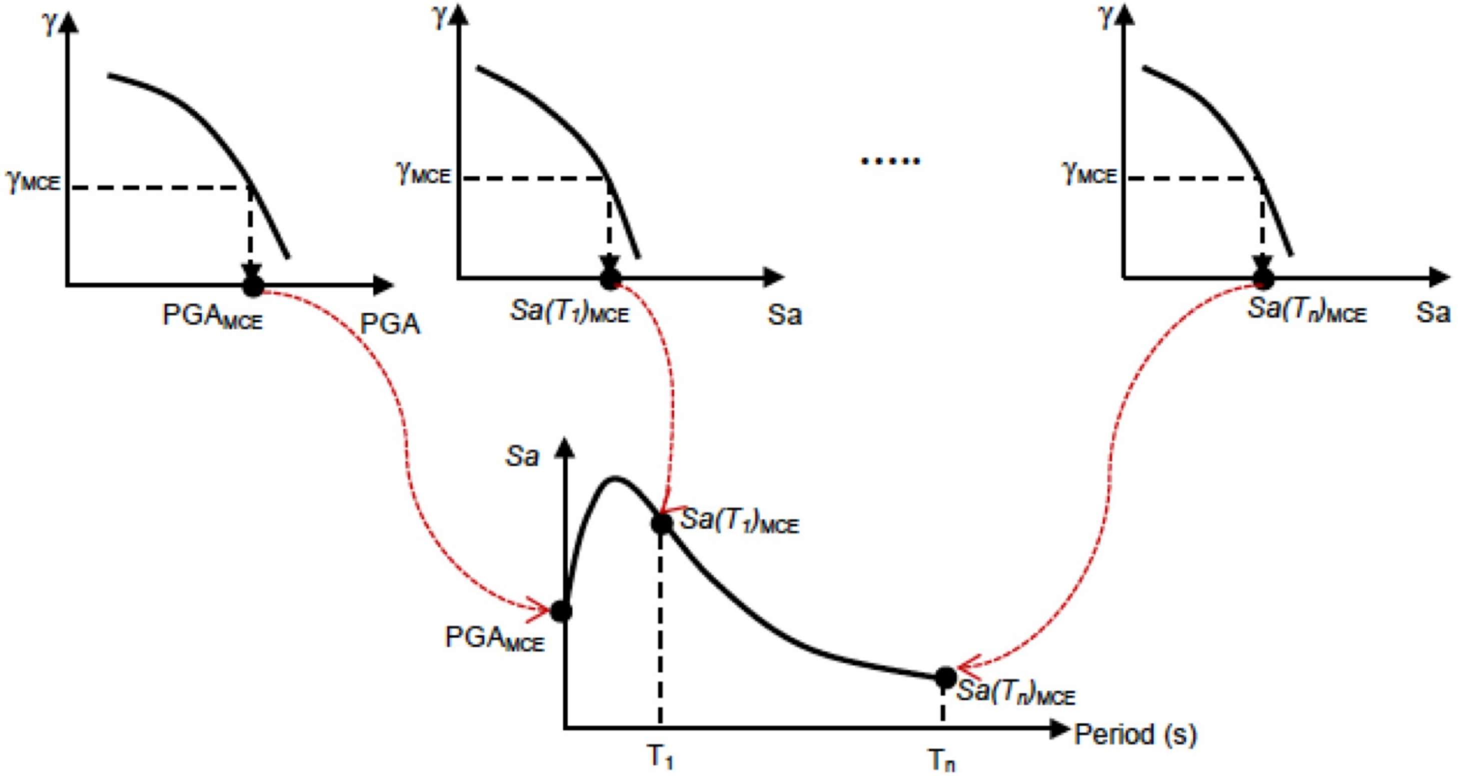
Uniform Hazard Spectra

UHS can be computed using GMPEs that support several spectral periods in the following way:

1) Choose the target return period to use for the calculation of the UHS (e.g., 475 years)

2) Compute the hazard curve for each spectral ordinate

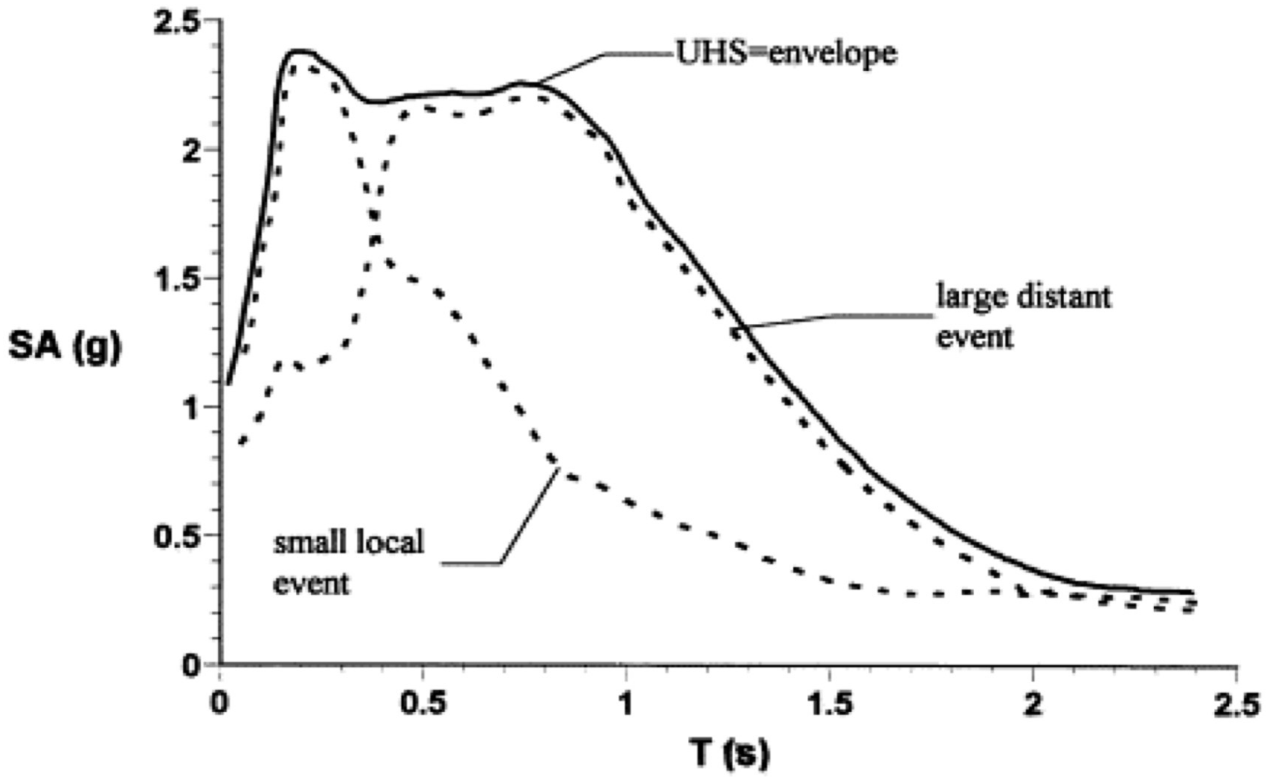
3) Select the Sa for the RP specified at point 1



This project is funded by the European Union

Uniform Hazard Spectra

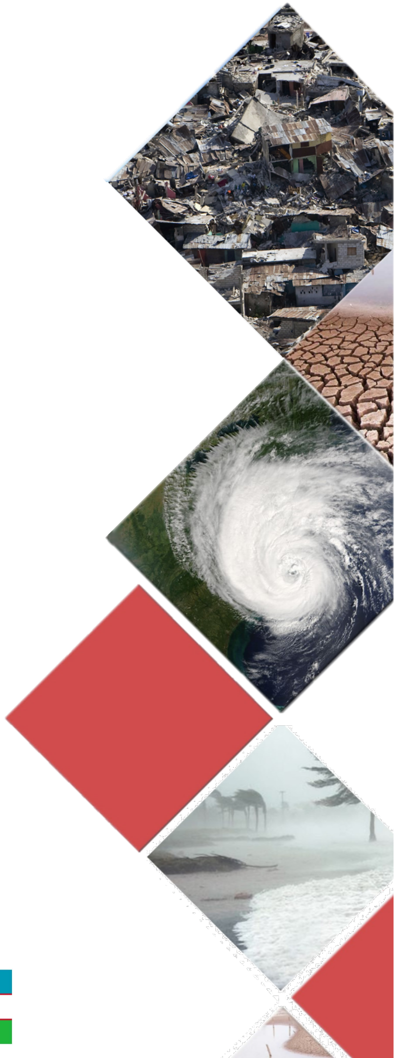
Since the hazard is computed independently for each spectral period, in general, a uniform hazard spectrum does not represent the spectrum of any single earthquake. Each "part" of the spectrum is sensitive to a generally different controlling scenario.



This project is funded by the European Union

Conclusions

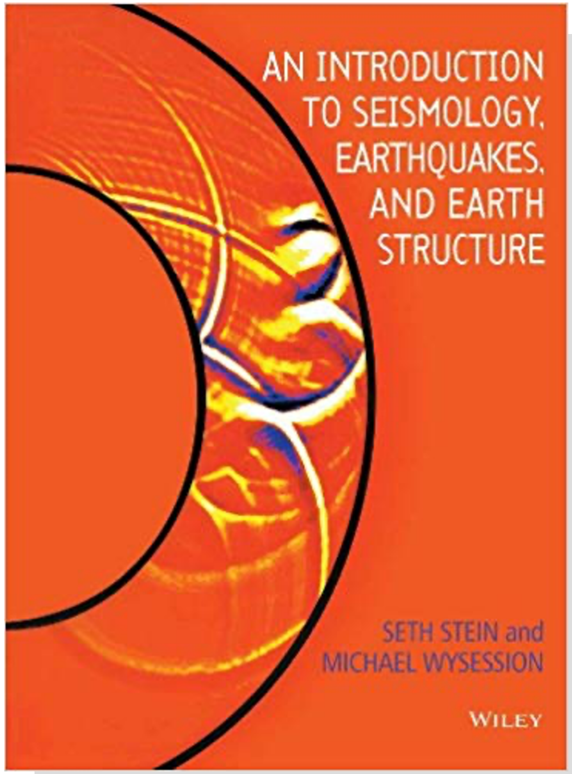
- Probabilistic Seismic Hazard Assessment (PSHA) is a powerful seismological tool to overcome the limitation of earthquake unpredictability.
- It provides engineers, insurers, decision makers and politician with a mean of evaluating the likelihood of damaging ground motion to happen, so that appropriate mitigation strategies can be applied.
- However, PSHA is a complex process, and it should be performed by experts with appropriate understanding of the matter and experience.
- PSHA itself is just a tool, and the quality of the result is highly driven be the knowledge we have for the study area and the availability of calibration data.
- Very common mistakes:
  - Mixing scales of applicability (e.g. regional and site-specific)
  - Comparison with occurrence of single events (mixing probabilistic with deterministic)

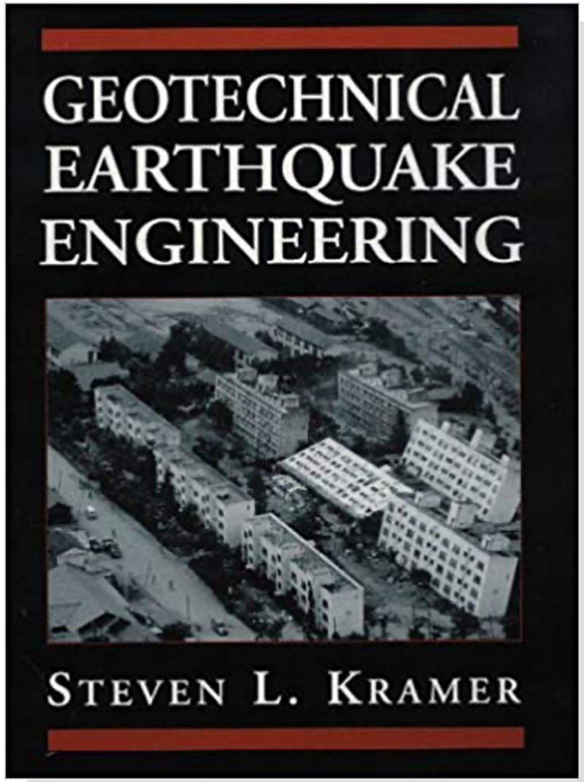


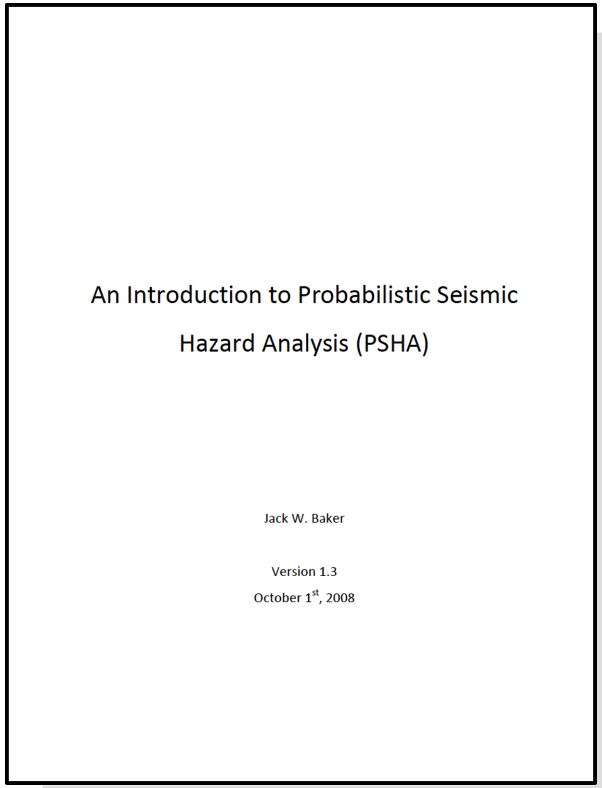
This project is funded by the European Union

Suggested textbooks and tutorials

- Stein S., and M. Wysession. An Introduction to Seismology, Earthquakes, and Earth Structure. 1st ed. Malden, MA: Blackwell, September 2002. ISBN 9780865420786.
- Kramer, S.L., Geotechnical Earthquake Engineering, Prentice Hall, 1996, ISBN 0133749436



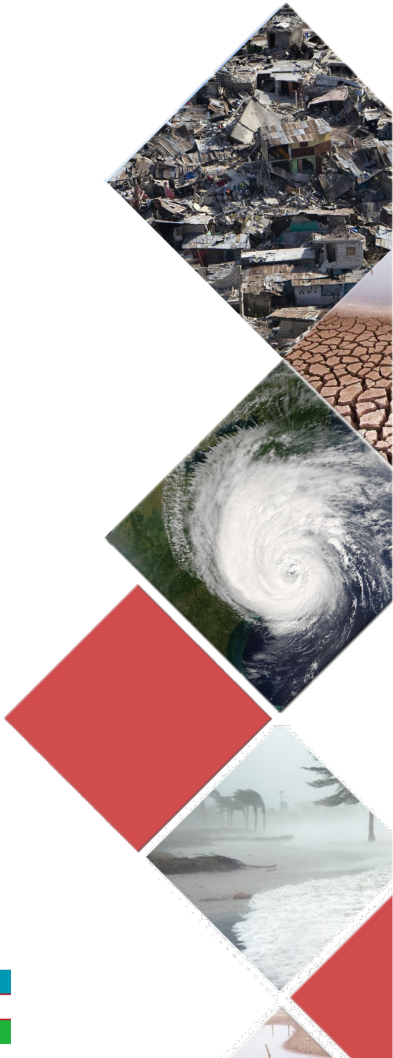



An Introduction to Probabilistic Seismic Hazard Analysis (PSHA)

Jack W. Baker

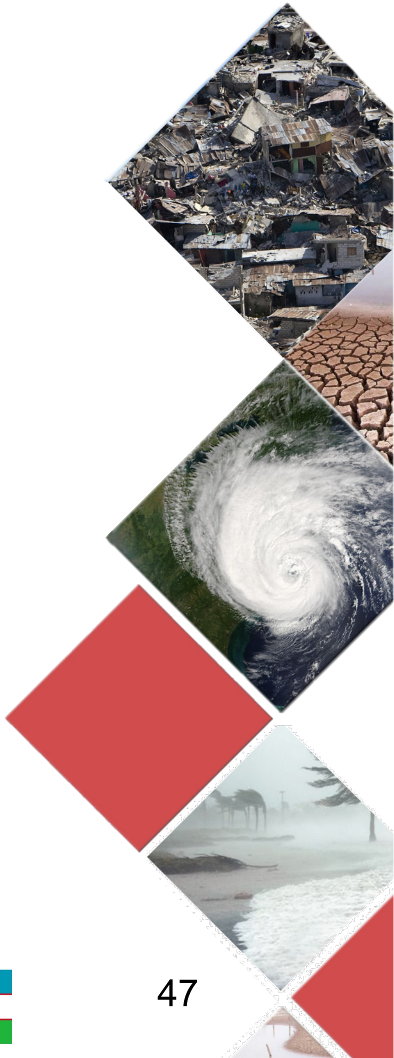
Version 1.3

October 1st, 2008



This project is funded by the European Union

Thank you very much for your attention!



This project is funded by the European Union