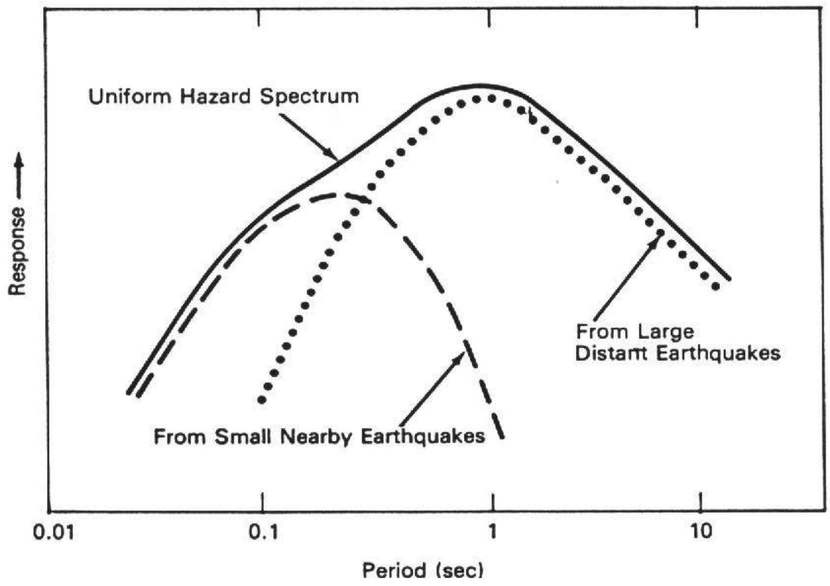
FACOLTA' DI INGEGNERIA DELL'UNIVERSITA' DEGLI STUDI ROMA III

Laurea specialistica in protezione del territorio dai rischi naturali

Corso di costruzioni in zona simica
Modulo di SISMOLOGIA



F.Sabetta

9. Calcolo della pericolosità
Spettri a pericolosità uniforme
Disaggregazione della pericolosità
Valutazione delle incertezze
Probabilistica vs. deterministica

Anno accademico 2017//18

Summary

PSHA computation

The effects of all the earthquakes of different sizes, occurring at different locations, in different earthquake sources, at different probabilities of occurrence, are integrated into **seismic hazard curves** that show the probability of exceeding different values of a selected ground motion parameter (e.g. PGA) at the site, during a specified period of time. For a given source the probability that a ground motion parameter **Y** will exceed a particular value **y*** is given by:

$$P[Y > y^*] = \int_{m_0}^{m_{max}} \int_{r_{min}}^{\infty} P[Y > y^* | m,r] \cdot f_M(m) \cdot f_R(r) \cdot dmdr$$

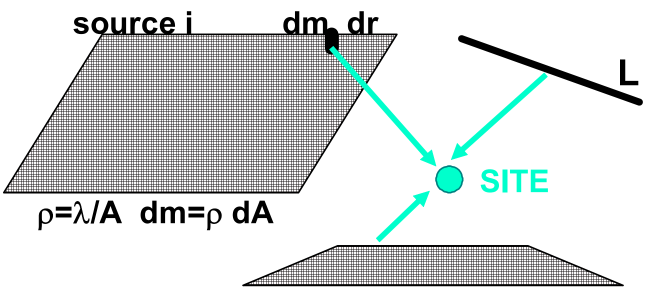
where **P[Y>y*|m,r]** is the probability, obtained from the attenuation, that an earthquake of magnitude **m** and distance **r** will exceed the ground motion level y*, $f_M(m)$ is the PDF of magnitude (recurrence relation) and $f_R(r)$ is the PDF of epicentral (or source) distance between site and various locations within the source.

If the site is in a region of **N** earthquake sources, each of which has a mean annual rate of exceedance $\lambda_{mi}=\exp(\alpha_i-\beta_i m)$ the above equation becomes:

$$P[Y > y^*] = \sum_{i=1}^{N} \lambda_{mi} \int_{m_0}^{m_{max}} \int_{r_{min}}^{\infty} P[Y > y^* | m,r] \cdot f_{Mi}(m) \cdot f_{Ri}(r) \cdot dmdr$$

$$f_{Mi}(m) = \beta_i e^{-\beta_i m}$$

$$f_{Ri}(r) = R / L \sqrt{r^2 - r_{min}^2}$$



The individual components of this eq. are sufficiently complicated that the integrals cannot be evaluated analytically. Numerical integration is therefore required and this can be done by a variety of **computer programs**, the most used being **SEISRISK III** (Bender & Perkins, 1987) and **CRISIS** (Ordaz et al., 2003, 2007)

The uniform distribution of earthquakes within a source zone often does not translate into a uniform **distribution of source-to-site distance which can be described by a probability density function**.

For a point source the distance R to the site is known to be r_s; the probability that $R=r_s$ is assumed to be 1 and the probability that $R \neq r_s$ is zero.

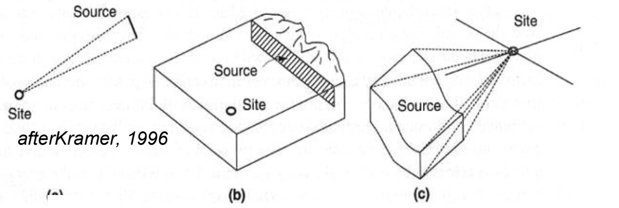


Figure 4.7 Examples of different source zone geometries: (a) short fault that can be modeled as a point source; (b) shallow fault that can be modeled as a linear source; (c) three-dimensional source zone.

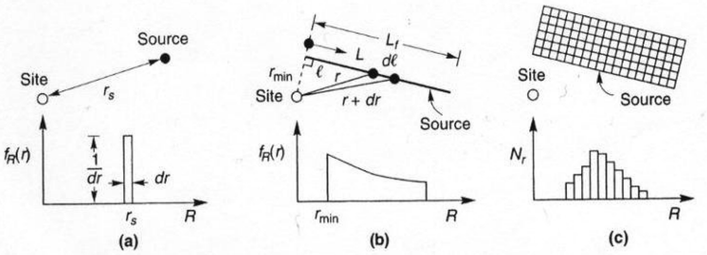


Figure 4.8 Examples of variations of source-to-site distance for different source zone geometries. The shape of the probability distribution can be visualized by considering the relative portions of the source zone that would fall between each of a series of circles (or spheres for three-dimensional problems) with equal differences in radius.

For a linear source the probability that an earthquake occurs on the small segment between l and $l+dl$ is the same as $r+dr$:

$f_L(l)dl = f_R(r)dr$ $\quad f_R(r)= f_L(l)dl/dr$

If earthquakes are uniformly distributed over the length of the fault $f_L(l)=l/L_f$.

Since $l^2 = r^2 - r_{min}^2$ the probability density function of R

$$f_R(r) = \frac{r}{L\sqrt{r^2 - r_{min}^2}}$$

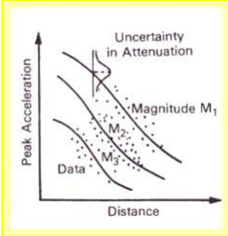
For bi or three-dimensional zones it is easier to **evaluate $f_R(r)$ by numerical rather than analytical methods**, dividing the source zone into a large number of discrete elements and constructing a histogram.

The underlying procedure to obtain seismic hazard curves is best illustrated by a simple example:

If the hazard is to be assessed for a site situated **r**₁ kilometres from the source, the first step is to select a value of PGA, say **0.2 *g***. The magnitude **M**$_{0.2}$ required to produce this level of acceleration can be obtained from the attenuation relationship.

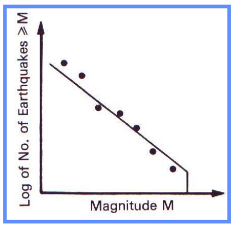
$$\log(PGA) = c_1 + c_2 M - c_3 \log(r^2 + h_0^2)^{1/2}$$

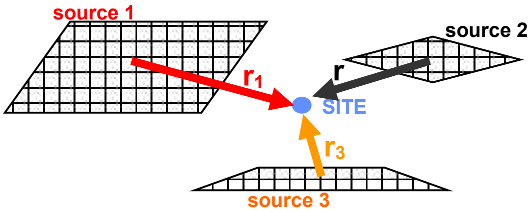
$$M_{0.2} = \frac{1}{c_2}\left[\log(0.2) - c_1 + \frac{c_3}{2}\log(r_1^2 + h_0^2)\right]$$



The mean annual rate of exceedance of earthquakes at the source 1 that have this magnitude can then be found from the recurrence relationship.

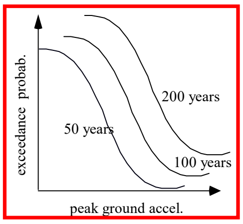
$$\lambda_{m1}(0.2) = 10^{(a - bM_{0.2})}$$





Repeating the calculation for several PGA values and summing over the different sources the hazard curves are obtained from the exponential-Poisson distribution.

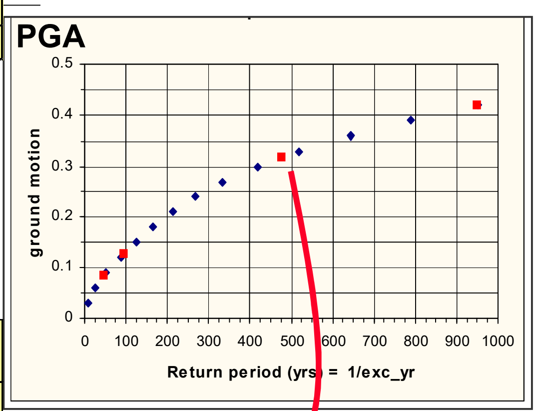
$$P(a > a_i | t) = 1 - e^{-t\sum_{i=1}^{3}\lambda_{mi}}$$



Output of the computer program SeisRisk III (Bender & Perkins, 1987) for a site located in southern Italy.

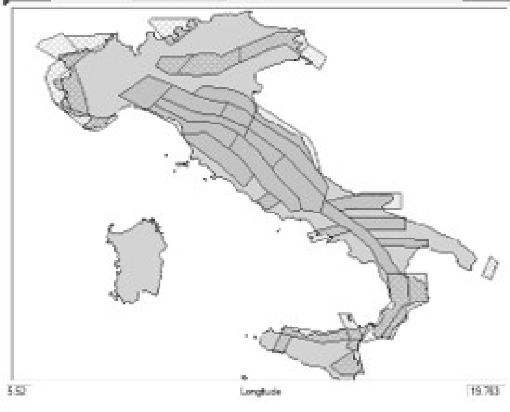
PGA (g)	annual freq.	λa cum. freq.	Tr=1/λa ret. period (yrs)
0,27	0,00073	0,00300	333,3
0,30	0,00060	0,00239	418,4
0,33	0,00047	0,00193	518,1
0,36	0,00037	0,00155	645,2

$$P(a > a_i | t) = 1 - e^{\lambda_a t} = 1 - e^{-t/T_r}$$



P. exc.	t exp. time (yrs)	Tr Ret period.	PGA (g)
10%	5	47	0,086
10%	10	95	0,127
10%	50	475	0,318
2%	50	2475	0,419

CRISIS program



CRISIS computer program can be obtained freeware from the Author.

It carries an user-friendly interface that makes the management of I/O data particularly easy compared to other codes.

INPUT:

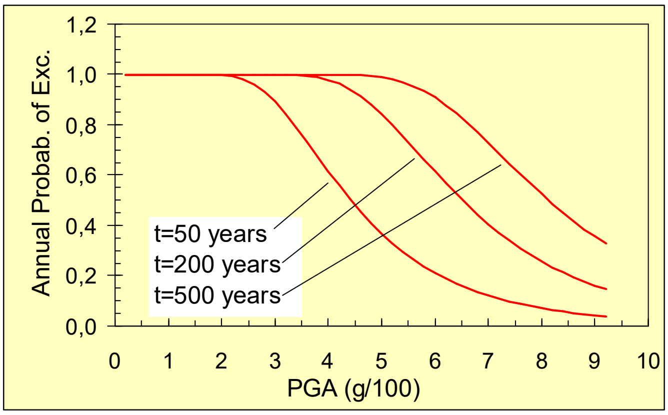
1. Coordinates of the site or grid of sites
2. Coordinates of seism. zones.
3. λ_o, β, M_o, and M_{max} for each zone.
4. Attenuation relations (choice included)
5. Type and number of values for which PSHA has to be computed.
6. Desired return periods.
7. Parameters controlling the spatial integration process (triangulation)

OUTPUT:

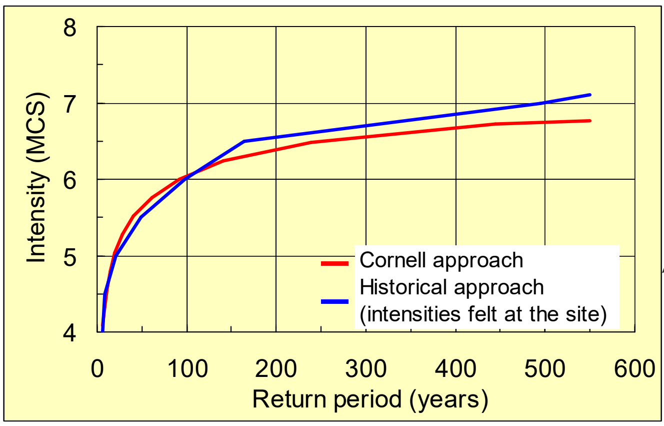
1. Result file (*.res).
2. Graphics file (*.gra).
3. Map file (*.map).
4. DES file (*.des).

File characteristics described in the help-on-line (Results).

Seismic hazard curves

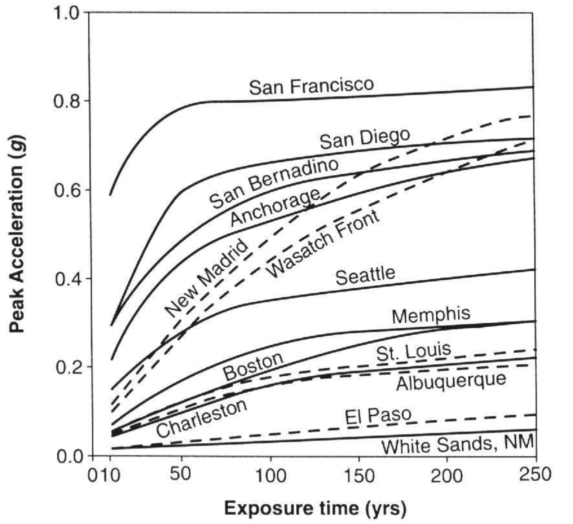


The basic output from a seismic hazard assessment for an individual site is a **hazard curve**, which shows the variation of the level of the particular strong-motion parameter considered, with either **probability of exceedance** within a specified period or **with return period.**

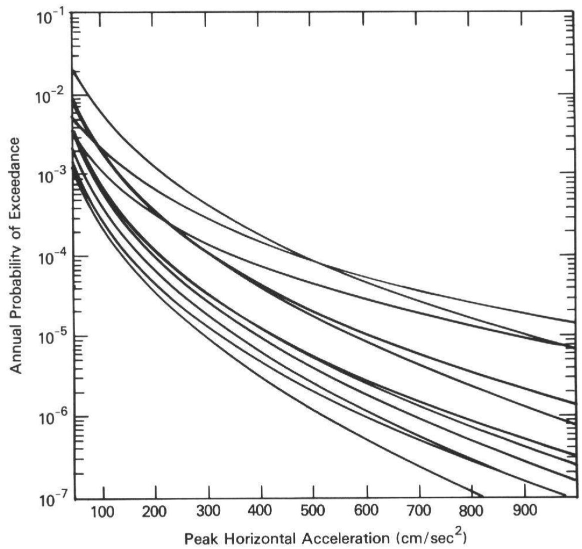


Seismic Hazard curves of the historical centre of Rome in terms of probability of exceedance versus PGA for different exposure times, and macroseismic intensity versus return period (*after Sabetta & Paciello, 1995*).

A hazard curve provides a convenient way to determine the design level of a particular ground-motion parameter, such as PGA, for different return periods or probabilities of exceedance. Comparison of hazard curves for different sites within a region or country can also provide a useful indication of the relative levels of short-term and long-term hazard.

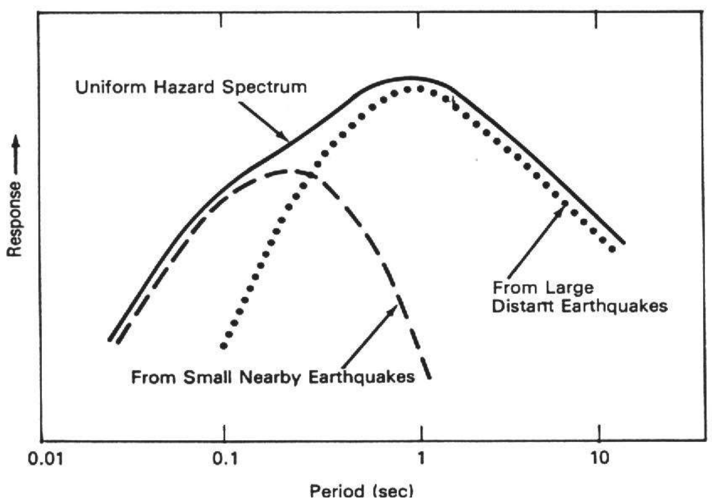


PGA with 10% prob. of exceedance over various exposure times for 14 areas in North America (after Kramer, 1996).



Hazard curves for the site of a nuclear power plant in Georgia based on source zone estimates by different teams of experts (after Reiter, 1990).

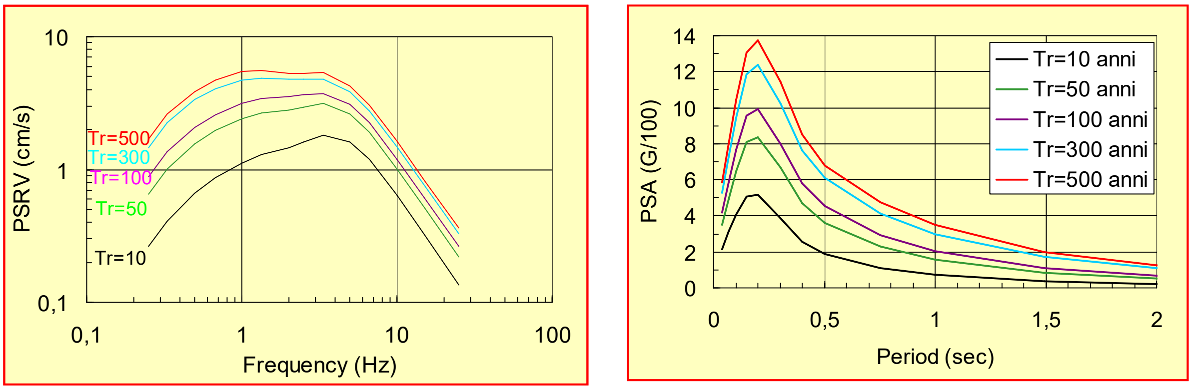
Uniform Hazard Spectra (UHS)



Schematic sketch of uniform hazard spectrum in which the contributions to hazard at shorter and longer periods come from different sources (after Reiter, 1990).

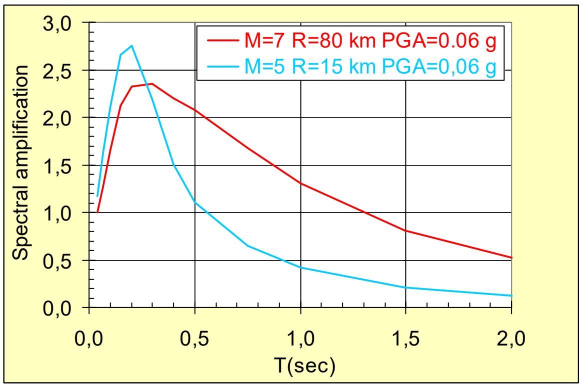
The way to obtain a Uniform **Hazard Spectrum (UHS)** is to perform the hazard assessment many times using **period-dependent attenuation equations for response spectral ordinates**. In this manner the spectrum can be constructed period-by-period, ensuring that it represents the same level of hazard across the entire range of periods. An important feature of the UHS, is that **it does not correspond to the expected movement from a single earthquake**. In many cases the UHS is actually an envelope of the spectra corresponding to different source zones, for example to areas of small magnitude earthquakes and more distant areas with larger events.

The **ordinates of UHS may be largely independent of each other**. In this figure the 0.1 sec. response of UHS is dominated by contributions from small, nearby earthquakes, while the 1 sec. response is dominated by large distant earthquakes. This is not a problem as long as no aspect of the engineering design requires the mutual consideration of both 0.1 and 1 second motion, as when two modes of a building response are contributing equally to its motion. **If they were, the use of UHS could be a source of additional conservatism because it would imply the simultaneous occurrence of both a small nearby earthquake and a large distant one**.



Uniform Hazard Spectra of the historical centre of Rome corresponding to different return periods (*after Sabetta & Paciello, 1995*).

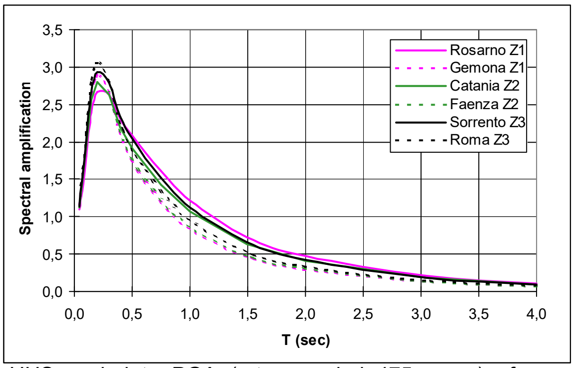
Deterministic and probabilistic spectra



Deterministic spectra estimated from the Sabetta & Pugliese (1996) attenuation relation

In deterministic spectra the shape depends on magnitude.

Probabilistic spectra depend on the relative contribution of different M-R couples, on their occurrence frequency (G-R relation), and on the scatter (N° of sigmas) of the attenuation relation incorporated in PSHA.



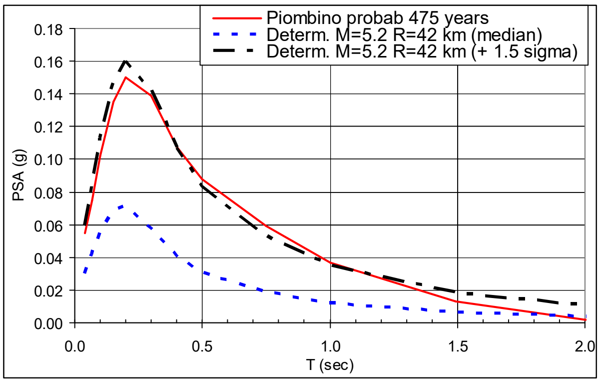
UHS scaled to PGA (return period=475 years) of some Italian municipalities belonging to different seismic zones (Z1 highest; Z3 lowest)

Most Italian sites are affected by the contribution of several sources (both weak-close earthquakes and strong-distant) so that their spectral shapes, if scaled to respective PGA, appear very similar.

The DSHA in the city of Piombino is clearly dominated by a single earthquake of M=5.2 and R=42 km.

Considering the moderate high frequency of occurrence of M=5.2 in the correspondent source zone (~1 every 120 years), the classical deterministic approach of median **+1/2** sigma is in this case correct.

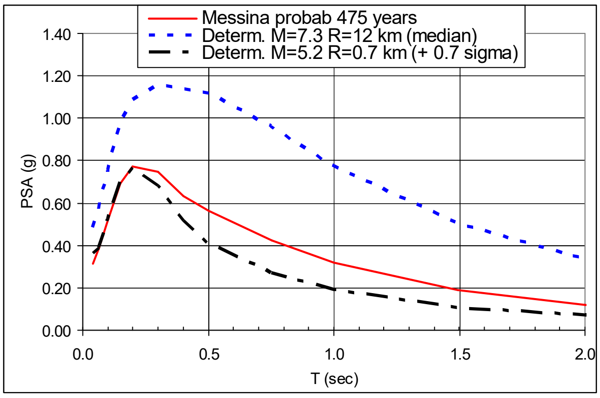
Spectral shapes match because there are no contributions from other **M-R** couples.



The DSHA in the city of Messina is dominated by two earthquakes: M=5.2, R=0.7 km and M=7.3, R=12 km.

In this case the standard determ. appr. (even without sigma) gives very high values due to the very low frequency of occurrence of M=7.3 (~1 every 1000 years). The determ. spectrum of M=5.2 (occ. freq. ~1 every 150 years) + 0.7 sigma gives comparable results only at low spectral periods.

Probabilistic spectral shape is intermediate between M=5.2 and M=7.3



Time dependent Models

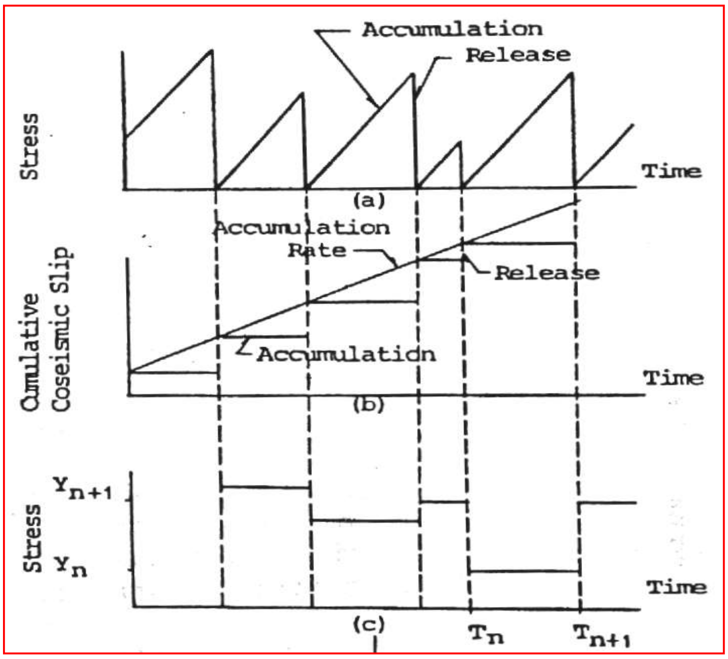
The assumption of spatial and temporal independence of earthquake occurrence, implicit in the PSHA based on the Cornell approach and Poisson process, is clearly not compatible with the processes of plate tectonics and elastic rebound that generate earthquakes.

If earthquakes occur to release strain energy that builds up over extended periods of time, the occurrence of a large earthquake should substantially reduce the chances of another independent large earthquake (from the same source) occurring shortly thereafter.

A number of models that account for prior seismicity have been proposed (Anagnos & Kiremidjian, 1984):

- *Renewal models* use arrival-time distributions other than exponential to allow the hazard rate to vary with time since last event (log-normal, gamma, and Weibull distributions are most common).
- *Time-predictable models* specify a distribution of the time to next earthquake that depends on the magnitude of the most recent event.
- *Slip-predictable models* consider the distribution of earthquake magnitude to depend on the time since the most recent event.
- *Markov models* incorporate a type of memory that describes the chances that a process moves from some "past State" to a particular "future state". The time for which the process stays in a particular state is exponentially distributed.
- *Semi-Markov models* are not restricted to exponential distribution and, for example, relate the probability of future earthquakes of various sizes to the most recent event and the elapsed time since its occurrence.

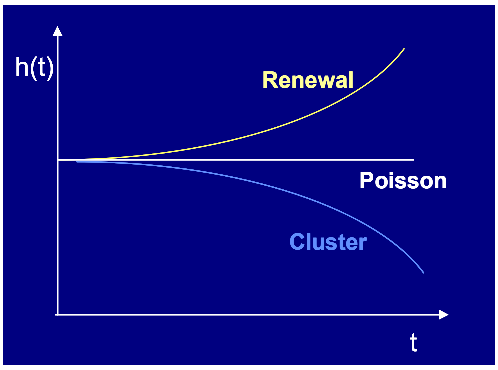
Slip-predictable models



Schematic representation of the application of a slip-predictable model for earthquake occurrence. (Kiremidjian & Suzuki, 1987)

The basic assumption of a "slip-predictable model" is that the stress released during an earthquake is proportional to the elapsed time since the last rupture, although the time that will elapse before the next event is random.
The issue is that for a good application of this model you need to know the occurrence time and the slip release of several earthquakes on a given fault.
Identification and dating of multiple events on a given fault are very rare in the world and almost inexistent in Italy.

Processo di Poisson e modelli "time dependent"



I modelli tipo "**Renewal**" o "**Slip predictable**" sono applicabili a singole faglie che mostrino comportamenti di tipo "terremoto caratteristico" e considerano che la probabilità di verificarsi di un terremoto è tanto **maggiore quanto maggiore è il tempo trascorso dall'ultimo evento**.

D'altra parte l'osservazione della sismicità storica mostra che spesso i terremoti seguono un comportamento a "**cluster**" (raggruppati nello spazio e nel tempo). In questo caso il rilascio di sforzo su di una faglia può determinare un aumento del campo di sforzo su faglie vicine e quindi la probabilità di verificarsi di un terremoto è tanto **minore quanto maggiore è il tempo trascorso dall'ultimo evento.**

Inoltre i modelli Time-depedent, oltre a proporre due approcci antitetici, richiedono dettagliate conoscenze sulle faglie sismogenetiche che non sempre sono disponibili. Ne consegue che **in attesa di studi più approfonditi** (in corso nell'ambito delle **iniziative internazionali del CSEP** Collaboratory for the Study of Earthquake Predictability) **il modello di Poisson**, in particolare nel caso di sorgenti multiple e poco conosciute, **è quello attualmente più utilizzato negli studi di pericolosità.**

De-aggregation of seismic hazard

For design, analysis, retrofit, or in general in any engineering design for which acceleration time-histories are required, an essential step is the definition of a "**design earthquake**". The minimum information required is a **magnitude-distance pair** defining the size of the earthquake and its location respect to the site.

A disadvantage of PSHA is that the concept of "design earthquake" is lost because it gives the combined effect of all magnitudes and distances from different sources, on the probability of exceeding a given ground motion level. Since all of the sources, magnitudes, and distances are mixed together, it is difficult to understand what is the controlling earthquake. **For example at a level of 10^{-4} per year, the PGA value could be 0.3 g. There is no indication as to whether this is associated with a nearby M=5.5 earthquake or a more distant M=7.5 event**.

Even with the imposed constraints on ***M*** and ***d*** there are many earthquake scenarios compatible with the design PGA value. Although the ground motions associated with each of these scenarios would have the **same PGA, they would be very different in terms of other parameters such the shape of the response spectrum and the duration of shaking**.

Therefore, some other criteria are required in order to select the single scenario which can be considered as most compatible with the hazard level. Several studies have addressed this problem, establishing a practice that has become known as **Deaggregation of Seismic Hazard** (Ishikawa & Kameda1994; Chapman, 1995; McGuire, 1995; Bazzurro & Cornell, 1999).

The method that has been most widely adopted is that due to McGuire (1995). Remembering the standard formulation of PSHA.

$$\lambda_{y^*} = P[Y > y^*] = \sum_{i=1}^{N} \lambda_{mi} \int_{m_0}^{m_{max}} \int_{r_{min}}^{\infty} P[Y > y^* | m,r] \cdot f_{Mi}(m) \cdot f_{Ri}(r) \cdot dmdr$$

it can be expressed explicitly as a function of the ground motion randomness ε, the number of logarithmic standard deviations above the median value predicted by the attenuation equation.

$$\lambda_{y^*} = \sum \lambda_{mi} \iiint P[Y > y^* | m,r,\varepsilon] \cdot f_{Mi}(m) \cdot f_{Ri}(r) \cdot f_{\varepsilon}(\varepsilon) dmdrd\varepsilon$$

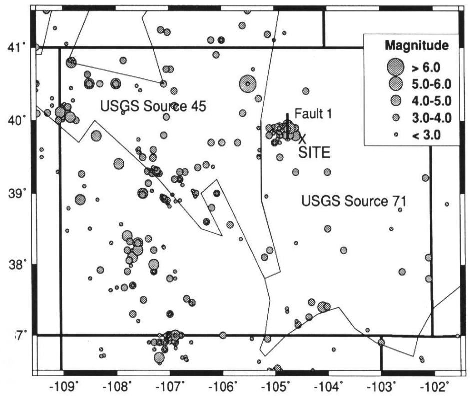
the probability in the integrand is replaced by

$$P[Y > y^* | m,r,\varepsilon] = \delta[\ln Y(m,r,\varepsilon) - \ln y]$$

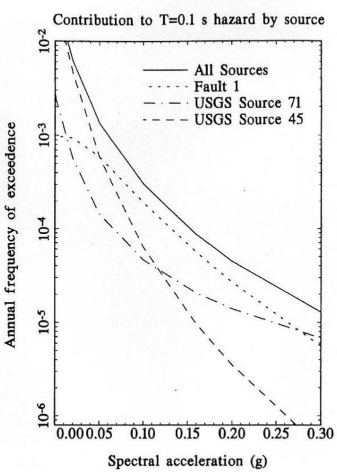
where δ is the Dirac delta function because the goal is to obtain M-r-ε sets that are equal to the target ground motion not that exceed it.

The marginal probability distribution of M, r and ε, is simply obtained removing the corresponding term from the integral, e.g for M:

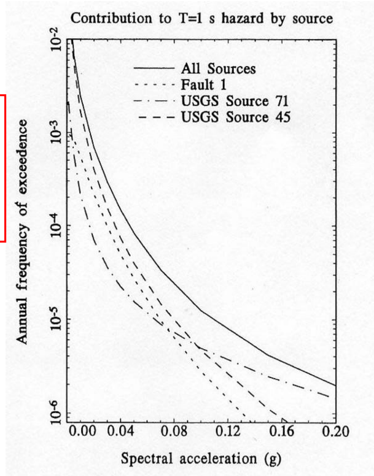
$$f'_M(m) = \sum \lambda_{mi} \iint \delta[\ln Y(m,r,\varepsilon) - \ln y] \cdot f_{Ri}(r) \cdot f_{\varepsilon}(\varepsilon) drd\varepsilon$$

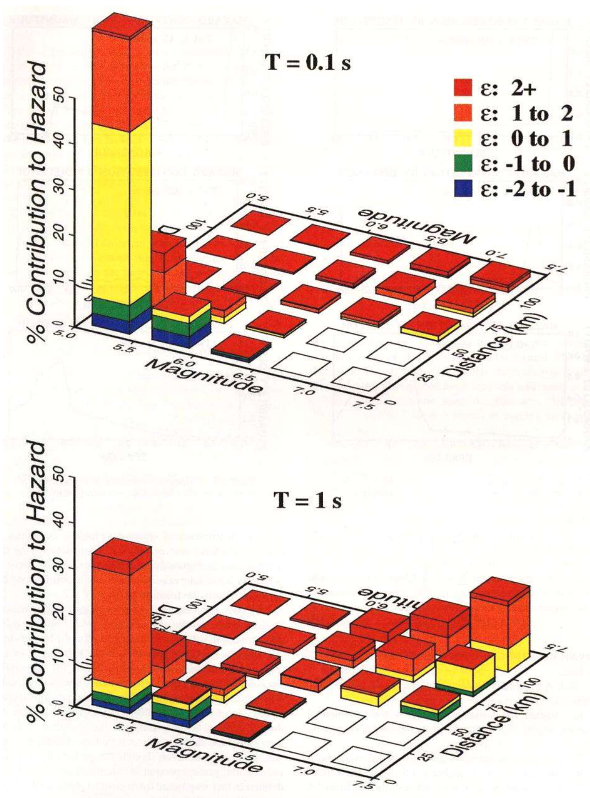


The deaggregation by source allows the dominant seismic source to be identified.



Historical seismicity in Colorado (USA) with sources 71, 45 and hypothetical fault 1, around the site considered by McGuire (1995).





Contributions to the 10,000-year hazard at the Colorado site by M, r and ε, for the ordinate of spectral acceleration (after McGuire, 1995).

The deaggregation by magnitude and distance "bins" allows the dominant scenario earthquake to be identified.

The results will be different for different probability levels (e.g 1,000 yr vs. 10,000 yr return periods).

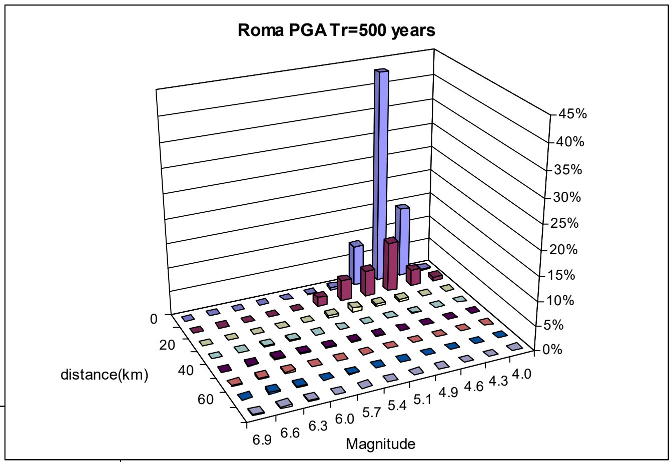
The choice of the width of the "bins" could be critical.

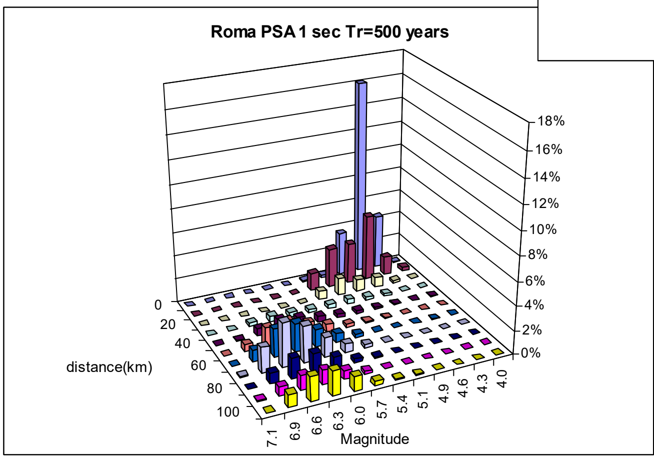
Wide intervals will result in large overlaps, permitting a single earthquake scenario, but, in such a case, the ground-motion parameters associated with the resulting event may differ greatly from the design values.

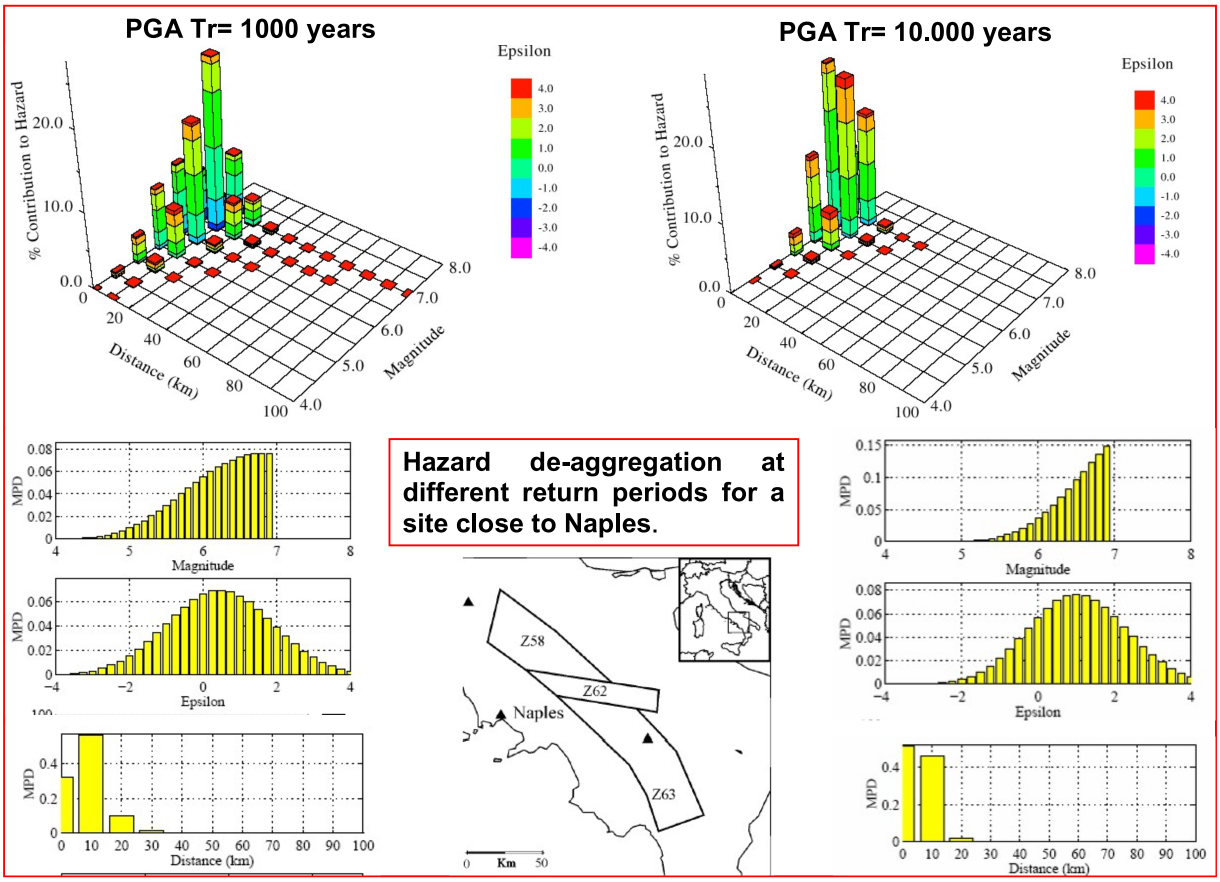
On the other hand, the use of small intervals will result in little overlap and hence the impossibility of finding a dominating earthquake scenario.

The process of de-aggregating seismic hazard is not difficult or time consuming, but it adds a huge amount of information and greatly improves the understanding of PSHA

Hazard de-aggregation for the city of Rome, showing for PGA the prevalence of a close low-seismicity source (Colli Albani, R=20 km, Mmax=5.5) and at at long spectral periods the appearance of a far high-seismicity source (Appennino Abruzzese, R=85 km, Mmax=7).

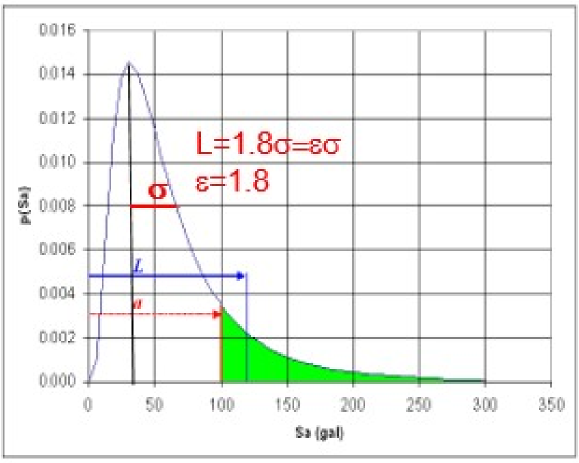






Hazard de-aggregation at different return periods for a site close to Naples.

ε n. of log standard deviations above the median value predicted by the GMPE



The shape of the probability density function of Sa depends on magnitude, distance, and GMPE employed, while **a** is the value for which seismic hazard is being computed.
It is sometimes of interest to know how much of the probability marked in green comes from the high percentiles of the distribution. For instance, how much of the probability comes from the area to the right of value L. Normally, L is indexed to an "epsilon" (**ε**) value

$$\varepsilon(T) = \frac{\ln Sa(T) - \mu_{\ln Sa}(M,R,T)}{\sigma_{\ln Sa}(T)}$$

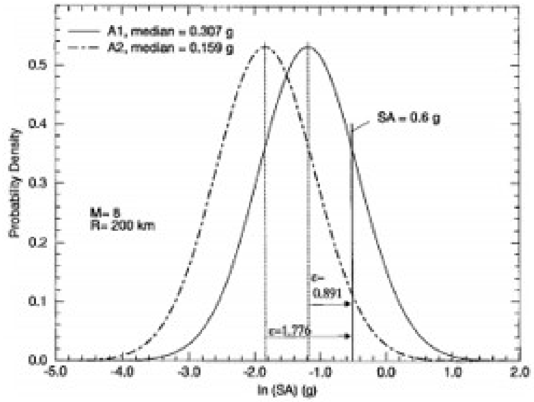
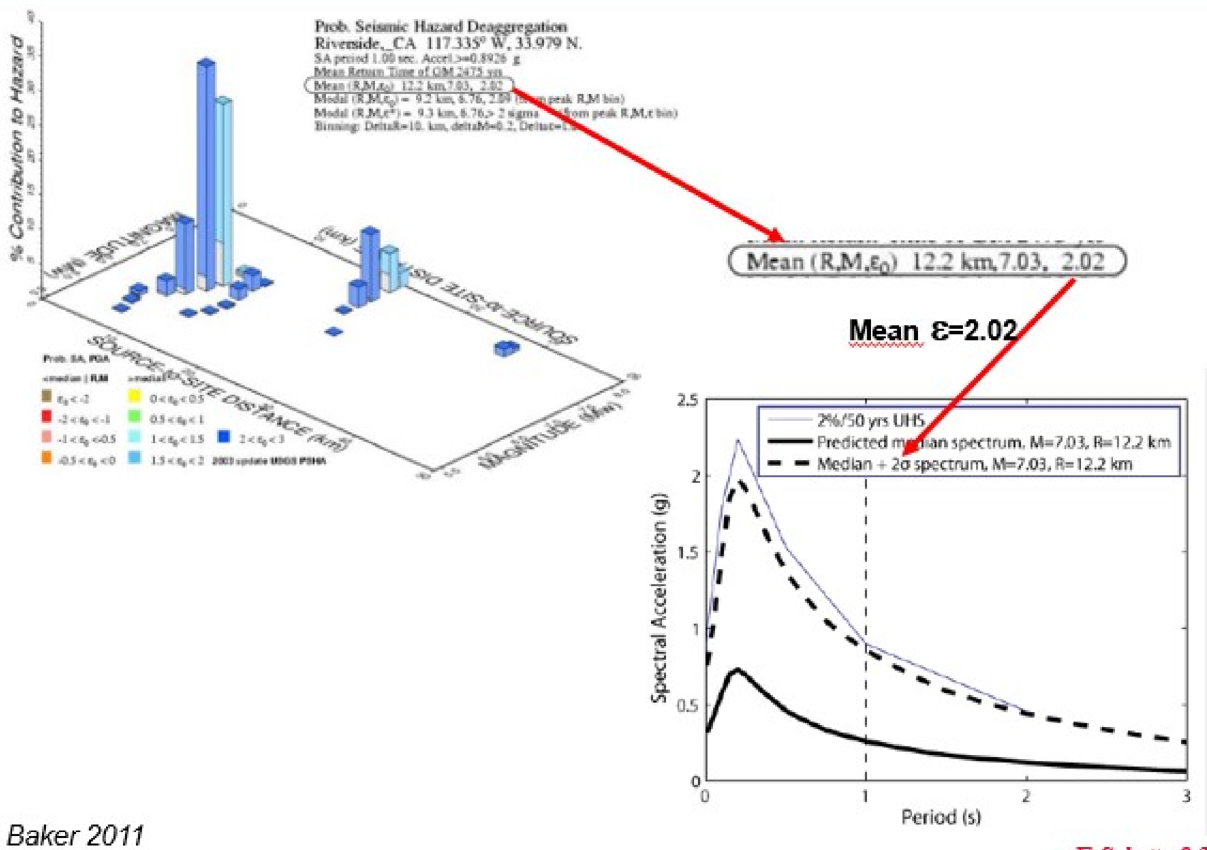


Figure 1. Ground-motion uncertainty p.d.f.s for an M 8 earthquake at distance 200 km from two ground-motion attenuation models used in the 1996 National Seismic Hazard maps. For each of these, the logarithmic σ is 0.751. The vertical line is located at $\ln(SA_0) = -0.51$, or $SA_0 = 0.6g$. PSHA computes exceedance probability, $\Pr[SA > SA_0] = \Pr[\ln(SA) > \ln(SA_0)]$, which is the area of the curves to the right of the vertical line. Median motions are for a BC rock site, with average Vs = 760 m/sec in the top 30 m.

The logarithm of *Y*, which we denote *y*, has a normal distribution, with mean, μ, and standard deviation, σ. Epsilon is defined as $\boldsymbol{\varepsilon = (y - \mu) / \sigma}$



Baker 2011

Aleatory and Epistemic Uncertainty

In the area of seismic hazard analysis (Bernreuter et al., 1989; EPRI, 1989; Budnitz et al. 1997), it has become common practice to distinguish and separately process uncertainties of two different types:

1) Random or **aleatory uncertainty:** uncertainty that reflects the variability of the outcome of a repeatable experiment**.**

Typical examples of aleatory uncertainty include **chance games** or repetitive observations of quantities which provide different outcomes (daily precipitation, maximum annual wind speed, etc.). In PSHA, examples of aleatory uncertainty are:

- ✓ **recurrence relations** (the Poisson model assumes that even though we know accurately the recurrence relation we cannot predict where or when the next earthquake will occur or what size it will be).
- ✓ **standard deviation of the attenuation relation** (no matter how accurately we know the magnitude and distance of a postulated earthquake, there still will be some uncertainty in predicting the ground motion).

Important attributes of aleatory uncertainty are:

- **it is objective** (it has a relative frequency interpretation);
- it does not depend on the amount of information available (**aleatory uncertainty can be quantified but not modified by gathering additional information**);
- probability theory applies to it.

2) scientific or **epistemic uncertainty:** uncertainty from ignorance or lack of knowledge. For instance, uncertainty on states and laws of nature is of this type. Specific examples linked to a subjective degree of belief about the real word could be: does God exist? Is the accused innocent or guilty? Is there life on planet Mars ? In PSHA, examples of epistemic uncertainty could be:

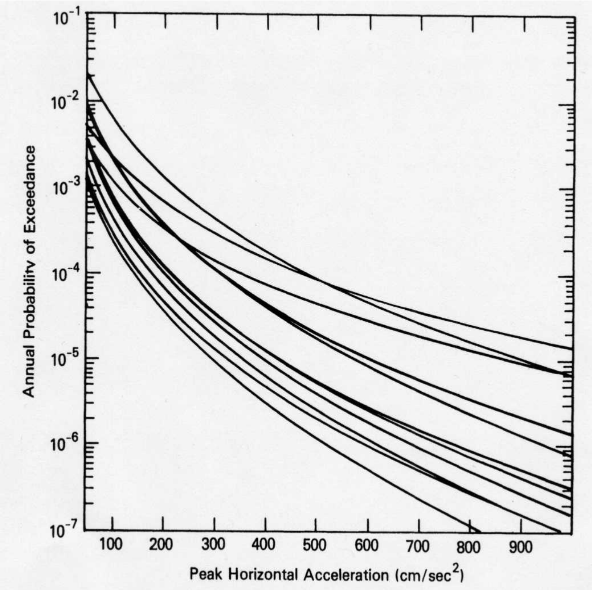
- ✓ **what and where are the seismic source zones?**
- ✓ **is a given fault seismically active? what is its maximum magnitude ?**
- ✓ **what is the best attenuation model to be adopted ?**

The main attributes of epistemic uncertainty are:

- it depends on the available information; **epistemic uncertainty can be reduced by collecting data and hence usually varies in time**;
- **it is generally subjective, with a degree-of-belief interpretation**;
- **probability theory may not apply to it**;

The classification of uncertainty into the above two types is not always obvious. Indeed, much of the uncertainty that is traditionally considered as aleatory should arguably be treated as epistemic.

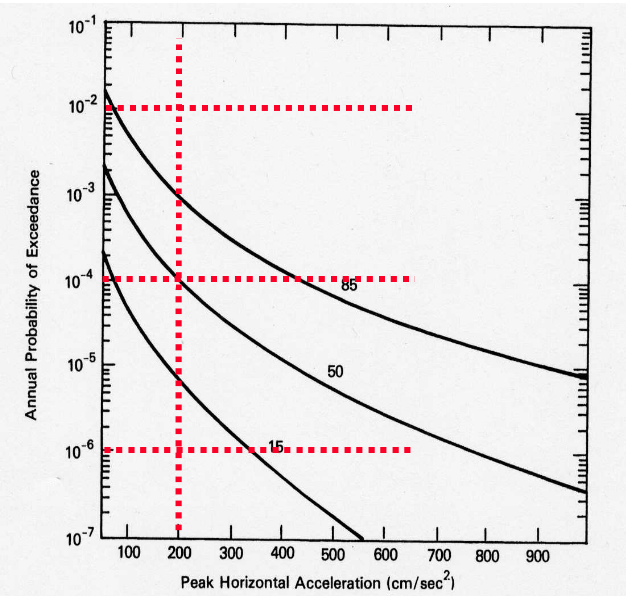
Treatment of uncertainties



Hazard curves for the Vogtle Nuclear Power Plant (Georgia) based on best estimate source zone of eleven experts (after Bernreuter et al., 1989)

One of the main problems associated with epistemic uncertainty in PSHA is that it is determined in large **by the use of expert judgment**.

More often than not epistemic uncertainty is assessed by **convening panels of experts to propose and weigh a set of alternate assumptions** with regard to seismic source definition, seismicity parameters, and ground motion models.
PSHA that incorporate epistemic uncertainties would include multiple scenarios and models.
Each model or combination can be used to calculate a single hazard curve and **the final product would be a group of discrete curves** that, given enough variations in the input, could number in the hundreds or thousands.



15th, 50th, and 85th percentile hazard curves for the Vogtle Nuclear Power Plant site in Georgia (after Bernreuter et al., 1989).

Usually the results are described by a set of simplified curves which indicate a central value and the upper and lower bounds. **Large bands of uncertainty often make the "decision makers" job more difficult.**

For the power plant in the figure on side the design was based on a PGA of 200 cm/sec^2. If an industrial facility had to be built in the vicinity of the plant, the choice if it had to be constructed or not, would be change according to the criterion of acceptability:

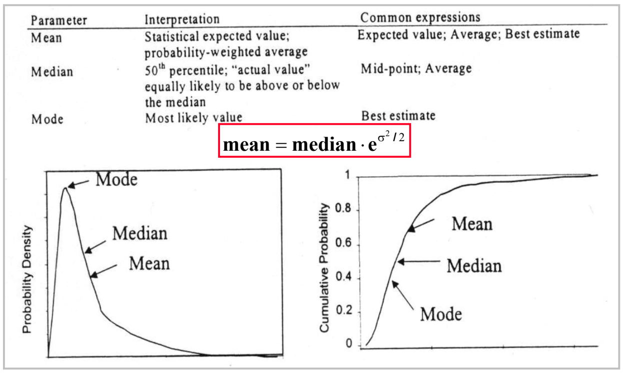
10^{-2} → yes

10^{-6} → no

10^{-4} → ?

As a result there is a great temptation to characterize large uncertainties trough the use of a single curve representing ***central estimates*** as the ***mean*** and the ***median***.
If uncertainties in PSHA were normally distributed the mean would be the same as the median and either could be used to obtain the same answers.

after Reiter, 1990



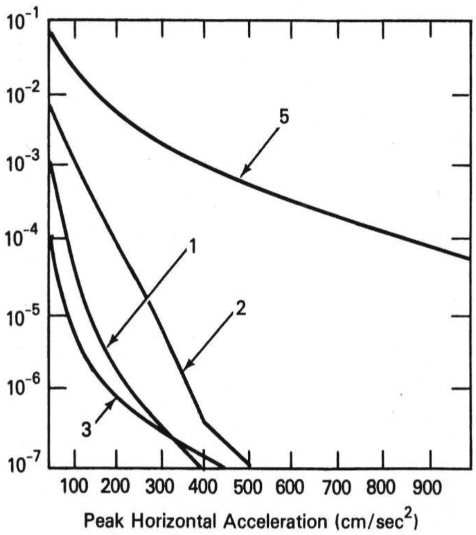
Parameter	Interpretation	Common expressions
Mean	Statistical expected value; probability-weighted average	Expected value; Average; Best estimate
Median	50th percentile; "actual value" equally likely to be above or below the median	Mid-point; Average
Mode	Most likely value	Best estimate

$$\boxed{\textbf{mean} = \textbf{median} \cdot e^{\sigma^2/2}}$$

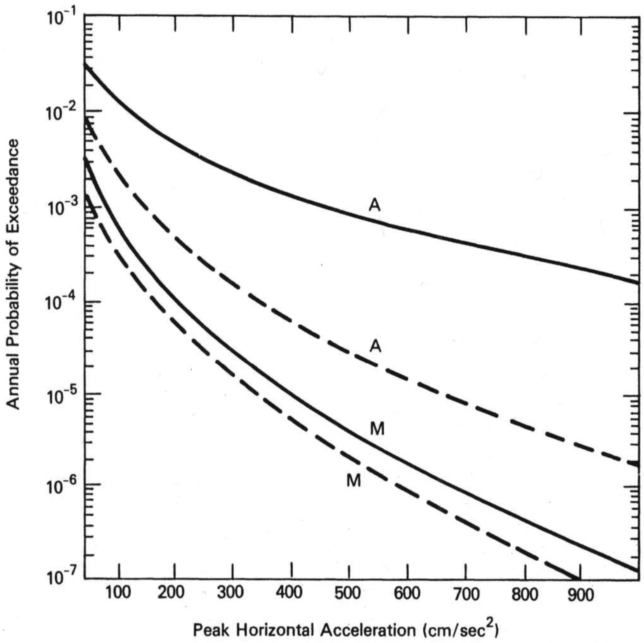
The uncertainty in PSHA appears closer to a log-normal distribution. Consequently the mean can be very different that the median.

For example, considering the former example of annual probabilities of exceedance of **10^{-2}, 10^{-4}, 10^{-6}, the median annual probability would be of 10^{-4} or 1/10,000, while the mean would be $10^{-2.47}$ or about 1/3,000.** Because of such asymmetry the **mean is most affected by the largest values** (if the two smallest estimates, 10^{-4}, 10^{-6}, were orders of magnitude less, the mean would change very little).

It follows that **mean estimates of PSHA can be skewed to the most conservative model**. Mean values have the advantage of being the expected values but they can fluctuate up or down, **depending not upon the majority of models but rather upon the outliers**.
The **median**, on the other hand **is not sensitive to any single model** and provides a seemingly attractive alternate to the mean. Unfortunately **it provides no indication of the width of the associated uncertainty**.
In the example above if the 3 hazard estimates were all annual probabilities of 10^{-4}, the mean would decrease significantly while the median would not change at all.

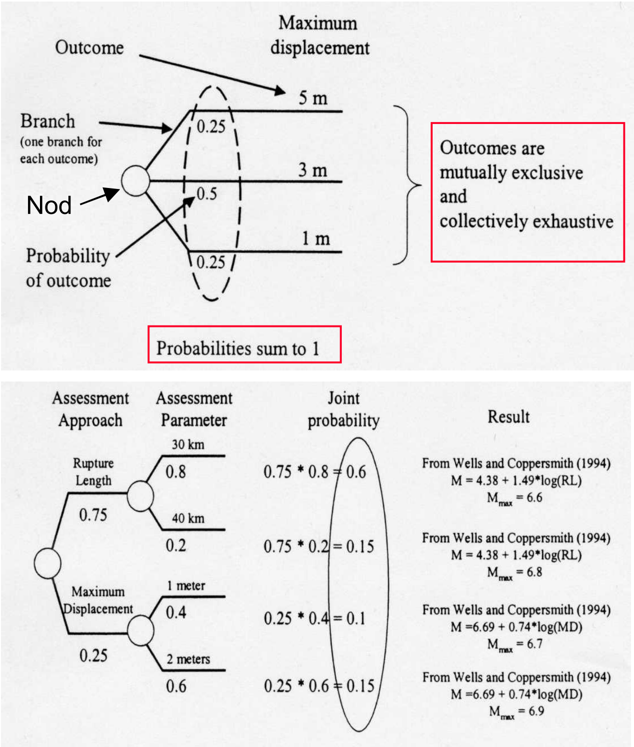


Computed seismic hazard at the Browns Ferry Nuclear Power Plant site (Alabama) using different ground motion models. Numbers on curves refer to which ground motion expert's model was used (after Bernreuter et al., 1989).



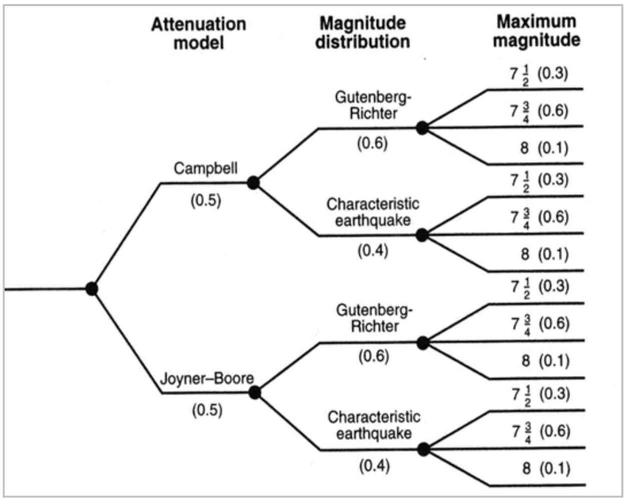
Seismic hazard at the Browns Ferry Nuclear Power Plant site in Alabama integrating all models and uncertainties. A is (arithmetic) mean and M is median. Results are shown with (solid line) and without (dashed line) the input of ground motion expert 5 (after Bernreuter and others 1989).

Logic trees



Example of a logic tree for the assessment of maximum magnitude (after Jenni, Geomatrix-

The use of ***logic trees*** (Coppersmith and Youngs, 1986) provides a convenient framework for the **explicit treatment of epistemic uncertainty**.
The logic tree approach allows the use of alternative models, each of which is assigned a weighting factor representing the relative likelihood of that model being correct.
It consists of a series of **nodes**, representing points at which models are specified, and **branches** that represent the the different models and/or parameters specified at each node.
The **sum of the probabilities** of all branches connected to a given node and that of all the terminal branches **must be 1**.
The **joint probability** of the combination of models and/or parameters of each terminal branch **is given by the product** of the probabilities of all prior branches.
The logic tree can be used as framework to explore sensitivity in the hazard assessment and thus to choose the optimum combination of choices and decisions



Example of a logic tree for incorporating epistemic uncertainty (after Kramer, 1996).

This logic tree terminates with a total of 2x2x3=12 branches.

For example, the relative likelihood of the combination of the Campbell attenuation, Gutenberg-Richter magnitude distribution, and maximum magnitude of 7.5, is 0.5x0.6x0.3=0.09.

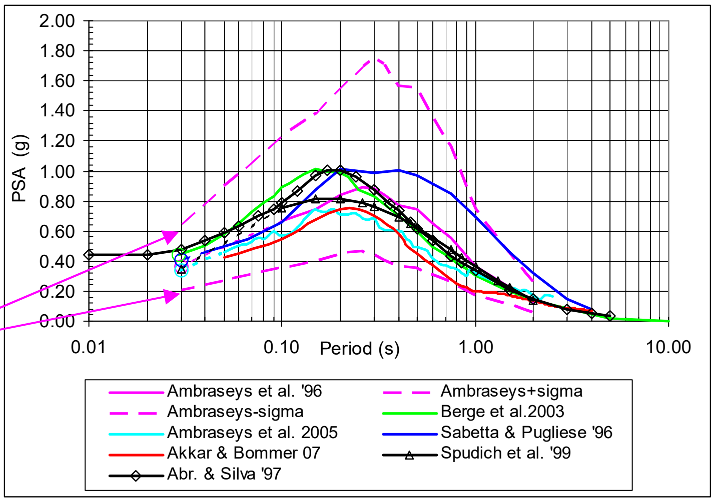
In this way it is possible to assign to each hazard curve, derived from the choice of particular models and parameters, the likelihood coming from the logic tree analysis, and determine the mean or median hazard curve together with confidence bands.

As we have seen, most of the modeling uncertainty in SHA is determined by expert judgment (generally reflecting the lack of data and/or of scientific knowledge). Unfortunately, scientific truth, in many aspects of SHA, may not be discernible even to the most carefully constructed polls of experts.
The purpose of SHA is to provide practical answers to practical questions. Society does not have the luxury to wait for the answers until the “truth” is discovered (Reiter,1990).

Summary of uncertainties

- ❑ Scientific uncertainty (epistemic)
- ✓ Due to lack of information
- ✓ Incorporated in PSHA using logic trees (leads to alternative hazard curves)
- ✓ Impacts the mean hazard

- ❑ Random variability (aleatory)
- ✓ Randomness in M, location, ground motion (ε)
- ✓ Incorporated in PSHA directly



It has to be remarked however that the distinction between epistemic and aleatory uncertainty **is not always so evident and essential**

PSHA versus DSHA

The most controversial and difficult question in SHA has often been **whether one should use PSHA or DSHA**. While there is a definite worldwide trend toward PSHA, the situation is by no means clear. In the field of nuclear safety alone, regulators trying to define the criteria for nuclear reactors and waste repositories, have switched back and forth between DSHA and PSHA. In many cases the question has been rephrased so that **the issue is not "whether" but rather "to what extent" a particular approach should be used.**

MAIN ADVANTAGES

DSHA

- It is entirely transparent and the results have an unambiguous physical interpretation.
- It is easy to check the design earthquake and computed ground motion.
- Does not require explicitly setting acceptable level of safety

PSHA

- It allows a formal way of dealing with uncertainty integrating large amounts of information and judgment
- It considers the frequency of earthquake occurrence.
- It considers the total hazard from all possible sources with their activity rate.

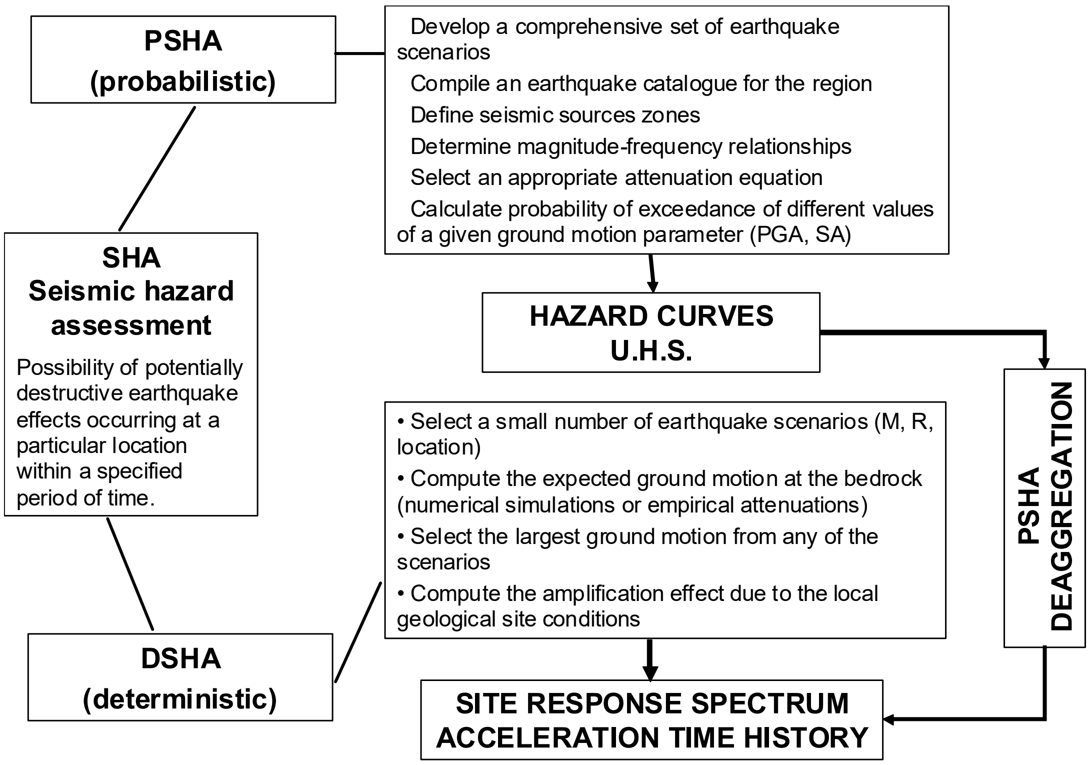
MAIN DISADVANTAGES

DSHA

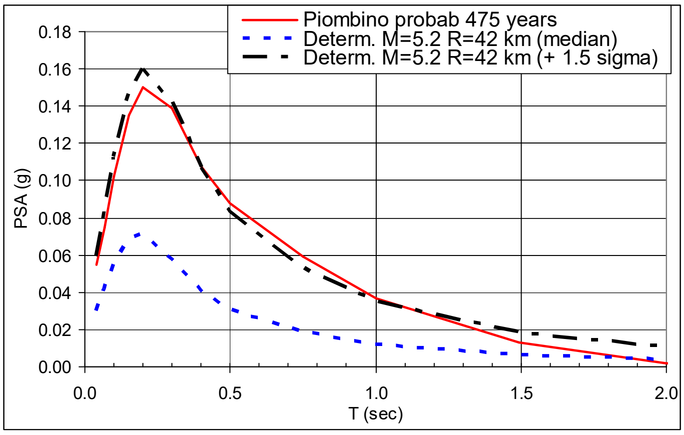
- It does not take into account the inherent uncertainty
- <u>It does not take into account the frequency of earthquake occurrence</u> (if applied to different regions may yield internal consistent scenarios which differ by more than an order of magnitude).
- It is often mistakenly thought to lead to the worse case ground motions

PSHA

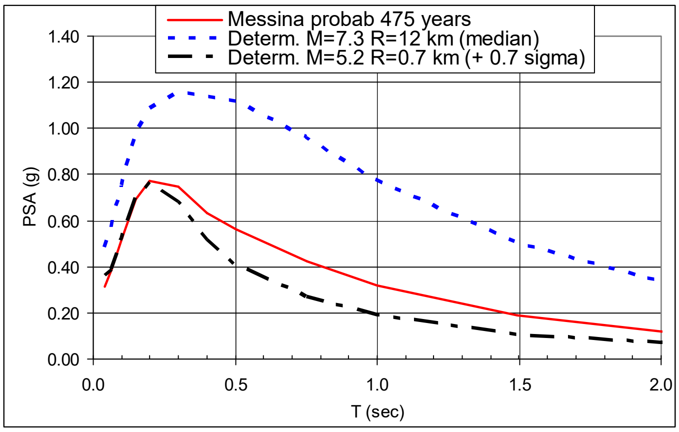
- It is not well understood by the engineering community
- It is more difficult to check the computations (including large quantities of data, theory and judgment may hidden the basic causative factors).
- It requires explicitly selecting a



In this case the deterministic approach of median +1/2 sigma provides similar results to PSHA because of the "normal" frequency of occurrence of earthquakes in the corresponding source zone (~1 every 120 years)



In this case DSHA (even without sigma) gives very high values due to the very low frequency of occurrence of M=7.3 earthquakes (~1 every 1000 years)..



Many textbooks and many papers in scientific journals present DSHA and PSHA as two mutually exclusive options for approaching seismic hazard assessment. This situation often gives the impression that the selection of either a deterministic or a probabilistic approach is the most fundamental choice in performing a seismic hazard assessment.

In fact the dichotomy between the two approaches is not as pronounced as often implied and there are many examples of hazard assessments combining elements of both methods. Probably the best choice is to use **Integrated approaches (deaggregation of PSHA or use of probabilities in DSHA).**

There are two fundamental principles that should guide a rational approach to seismic hazard assessment:

- It is impossible to perform SHA without making some deterministic and subjective decisions regarding the input.
- **The analysis must fit the needs**. What is really important is the probability of the engineering consequences of the earthquake action on the structure, rather than the probability of occurrence of the earthquake actions themselves.

It is obvious, for example, that the seismic analysis needed to prevent an undue **radioactive** release from an **underground repository during its 10,000 years lifetime** is quite different than the analysis needed to prevent the collapse of a **4 story building during its 50 years lifetime**.

The approach should be selected or designed according to the actual engineering requirements and always kept within the context of seismic risk evaluation.

after Reiter, 1990 and Bommer, 2001a