GEM

GLOBAL
EARTHQUAKE
MODEL

working
together to
assess
risk

Introduction to
Seismic Hazard Analysis

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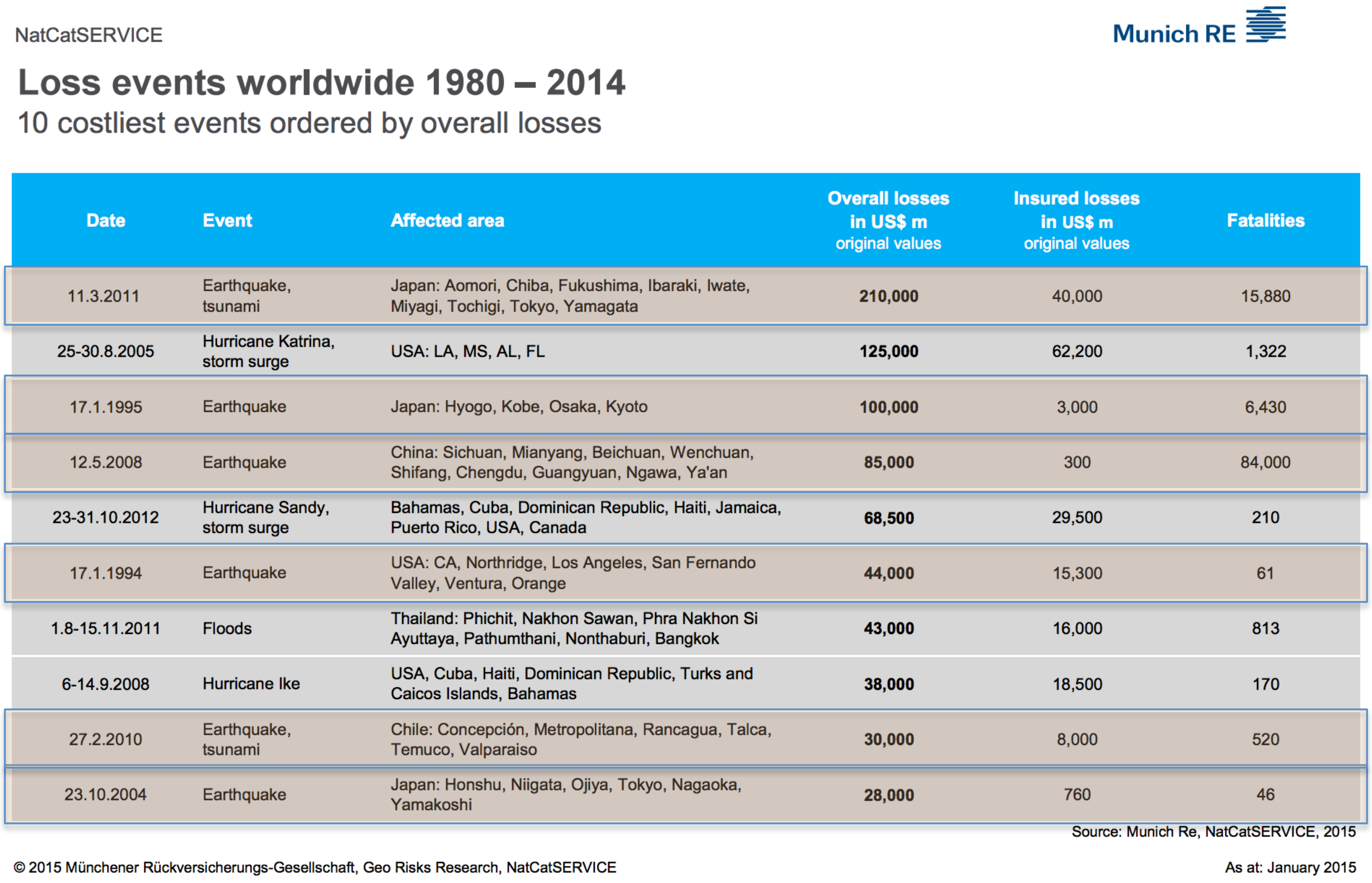
Global Earthquake Model (GEM), Pavia Italy

Addis Ababa, 29 June 2016

OPENQUAKE

Earthquake Hazard – A widespread danger

Earthquakes are one of the most costly natural hazards worldwide



NatCatSERVICE

Munich RE

Loss events worldwide 1980 – 2014

10 costliest events ordered by overall losses

Date	Event	Affected area	Overall losses in US$ m original values	Insured losses in US$ m original values	Fatalities
11.3.2011	Earthquake, tsunami	Japan: Aomori, Chiba, Fukushima, Ibaraki, Iwate, Miyagi, Tochigi, Tokyo, Yamagata	**210,000**	40,000	15,880
25-30.8.2005	Hurricane Katrina, storm surge	USA: LA, MS, AL, FL	**125,000**	62,200	1,322
17.1.1995	Earthquake	Japan: Hyogo, Kobe, Osaka, Kyoto	**100,000**	3,000	6,430
12.5.2008	Earthquake	China: Sichuan, Mianyang, Beichuan, Wenchuan, Shifang, Chengdu, Guangyuan, Ngawa, Ya'an	**85,000**	300	84,000
23-31.10.2012	Hurricane Sandy, storm surge	Bahamas, Cuba, Dominican Republic, Haiti, Jamaica, Puerto Rico, USA, Canada	**68,500**	29,500	210
17.1.1994	Earthquake	USA: CA, Northridge, Los Angeles, San Fernando Valley, Ventura, Orange	**44,000**	15,300	61
1.8-15.11.2011	Floods	Thailand: Phichit, Nakhon Sawan, Phra Nakhon Si Ayuttaya, Pathumthani, Nonthaburi, Bangkok	**43,000**	16,000	813
6-14.9.2008	Hurricane Ike	USA, Cuba, Haiti, Dominican Republic, Turks and Caicos Islands, Bahamas	**38,000**	18,500	170
27.2.2010	Earthquake, tsunami	Chile: Concepción, Metropolitana, Rancagua, Talca, Temuco, Valparaiso	**30,000**	8,000	520
23.10.2004	Earthquake	Japan: Honshu, Niigata, Ojiya, Tokyo, Nagaoka, Yamakoshi	**28,000**	760	46

Source: Munich Re, NatCatSERVICE, 2015

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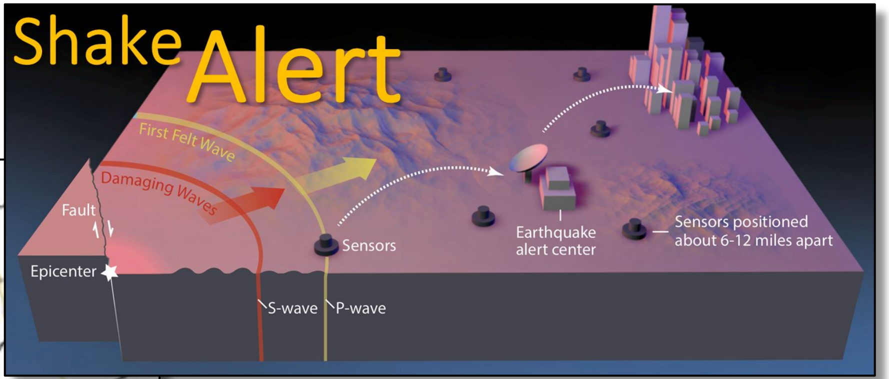
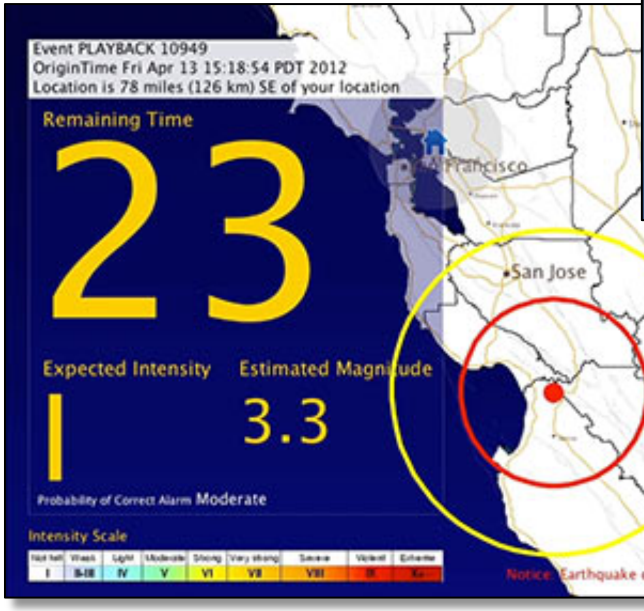
As at: January 2015

Earthquake Hazard – Forecasting

Reduction of fatalities could ideally be carried out through short-term forecasting with:

- Analysis of precursors (highly debatable)
- Early warning systems (large investment, practical limitations)




Event PLAYBACK 10949
OriginTime Fri Apr 13 15:18:54 PDT 2012
Location is 78 miles (126 km) SE of your location

Remaining Time
23

Expected Intensity
I

Estimated Magnitude
3.3

Probability of Correct Alarm Moderate

Intensity Scale

Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
I	II-III	IV	V	VI	VII	VIII	IX	X+

Notice: Earthquake data may be prelimina

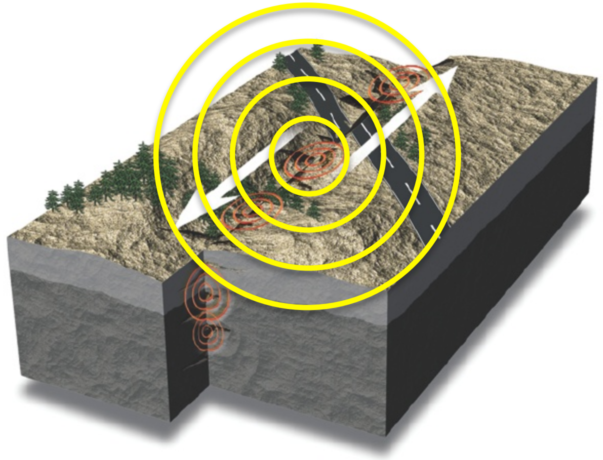
USGS ShakeAlert
EEW Program

Earthquake Hazard – Ground Shaking Level

Reduction of losses should 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**

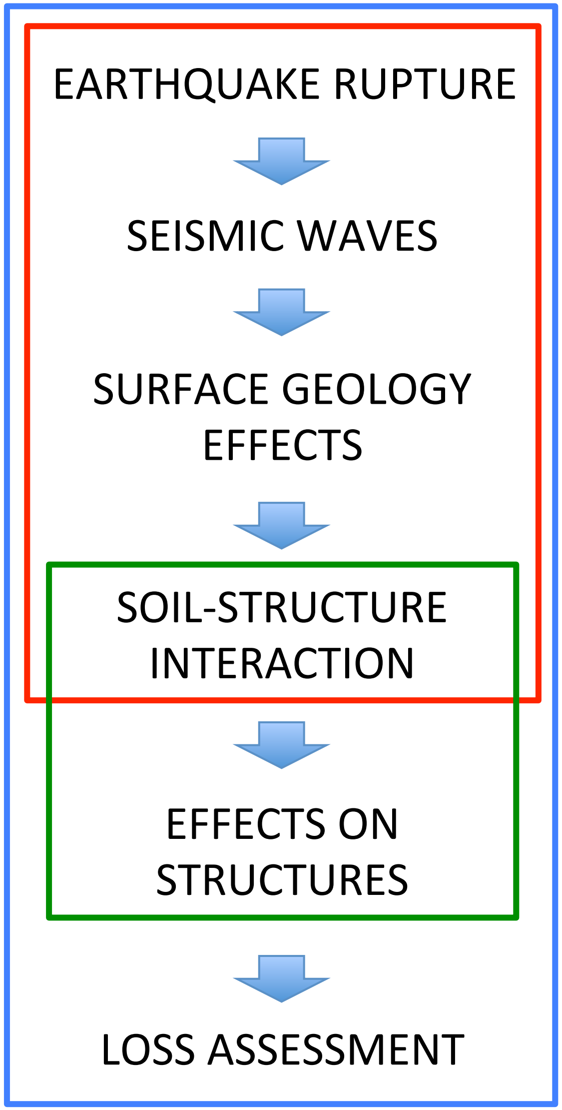
Question is: how and how precisely this level can be defined, given the little knowledge we have of the earthquake process?



http://www.howitworksdaily.com/

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

Earthquake Hazard and Risk



EARTHQUAKE RUPTURE

SEISMIC WAVES

SURFACE GEOLOGY EFFECTS

SOIL-STRUCTURE INTERACTION

EFFECTS ON STRUCTURES

LOSS ASSESSMENT

Seismic Hazard is therefore an essential component of Earthquake Risk Assessment

$$R = H * E * V$$

Seismic Hazard (H)

Physical Vulnerability (V)
Exposure/Inventory (E)

Risk (R)

End-Users Perspective

1) Engineers

- For what level of ground motion should I design my structure?
- What are the possible earthquake scenarios that may pose a threat to my structure?
- The Building Standard says I should ensure this performance level – how do I know how resistant to make my structure to ensure this?
- What if I want to achieve different performance objectives (e.g. “operational”, “life-safety”, “no-collapse”)?

2) Insurers

- What is the probability of my exceeding X amount of loss from my portfolio in the next T years?
- The Catastrophe Bond will trigger when “… earthquake occurs in this cell … ground shaking exceed this value here…” – how likely is this to happen?

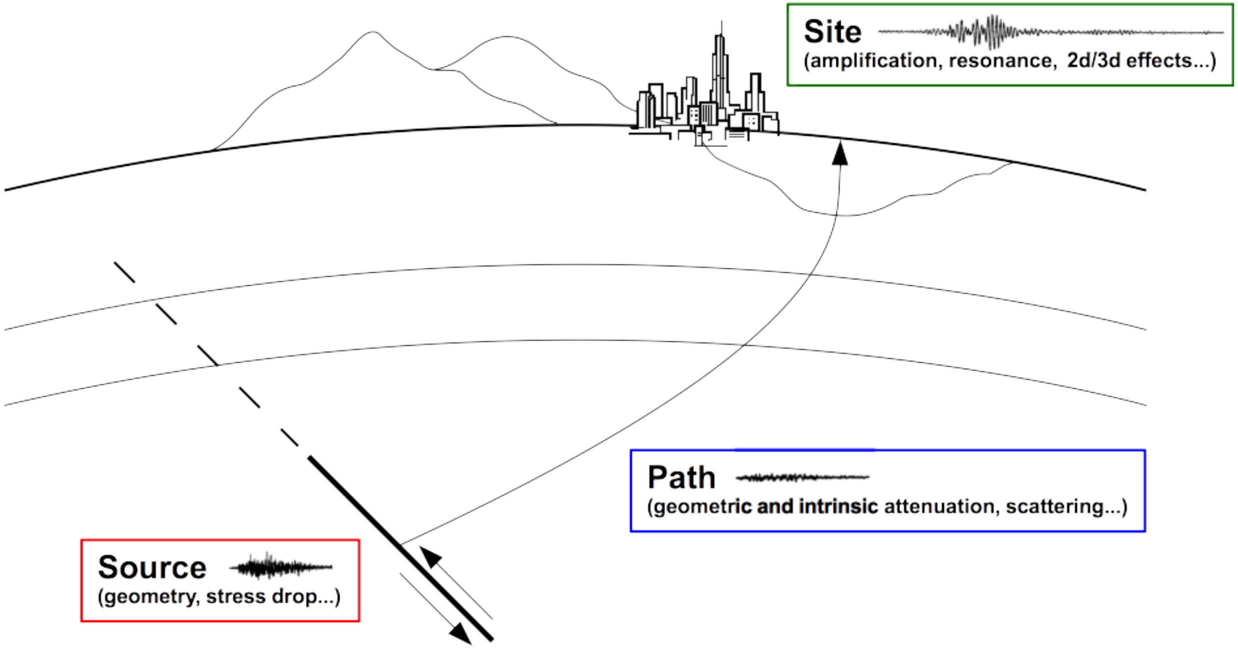
3) Decision Makers & Public

- Will this property be damaged/destroyed?
- How likely is this to happen?
- What is the best course of action to take (cost-benefit)?
- What sort of earthquakes can occur? What might happen when they do?

SHA Requirements

For the calculation of hazard associated to a region is essential to know:

- **Where** the earthquakes occur and the geometry of the seismic sources
- **How often** earthquakes occur on each seismic source
- **The size** of the earthquakes generated by each source
- **Mechanical properties** of geological materials through which seismic waves will propagate (including surface geology)



Deterministic vs. Probabilistic Approach

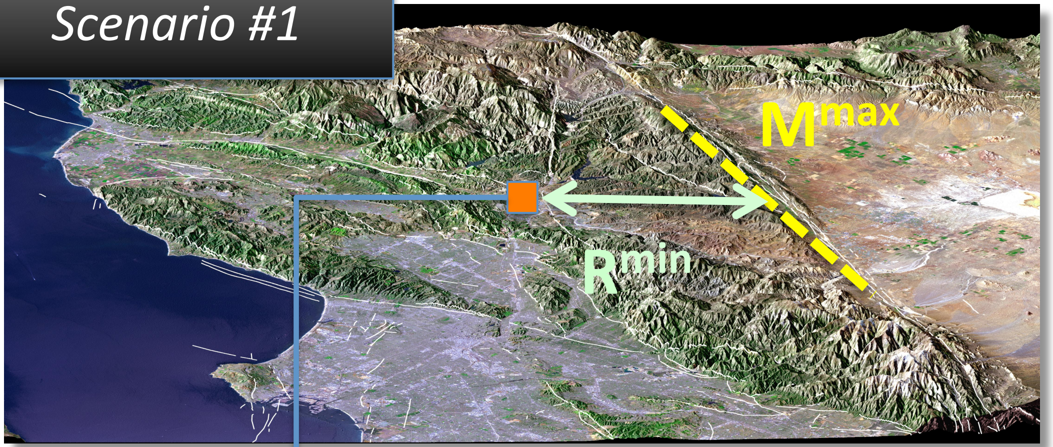
Two are the main methodologies currently adopted for seismic hazard analysis:

Deterministic. Also called the "*Worst Case Scenario*"
One or a few earthquake 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 taking into account their probability of occurrence i.e. all ruptures (magnitude+distance) and levels of uncertainty on ground motion.

Deterministic Approach – Defining the “worst case”

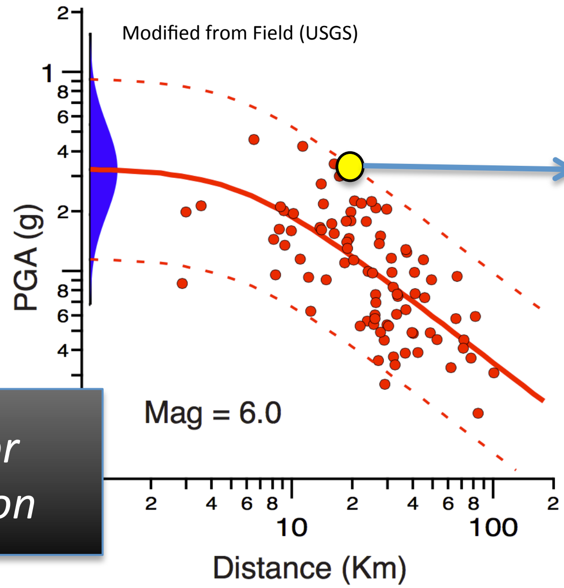
Scenario #1



http://eoimages.gsfc.nasa.gov

Many issues:

- Largest earthquake in the source?
- Closest earthquake to source?
- Worst possible or plausible scenario?

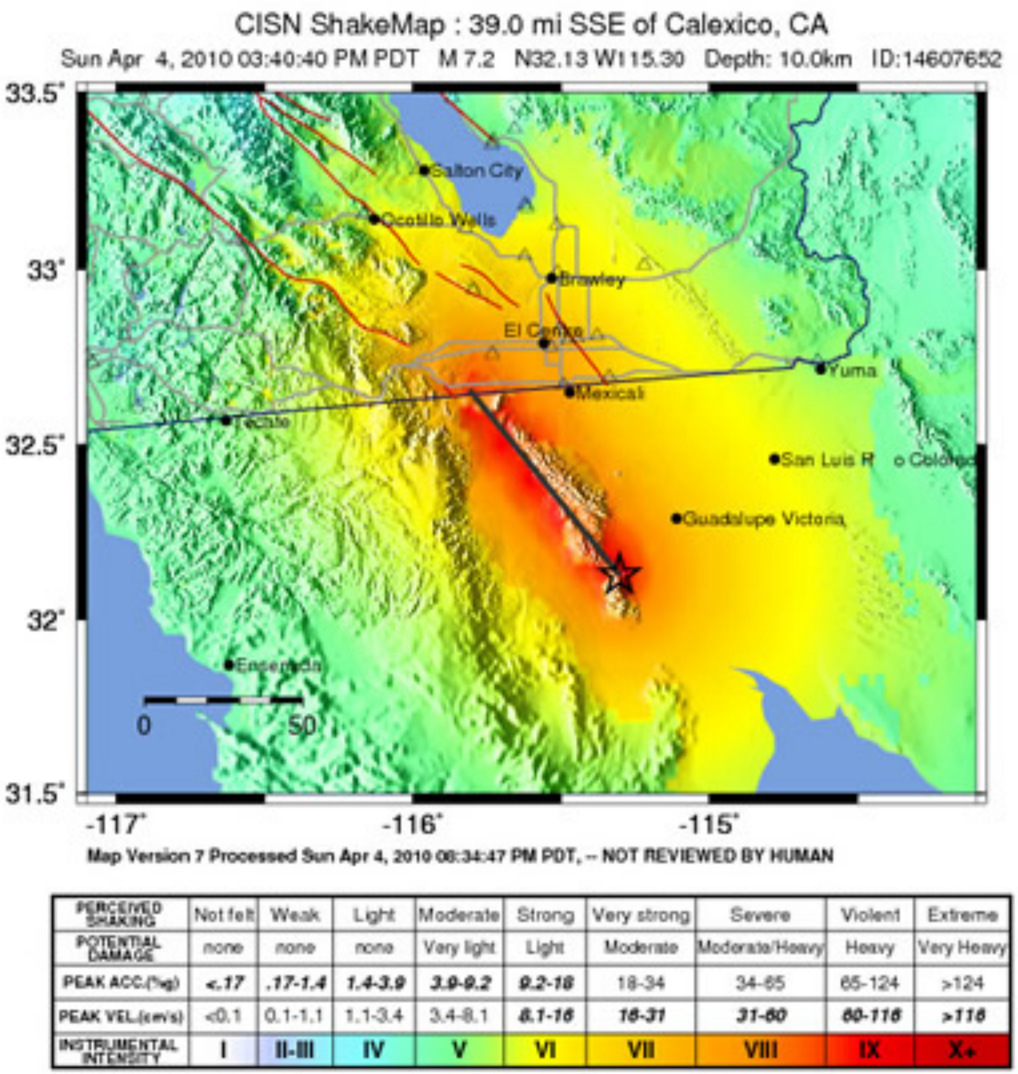


Modified from Field (USGS)

PGA @ 20Km + σ

GMPE or Simulation

Scenario Models - ShakeMap Example



CISN ShakeMap : 39.0 mi SSE of Calexico, CA

Sun Apr 4, 2010 03:40:40 PM PDT M 7.2 N32.13 W115.30 Depth: 10.0km ID:14607652

Map Version 7 Processed Sun Apr 4, 2010 08:34:47 PM PDT, -- NOT REVIEWED BY HUMAN

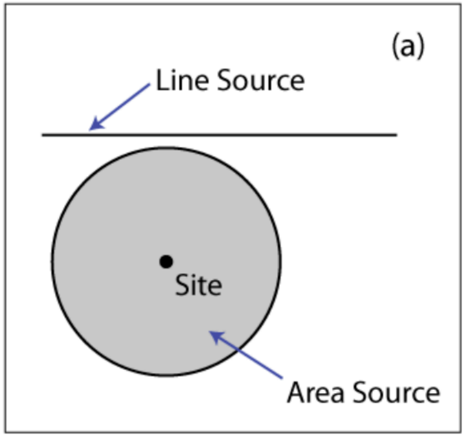
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1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

PSHA - Basic Workflow

Probabilistic hazard is computed by taking into account **all the possible scenarios** generated by all the sources within a certain distance from the investigated site

Where

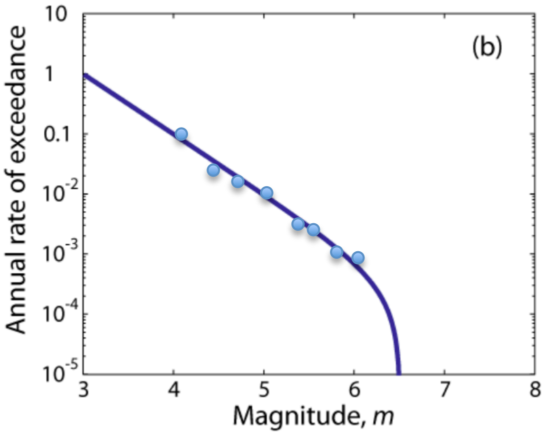
Seismogenic Zone Models



Modified from Baker (2008)

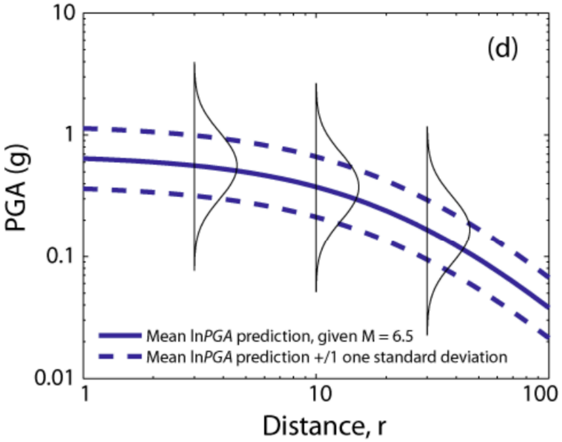
When (how often)

Recurrence Models



How

Ground Motion Models



PSHA – Basic Equation

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:

$$\lambda(IM > x) = \sum_{i=1}^{n_{sources}} \lambda(M_i > m_{\min}) \int_{m_{\min}}^{m_{\max}} \int_{r_{\min}}^{r_{\max}} \underline{P(IM > x \mid m,r)}\, \underline{f_{M_i}(m)}\, \underline{f_{R_i}(r \mid m)}\, dr\,dm$$

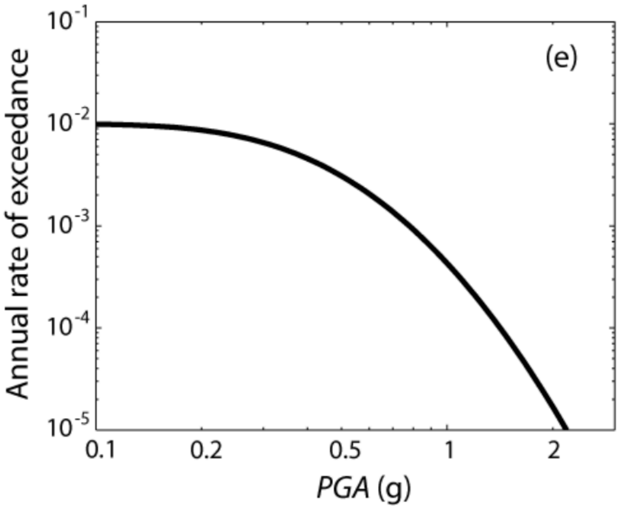
Loop over distances

Loop over magnitudes

Loop over sources

The annual rate λ is then translated into probability by assuming a **Poisson recurrence model** (independent events):

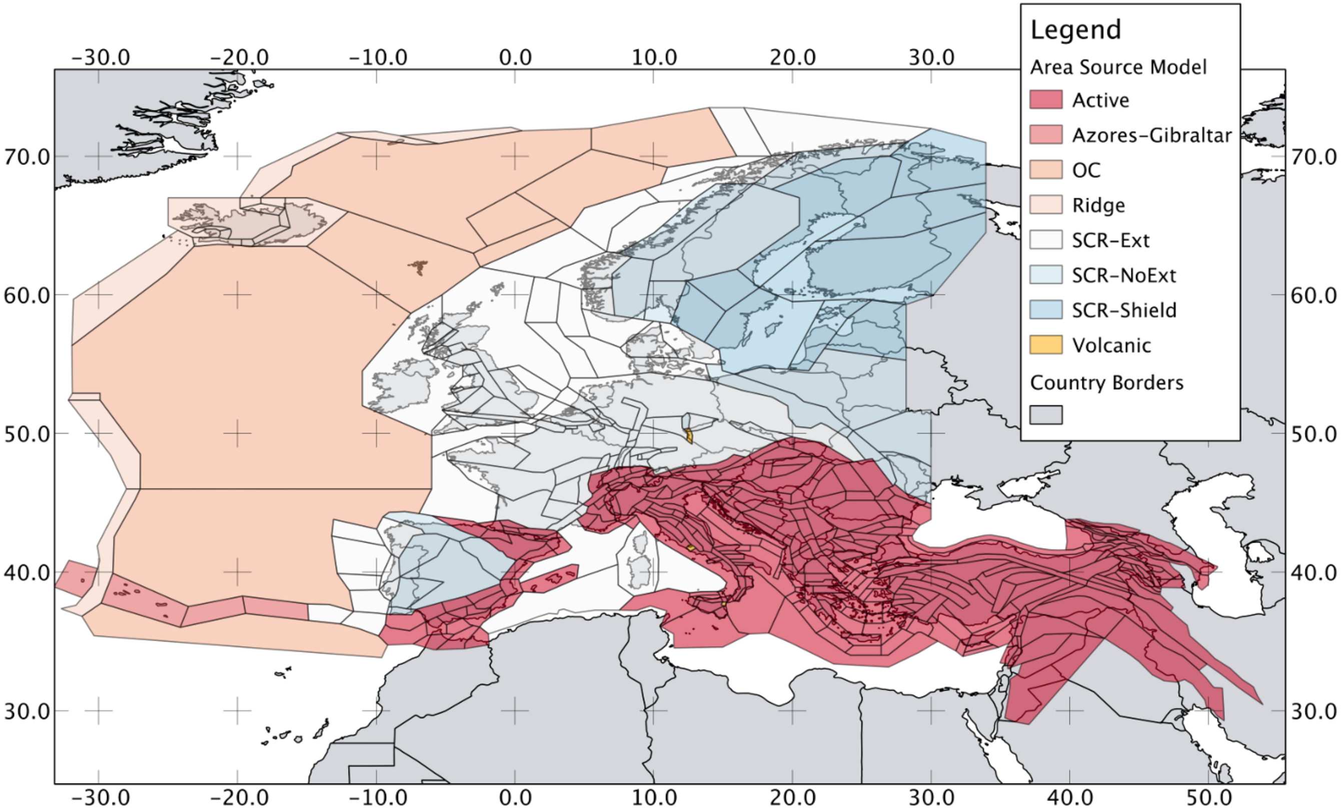
$$P(IM > x) = 1 - e^{-\lambda(IM > x)t}$$



Seismogenic Zones

Distributed Seismicity:

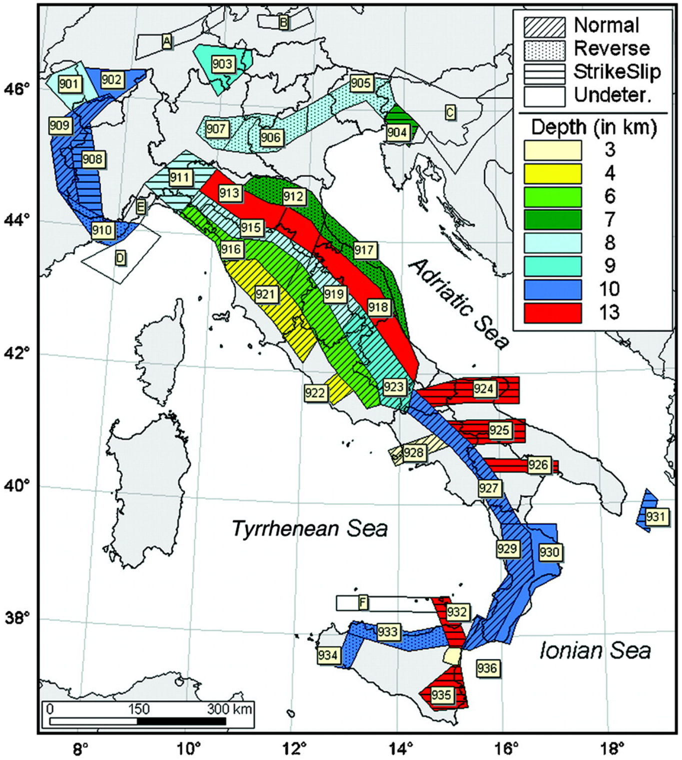
- Single points
- Grid representations (e.g. smoothed seismicity)
- Polygon of Uniform Seismicity (so far the most widely used approach)



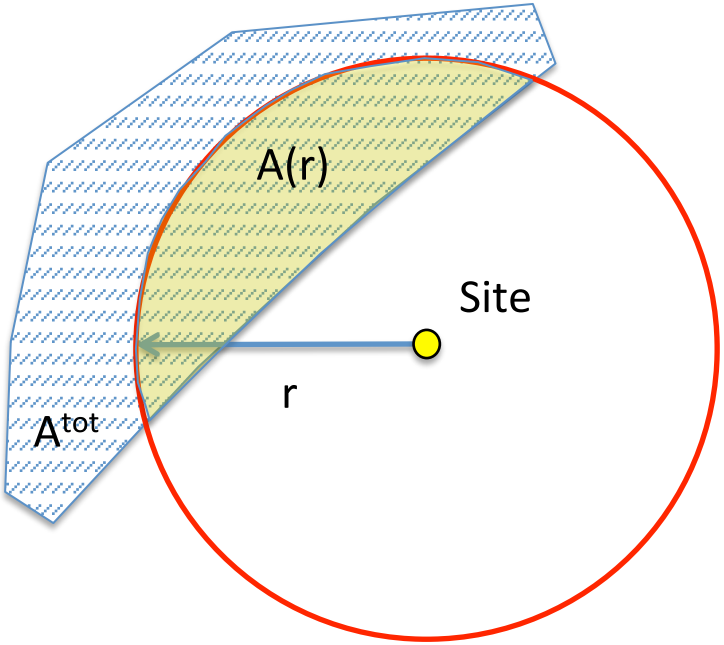
SHARE Area Source Zonation Model

Area Sources Zones

Uniform Area Source Model of Italy
(modified from Meletti et al., 2008)



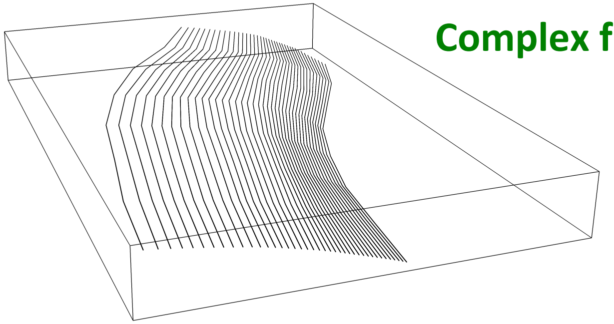
Source Zone 1



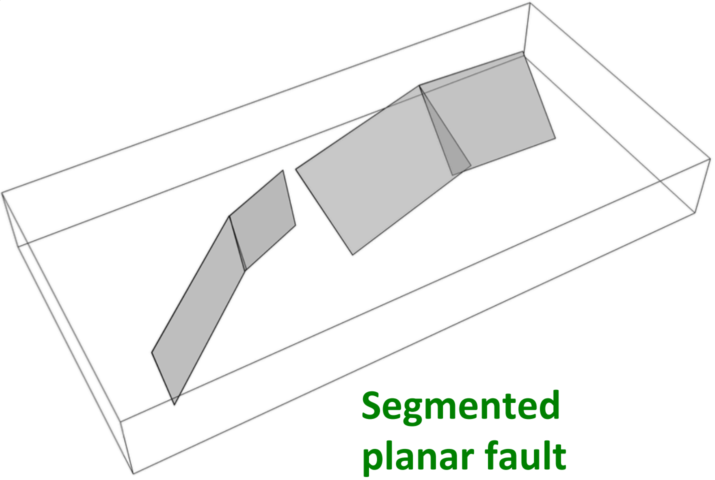
The cumulative probability $P(R < r)$ can be seen as the area of the sub-zone within a distance r from the site, divided by the area of the total source zone

Active Faults

- If fault geometry is sufficiently known, it can be modeled as a three-dimensional surface
- Such approach can be used for active shallow faults as well as larger subduction interfaces

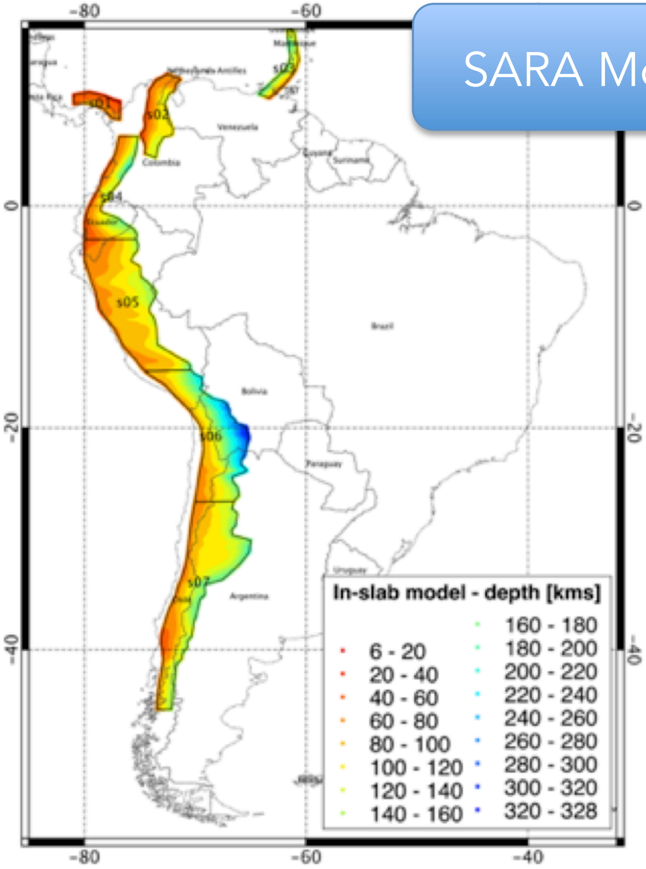


Complex fault



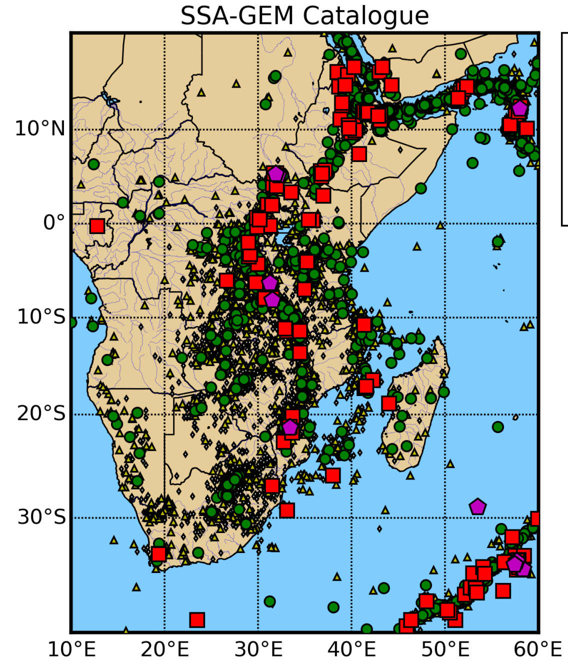
Segmented planar fault

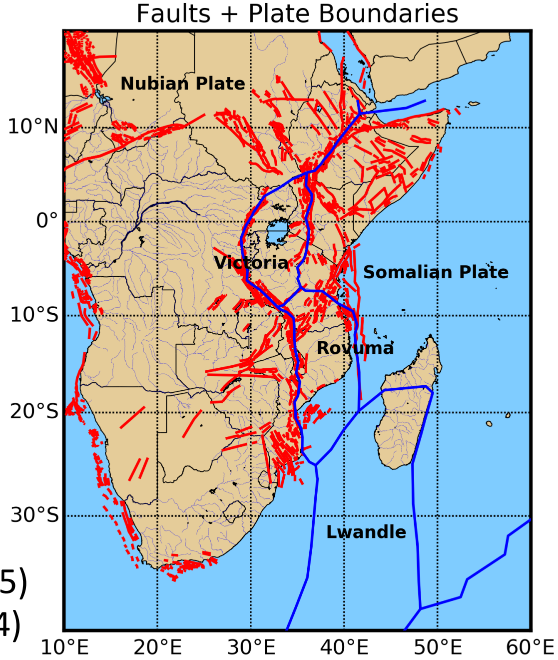
SARA Model

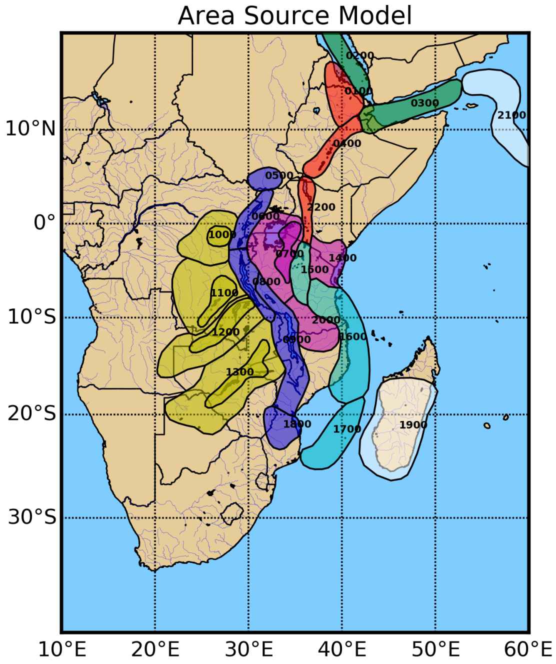


Building a Seismic Source Model

- Primary data resource is the **homogenized earthquake catalogue**
- Models of recurrence often determined from observed (instrumental and historical seismicity) within the source


SSA-GEM Catalogue


Faults + Plate Boundaries

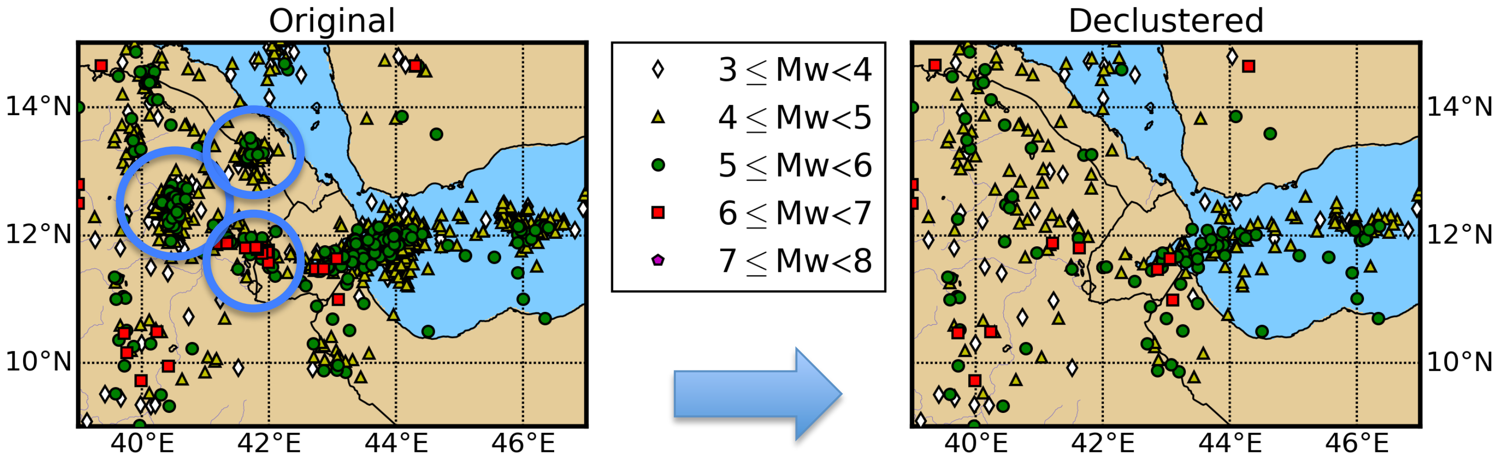

Area Source Model

Macgregor (2015)
Saria et al. (2014)

Seismicity Analysis

To obtain estimates of stationary seismicity rates the recurrence models need to be fit to earthquake catalogues that are:

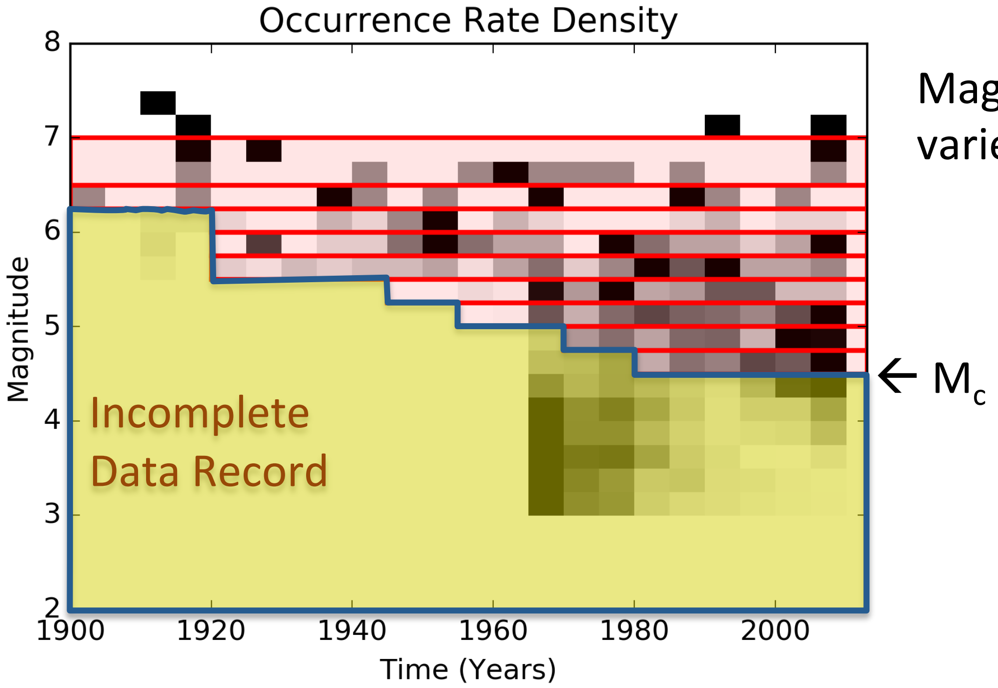
1) Purged of non-Poissonian Events (i.e. foreshocks and aftershocks) which are dependent ➔ **Declustering**



Seismicity Analysis

2) Spatially and temporally complete (i.e. are recording all events above a given magnitude for a particular space-time window)

➔ **Completeness Analysis**



Magnitude of completeness varies as function of time

Magnitude occurrence relations

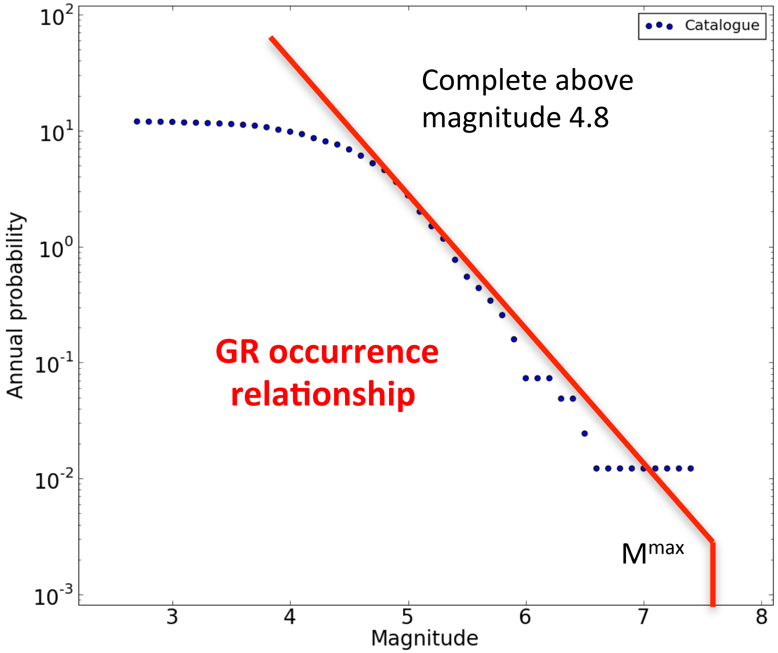
Temporal distribution of seismicity is modeled assuming a given magnitude occurrence relation

The most widely used relation is the **Gutenberg-Richter exponential law**:

$$N(M > m) = \mathrm{e}^{a-bM}$$

Calibration of coefficients ***a*** and ***b*** is a key issue in PSHA

5.23 earthquakes above magnitude 4.8 per year

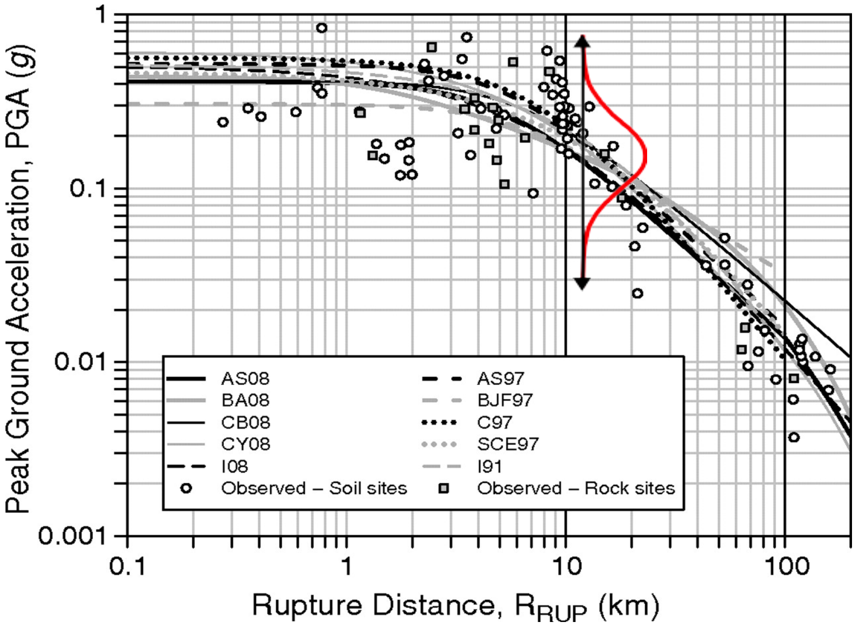


Recurrence models typically fit to catalogue using maximum likelihood techniques

Ground Motion Modeling

The easiest way to model ground motion is perhaps the use of Ground Motion Prediction Equations (GMPEs)

$$\log IM_{ij} = f\left(M_i\right) + f\left(R_{ij}, M_i\right) + f\left(R_{ij}\right) + f\left(S_j\right) + f\left(F_{ij}\right) + z_{E,i}\tau + z_{A,ij}\sigma$$



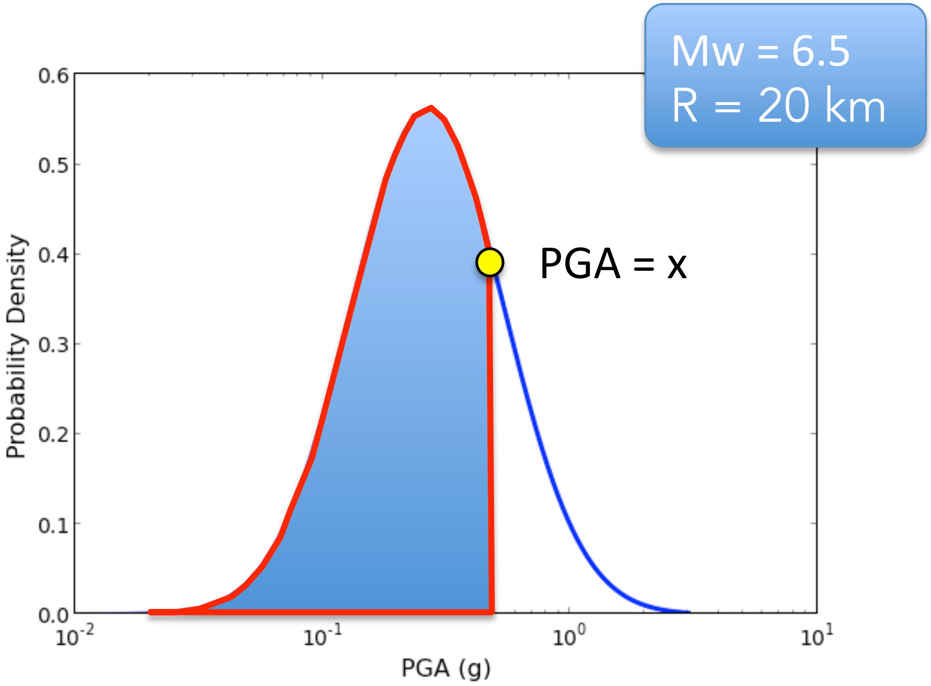
GMPE terms are representations of a given physical model, whose reliability can be increased with the availability of new empirical information

$$IM = PGA, PGV, SA...$$

Ground Motion Prediction

A fundamental property of GMPEs is the assumption that the aleatory variability can be represented by a **lognormal distribution** characterized by a **median** ground motion and the corresponding **standard deviation**

P(IM > x | M, R) can then be easily determined as the probability that IM will exceed the value x



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 is connected with 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: aleatory uncertainty is irreducible whereas epistemic uncertainty can be potentially reduced

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

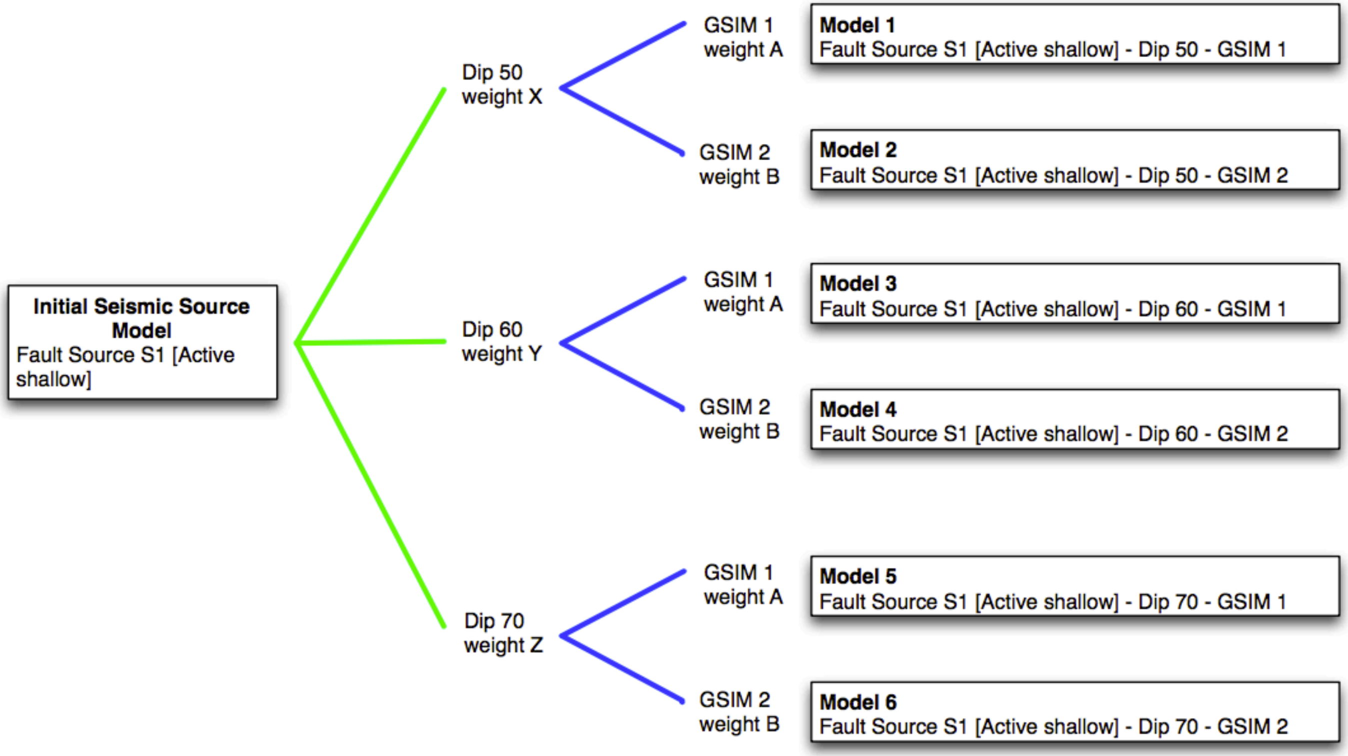
Examples: Earthquake location, uncertainty on ground motion estimates

2) Epistemic uncertainty is formally taken into account by using alternative models (or parameterizations) within a logic-tree structure

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

Logic- Tree Strategy – Weights and Branches

Epistemic uncertainties modeled by including multiple models in logic trees
Each model is assigned weights



Initial Seismic Source Model
Fault Source S1 [Active shallow]

Model 1
Fault Source S1 [Active shallow] - Dip 50 - GSIM 1

Model 2
Fault Source S1 [Active shallow] - Dip 50 - GSIM 2

Model 3
Fault Source S1 [Active shallow] - Dip 60 - GSIM 1

Model 4
Fault Source S1 [Active shallow] - Dip 60 - GSIM 2

Model 5
Fault Source S1 [Active shallow] - Dip 70 - GSIM 1

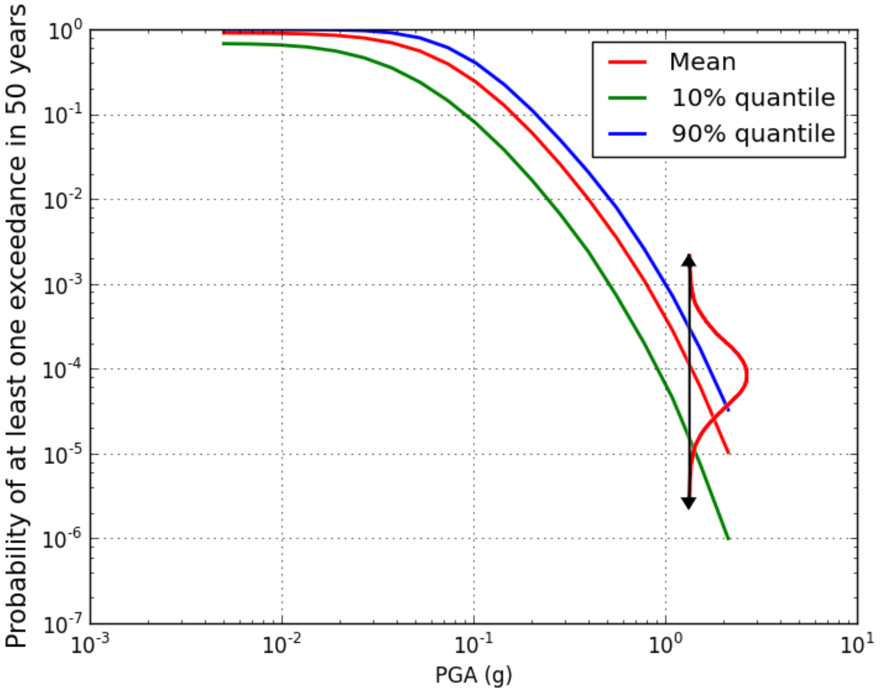
Model 6
Fault Source S1 [Active shallow] - Dip 70 - GSIM 2

How to assign weights?

- Based on fits to observed data? (**Empirical approach**)
- Based on theoretical representation of the physics of the process? (**Physical approach**)

Logic-Tree Strategy – 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

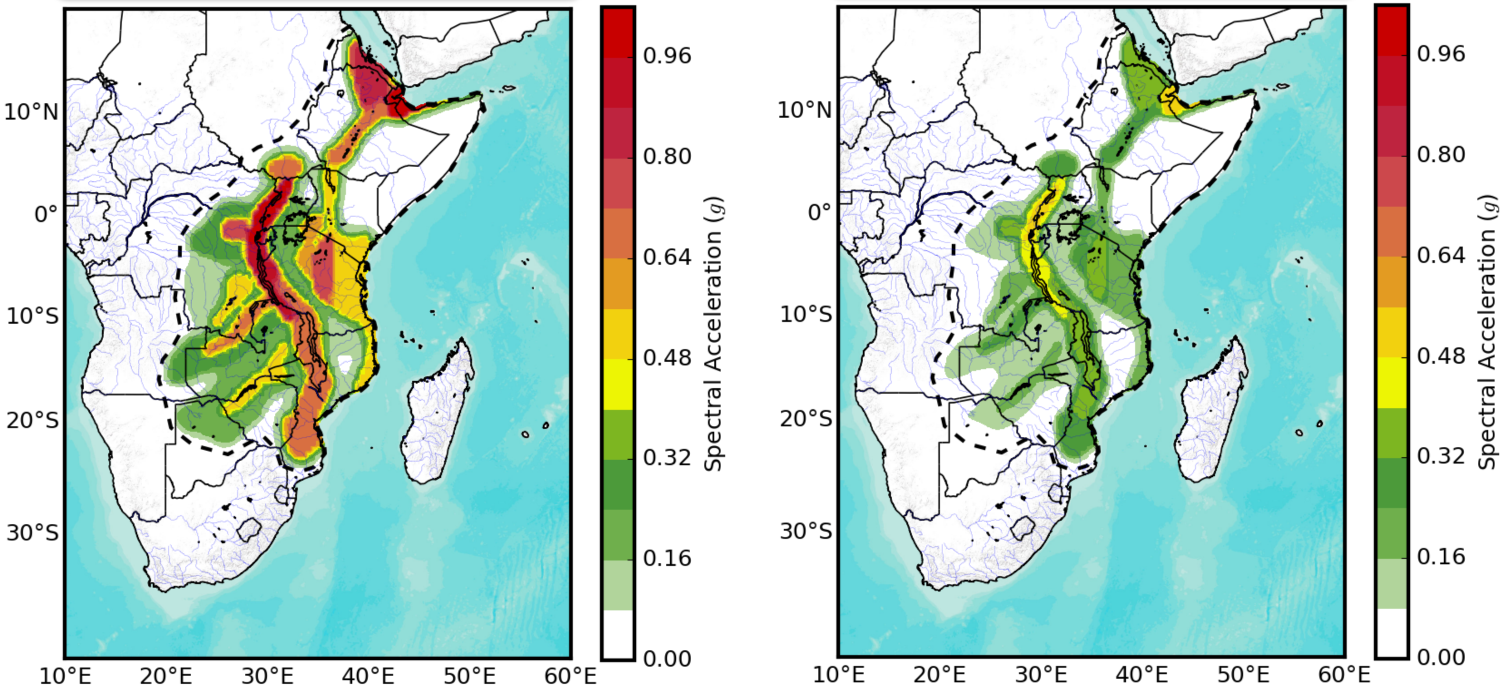
HOWEVER

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

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

PSHA Outputs – Hazard Maps

Shows the uniform probability of exceedance of a given ground motion measure for a given return period

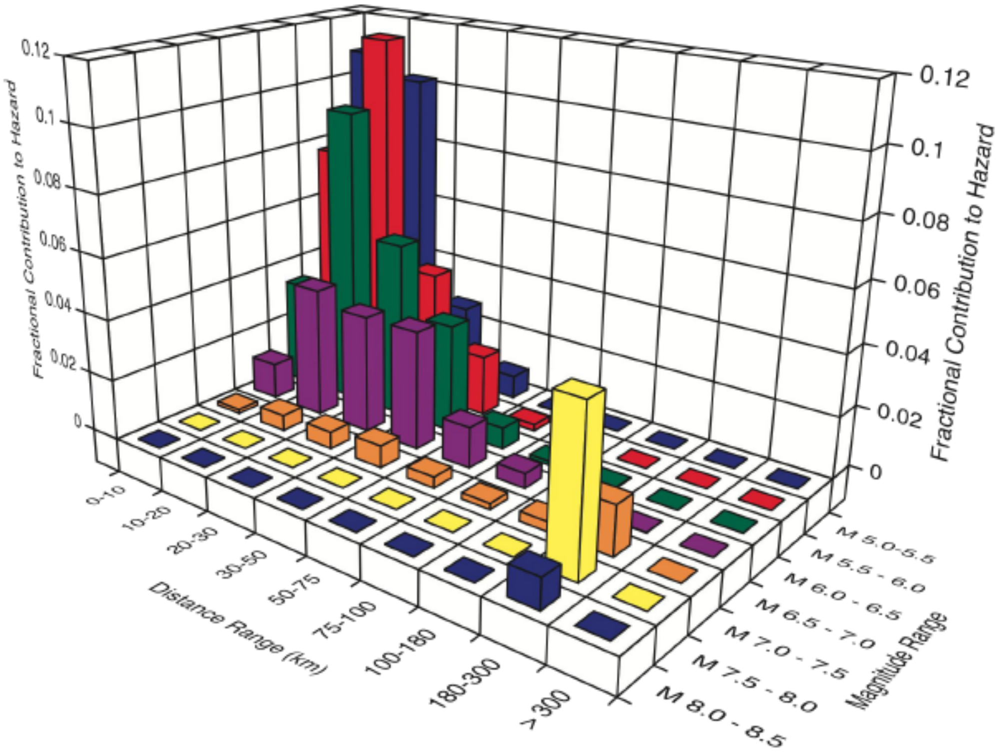

2% Probability in 50 years

10% Probability in 50 years

Spectral Acceleration @ 2 seconds

PSHA Outputs - Disaggreagation

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



Can identify scenarios that represent the greatest likelihood of contributing to the hazard

Thank you!

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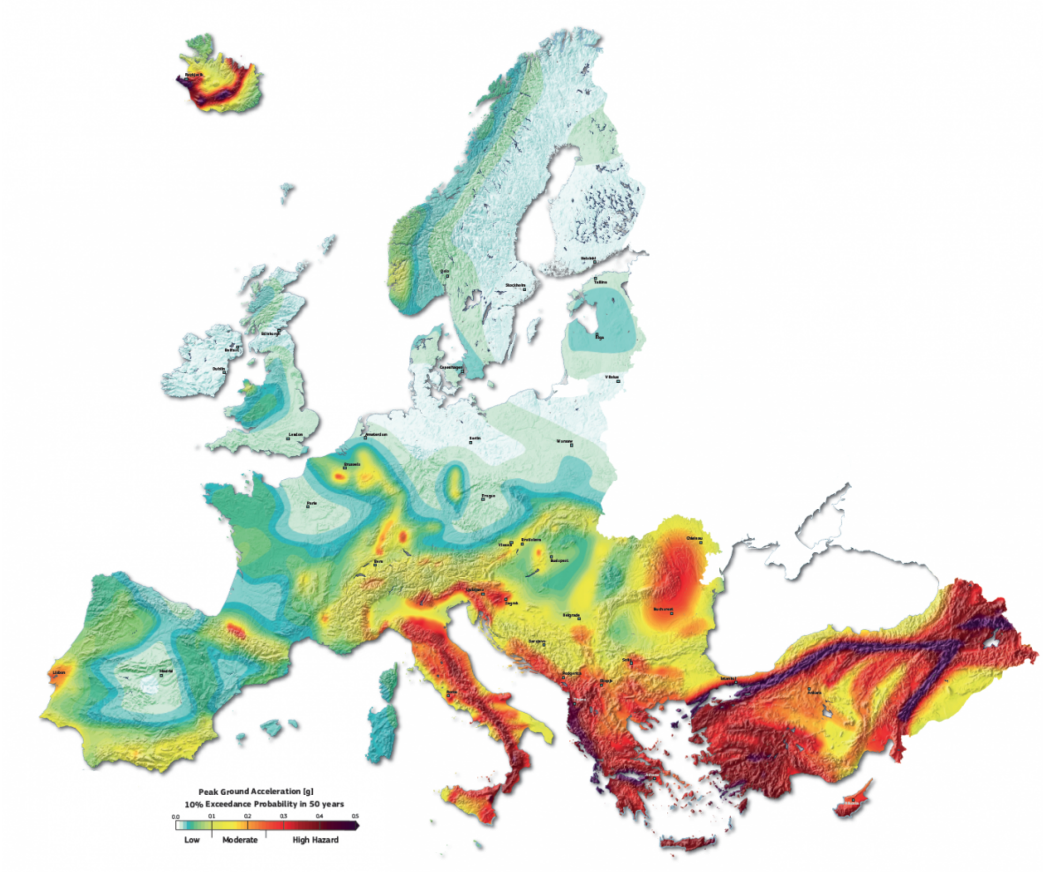
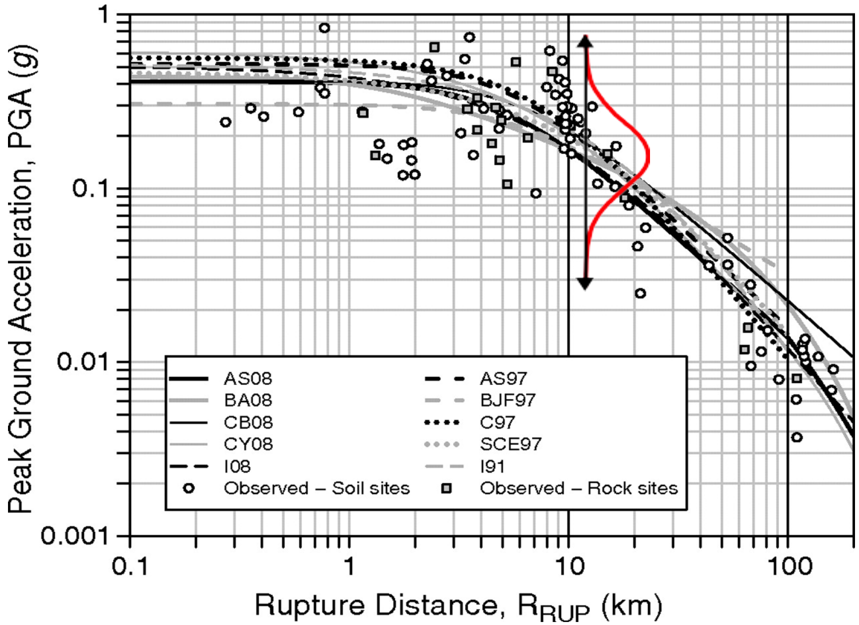

London
Amsterdam
Copenhagen
Vilnius
Berlin
Warsaw
Brussels
Paris
Prague
Vienna
Bratislava
Budapest
Bern
Chisinau
Ljubljana
Zagreb
Belgrade
Bucharest
Sarajevo
Sofia
Podgorica
Skopje
Istanbul
Peak Ground Acceleration [g]
10% Exceedance Probability in 50 years
0.0
0.1
0.2
0.3
0.4
0.5
Low
Moderate
High Hazard

Ground Motion Prediction

The easiest way to model ground motion is perhaps the use of Ground Motion Prediction Equations (GMPEs)

$$\Omega_{ij}(f,r) = \underbrace{\omega \cdot \Omega_i \cdot f_c^{\gamma}/(f_c^{\gamma} + f^{\gamma})}_{\text{Source Spectrum}} \cdot \underbrace{S_{ij}(r) \cdot \exp(-\pi \cdot f^{1-\alpha} \cdot t_{ij}^{*})}_{\text{Path Effects}} \cdot \underbrace{A_j(f) \cdot \exp(-\pi \cdot f^{1-\alpha} \cdot K_j)}_{\text{Site Effects}}$$



GMPE terms are representations of a given physical model, whose reliability can be increased with the availability of new empirical information

Logic-Tree Strategy – Over Reliance?

The problem:

- Less data/knowledge implies greater epistemic uncertainty
- But if considering published (e.g. peer-reviewed) models, usually the case that more models will be available from regions with more data (e.g. more GMPEs for active shallow crust than for stable crust)
- More use of more available models increases epistemic uncertainty in regions with more data, and therefore epistemic uncertainty is lower in regions with less data!
- Need for a “minimum generic uncertainty” for regions with sparse data