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"2nd Workshop on Earthquake Engineering for Nuclear Facilities: Uncertainties in Seismic Hazard"

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PSHA quality requirements in relation to the engineering applications

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"PSHA quality requirements in relation to the engineering applications"

[formerly :
PSHA quality requirements as a function of SPSA final objectives (levels, operating modes, type of facility) ,
C. Stepp]

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Overview

- Some generalities on hazard assessment
  - goals and applications : probability level, ground motion parameter (pga ≠ time history)
  - DSHA / PSHA
- dealing with uncertainties in PSHA
  - Types of uncertainties
    - Epistemic / Aleatory
  - origins of uncertainties
    - data : raw, reprocessed
    - methods : method themselves, parameters
  - An example : Ground Motion Predictive Equations
  - ? experts ?
- Quality requirements / Quality criteria ?
  - Personal recommendations

Engineering applications

- Probability level
  - $2.\ 10^{-3}$, $10^{-4/5}$, $10^{-7/8}$
  - Design motion / Scenario earthquakes (deaggregation)
- One single site / a whole area
  - (plant / lifeline)
- GM parameter
  - pga / pgv / pgd
  - Sa (T) / Sa (f)
  - Time histories (deaggregation)

Deterministic Approach

Select a small number of individual earthquake scenarios: M,R (Location) pairs

Compute the ground motion for each scenario (typically use ground motion with 50% or 16% chance of being exceeded if the selected scenario earthquake occurs)

Select the largest ground motion from any of the scenarios

Deterministic seismic hazard analysis (DSHA)

<u>Comments</u>

DSHA produces scenario earthquake for design

As commonly used, believed to produce worst-case scenario

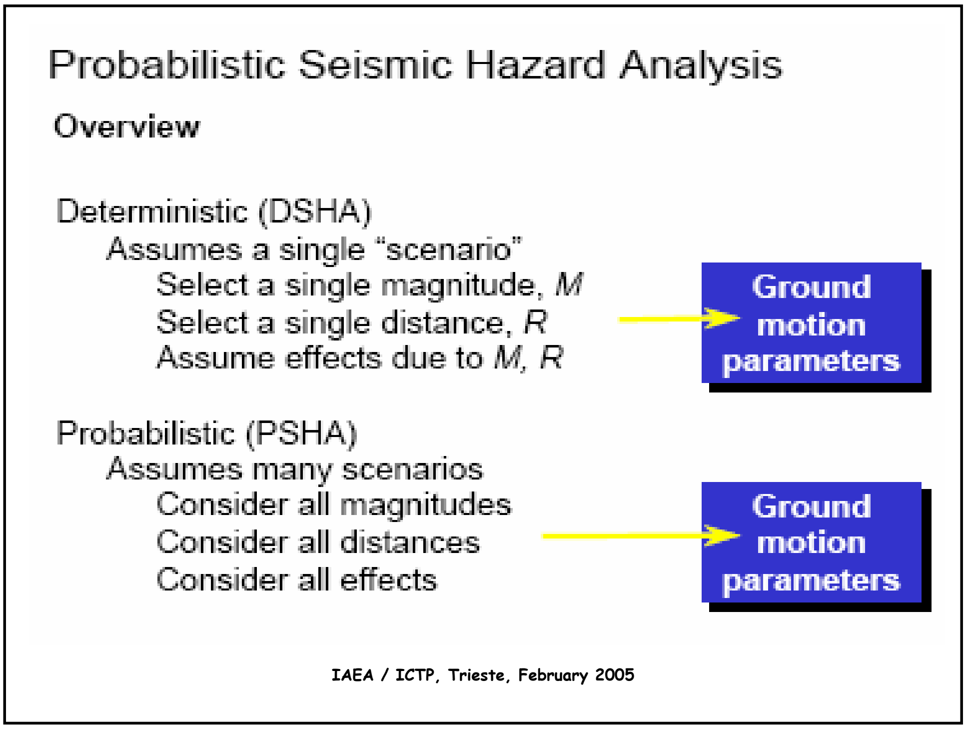
DSHA provides no indication of how likely design earthquake is to occur during life of structure

- Design earthquakes may occur every 200 years in some places, 10 000 years in others

DSHA can require subjective opinions on some input parameters

Variability in effects not rationally accounted for

DSHA calculations are relatively simple, but implementation of procedure in practice involves numerous difficult judgements. The lack of explicit consideration of uncertainties should not be taken to imply that those uncertainties do not exist



Probabilistic Seismic Hazard Analysis

Overview

Deterministic (DSHA)
- Assumes a single "scenario"
  - Select a single magnitude, *M*
  - Select a single distance, *R*
  - Assume effects due to *M, R*

→ **Ground motion parameters**

Probabilistic (PSHA)
- Assumes many scenarios
  - Consider all magnitudes
  - Consider all distances
  - Consider all effects

→ **Ground motion parameters**

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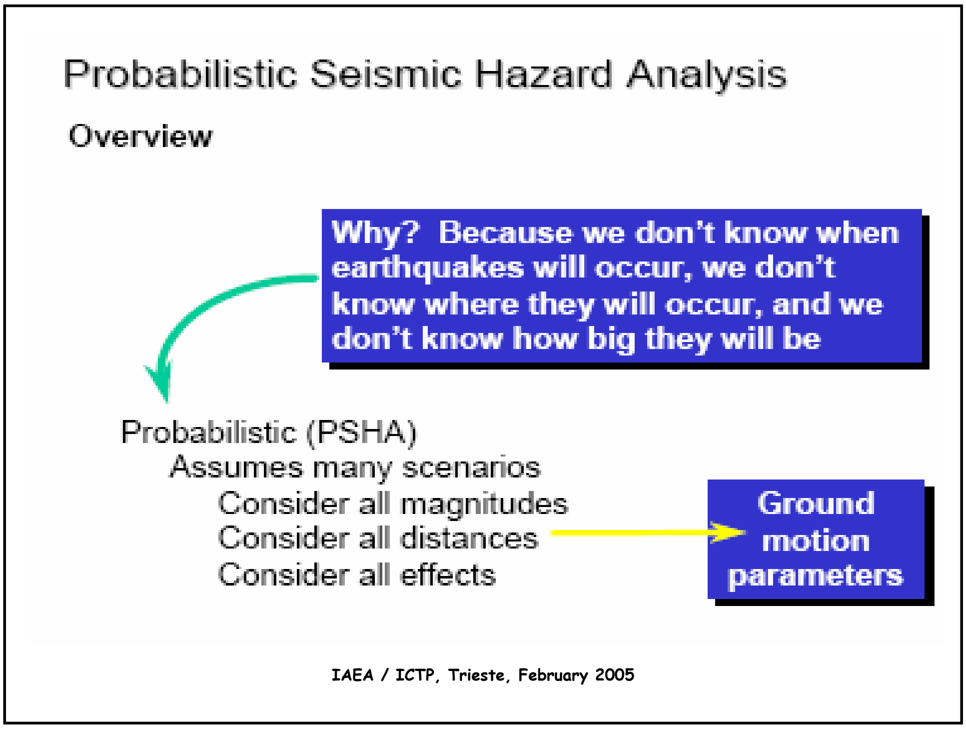

Probabilistic Seismic Hazard Analysis

Overview

Why? Because we don't know when earthquakes will occur, we don't know where they will occur, and we don't know how big they will be

Probabilistic (PSHA)
- Assumes many scenarios
  - Consider all magnitudes
  - Consider all distances
  - Consider all effects

→ **Ground motion parameters**

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Goal of a PSHA

- To represent the center, the body, and the range of the technical interpretations that the larger informed technical community would have if they were to conduct the study

(SSHAC, 1997)

Uncertainty in seismic hazard assessment

Incorporating uncertainties involves

identifying and quantifying them

estimating the impact on the hazard calculations

estimating the impact on the uncertainty on hazard estimates

Qualitative descriptions of uncertainty

Common	Probability										
expression	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Probable											
Fairly unlikely											
Possible											
Improbable											
Fairly likely											

Quality in PSHA studies

implies a careful and justified quantification of all uncertainties

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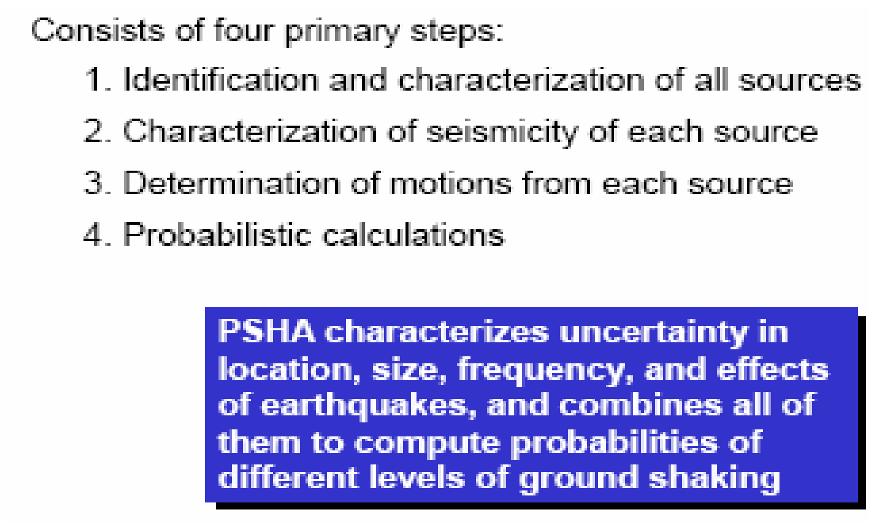
PSHA



Consists of four primary steps:

1. Identification and characterization of all sources
2. Characterization of seismicity of each source
3. Determination of motions from each source
4. Probabilistic calculations

PSHA characterizes uncertainty in location, size, frequency, and effects of earthquakes, and combines all of them to compute probabilities of different levels of ground shaking

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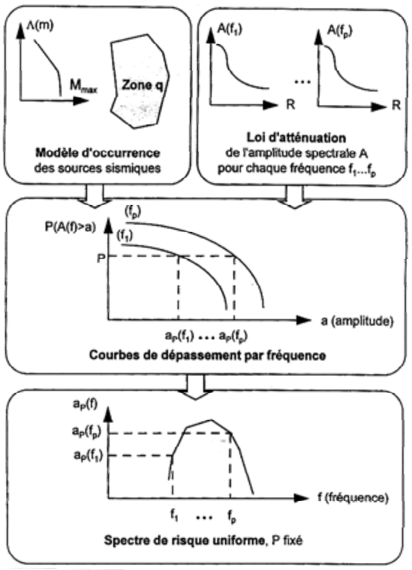
Probabilistic approach

- Delimitation of "homeogeneous" seismotectonic units
  - Faults / Areal / Volume
  - Recurrence laws (distribution N,M)
    - a, b, Mmin, Mmax
  - Depths
- Ground motion prediction equation
  - $Y = f(M, R, \varepsilon)$
- Exceedance probabilities for a single site
  - $p(y^*)=P(Y > y^*)$
  - loop over y^* : hazard curve
- Loop over frequencies
  - Uniform hazard spectra
- Loop over sites
  - Hazard maps

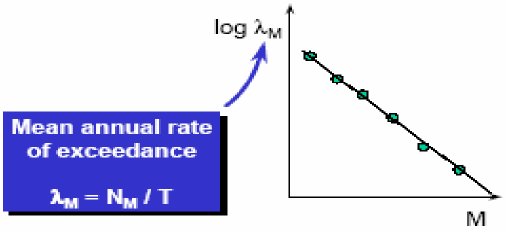


Probabilistic Approach

- Source Characterization
  - Develop a comprehensive set of possible scenario earthquakes: M, R (location)
  - Specify the rate at which each scenario earthquake (M,R) occurs

PSHA

Distribution of earthquake magnitudes



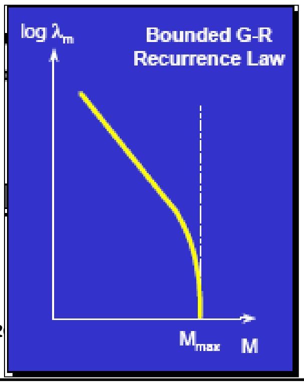
Distribution of earthquake magnitudes

Every source has some maximum magnitude

Distribution must be modified to account for M_{max}

Bounded G-R recurrence law

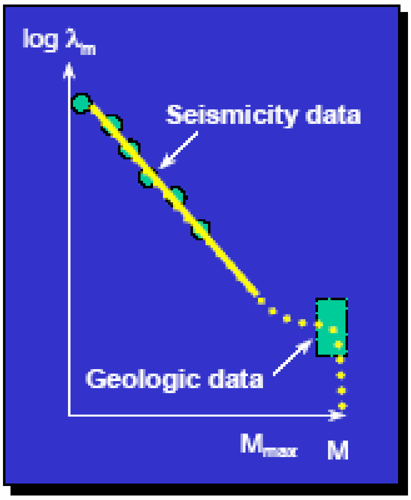
$$\lambda_m = \nu \frac{\exp[-\beta(m - m_o)] - \exp[-\beta(m_{\max} - m_o)]}{1 - \exp[-\beta(m_{\max} - m_o)]}$$

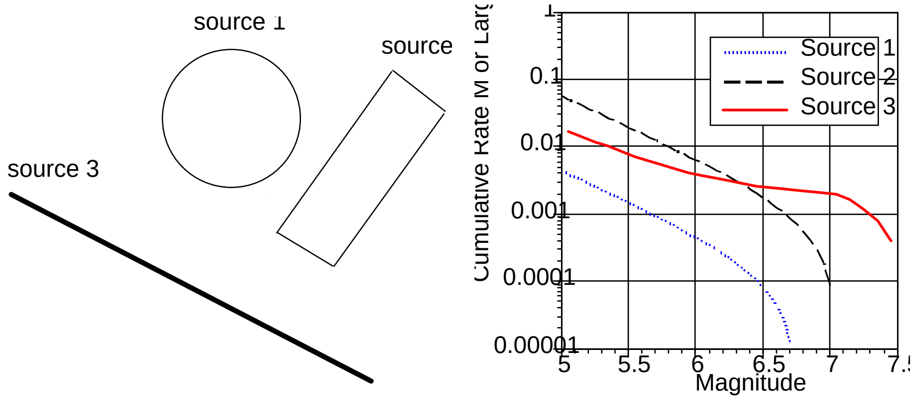


Distribution of earthquake magnitudes

Characteristic Earthquake Recurrence Law

Paleoseismic investigations
- Show similar displacements in each earthquake
- Inividual faults produce characteristic earthquakes
- Characteristic earthquake occur at or near M_{max}
- Could be caused by geologic constraints
- More research, field observations needed





PSHA / Temporal Uncertainty

Temporal uncertainty

Poisson process - describes number of occurrences of an event during a given time interval or spatial region.

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

Poisson process

$$P[N=n]=\frac{\mu^n e^{-\mu}}{n!}$$

where n is the number of occurrences and μ is the average number of occurrences in the time interval of interest.

Poisson process

Letting $\mu = \lambda t$

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

Then

$$\begin{aligned}P[N\geq 0]&=P[N=1]+P[N=2]+P[N=3]+\ldots+P[n=\infty]\\&=1-P[N=0]\\&=1-e^{-\lambda t}\end{aligned}$$

Temporal uncertainty

Then, the annual rate of exceedance for an event with a 10% probability of exceedance in 50 yrs is

$$\lambda=-\frac{\ln(1-0.1)}{50}=0.0021$$

The corresponding return period is $T_R = 1/\lambda = 475$ yrs.

For 2% in 50 yrs, $\lambda = 0.000404$/yr ⟶ $T_R = 2475$ yrs

Probabilistic Approach

- Source Characterization

- Ground Motion Characterization
  - Develop a full range of possible ground motions for each earthquake scenario (ε = number of std dev above or below the median) : GMPE Ground Motion Predictive Equation
  - Specify the probability of each ground motion for each scenario

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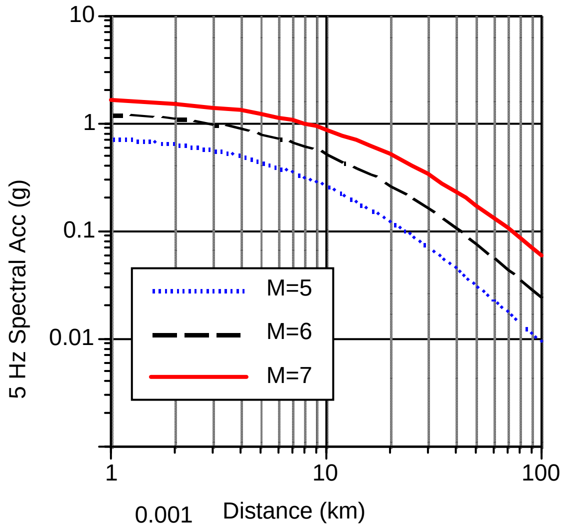
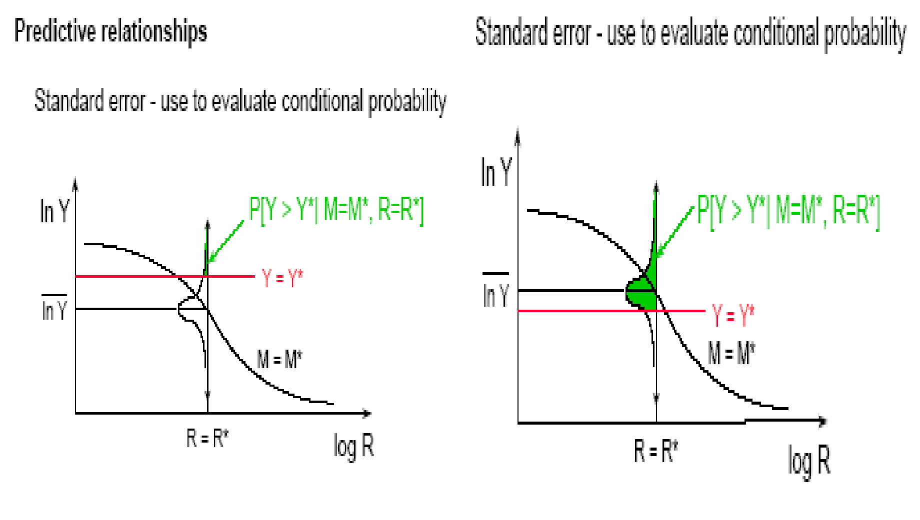
Median Ground Motion



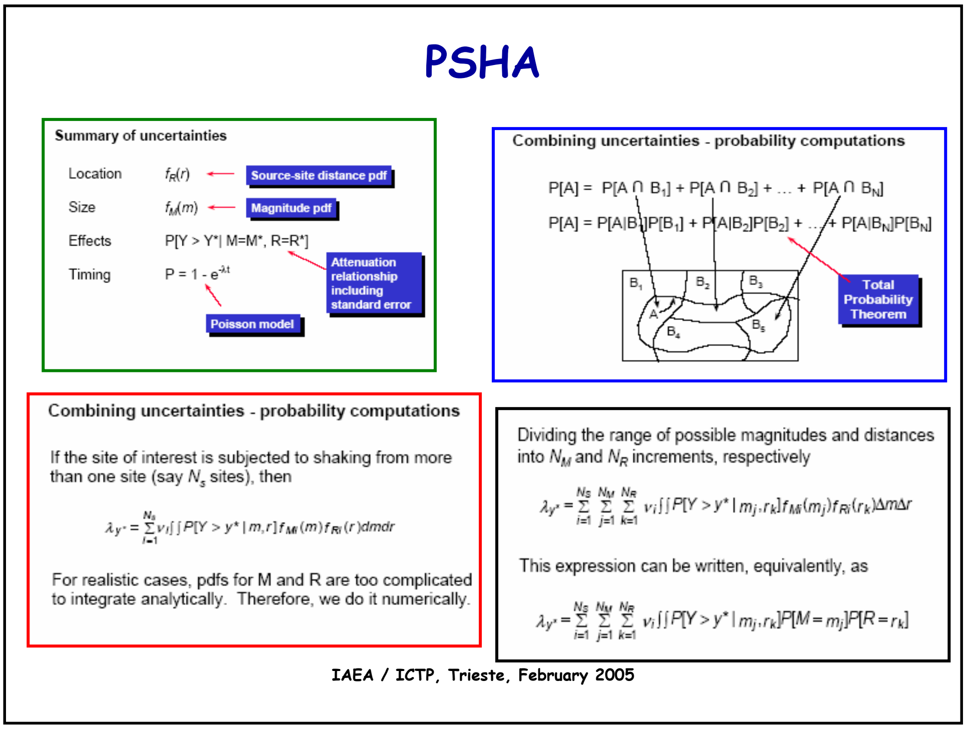
PSHA - GMPE



Probabilistic Approach (cont)

- Hazard Calculation
  - Rank scenarios (M,R, ε) in order of decreasing severity of shaking (often, use Sa)
  - Table of scenarios with ground motions and rates
  - Sum up rates of scenarios (hazard curve)

- Select a ground motion for the design hazard level
  - Back off from worst case ground motion until the sum of the rates of scenarios exceeding the ground motion is *"large enough to warrant consideration"* (e.g. the design hazard level)



PSHA

Summary of uncertainties

Location $f_R(r)$ ← **Source-site distance pdf**

Size $f_M(m)$ ← **Magnitude pdf**

Effects P[Y > Y*| M=M*, R=R*] ← **Attenuation relationship including standard error**

Timing $P = 1 - e^{-\lambda t}$ ← **Poisson model**

Combining uncertainties - probability computations

$$P[A] = P[A \cap B_1] + P[A \cap B_2] + \dots + P[A \cap B_N]$$

$$P[A] = P[A|B_1]P[B_1] + P[A|B_2]P[B_2] + \dots + P[A|B_N]P[B_N]$$

Total Probability Theorem

Combining uncertainties - probability computations

If the site of interest is subjected to shaking from more than one site (say N_s sites), then

$$\lambda_{y^*} = \sum_{i=1}^{N_s} \nu_i \int\int P[Y > y^* \mid m, r] f_{Mi}(m) f_{Ri}(r) dm dr$$

For realistic cases, pdfs for M and R are too complicated to integrate analytically. Therefore, we do it numerically.

Dividing the range of possible magnitudes and distances into N_M and N_R increments, respectively

$$\lambda_{y^*} = \sum_{i=1}^{N_S} \sum_{j=1}^{N_M} \sum_{k=1}^{N_R} \nu_i \int\int P[Y > y^* \mid m_j, r_k] f_{Mi}(m_j) f_{Ri}(r_k) \Delta m \Delta r$$

This expression can be written, equivalently, as

$$\lambda_{y^*} = \sum_{i=1}^{N_S} \sum_{j=1}^{N_M} \sum_{k=1}^{N_R} \nu_i \int\int P[Y > y^* \mid m_j, r_k] P[M = m_j] P[R = r_k]$$

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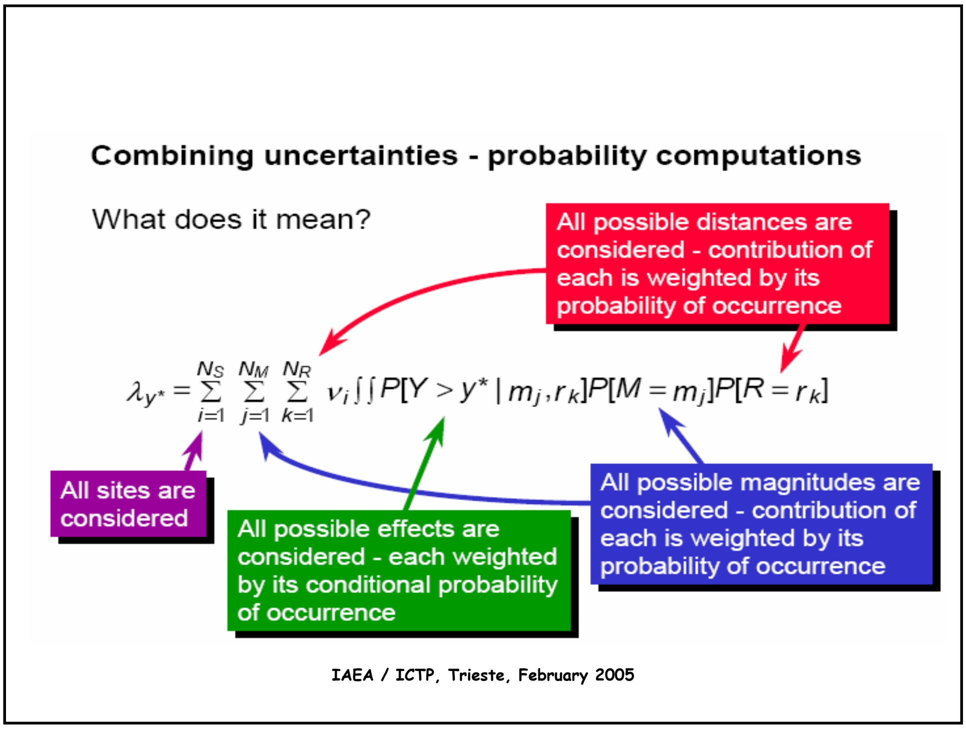

Combining uncertainties - probability computations

What does it mean?

$$\lambda_{y^*} = \sum_{i=1}^{N_S} \sum_{j=1}^{N_M} \sum_{k=1}^{N_R} \nu_i \int\int P[Y > y^* \mid m_j, r_k] P[M = m_j] P[R = r_k]$$

All possible distances are considered - contribution of each is weighted by its probability of occurrence

All sites are considered

All possible effects are considered - each weighted by its conditional probability of occurrence

All possible magnitudes are considered - contribution of each is weighted by its probability of occurrence

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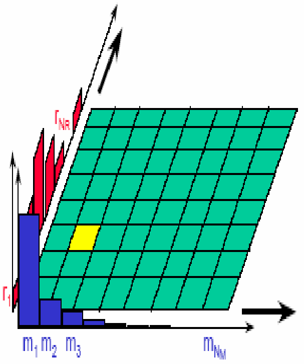
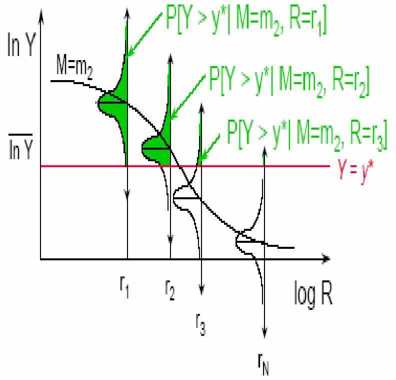
PSHA

N_M x N_R possible combinations
Each produces some probability of exceeding y^*
Must compute $P[Y > y^* | M=m_j, R=r_k]$ for all m_j, r_k



Compute conditional probability for each element on grid
Enter in matrix (spreadsheet cell)



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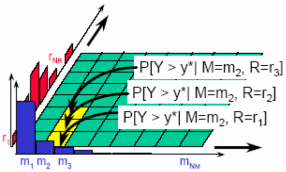
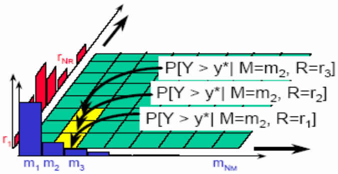
PSHA

"Build" hazard by:
computing conditional probability for each element
multiplying conditional probability by $P[m_j]$, $P[r_k]$, ν_i
Repeat for each source - place values in same cells

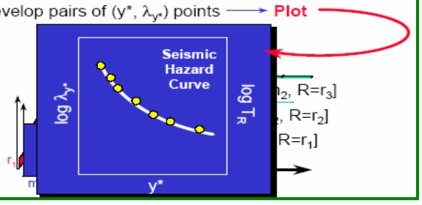


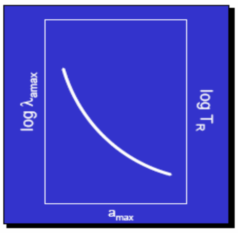
When complete (all cells filled for all sources),

Sum all λ-values for that value of $y^* \longrightarrow \lambda_{y^*}$



Choose new value of y^*
Repeat entire process
Develop pairs of (y^*, λ_{y^*}) points $\longrightarrow$ **Plot**





Seismic hazard curve shows the mean annual rate of exceedance of a particular ground motion parameter. A seismic hazard curve is the ultimate result of a PSHA.

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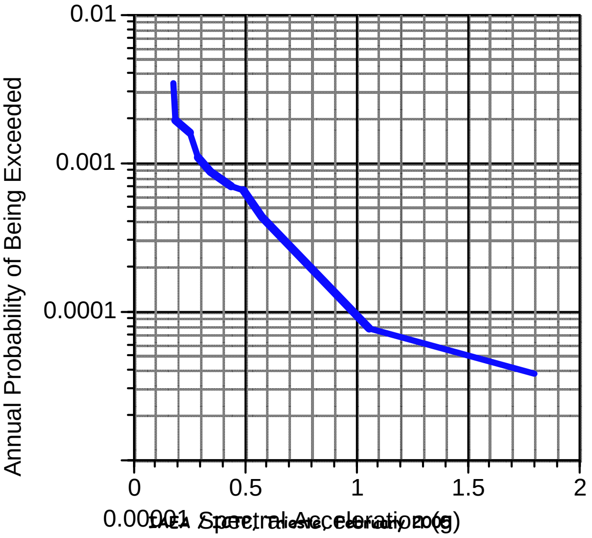
Partial List of Scenarios

Source	Mag	R (km)	Rate of Sa	Median Sa	Std Dev	ε	P(e)	Sa(g)	Rate
1	6,50	2	0,00022	1,38	0,53	0,5	0,175	1,80	0,000038
1	5,00	2	0,00180	0,58	0,73	0,0	0,197	0,58	0,000355
1	5,00	10	0,00180	0,24	0,73	1,0	0,121	0,49	0,000218
2	5,50	40	0,02216	0,07	0,66	1,5	0,066	0,18	0,001453
2	6,00	40	0,00786	0,10	0,59	1,5	0,066	0,25	0,000516
2	6,50	40	0,00279	0,16	0,52	1,5	0,066	0,35	0,000183
3	7,25	60	0,00170	0,19	0,42	2,0	0,028	0,44	0,000047
3	7,25	60	0,00170	0,19	0,42	1,0	0,121	0,29	0,000206
3	7,25	60	0,00170	0,19	0,42	0,0	0,197	0,19	0,000336

Rank Scenarios by Ground Motion

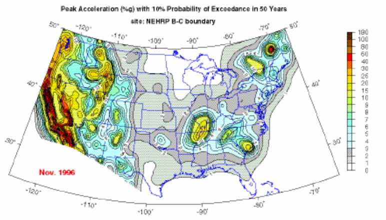
Source	Mag	R (km)	ε	Sa(g)	Rate	Hazard
1	6,50	2	0,5	1,80	0,000038	0,000038
1	5,00	10	0,0	0,58	0,000355	0,000432
3	7,25	60	1,0	0,49	0,000218	0,000649
2	6,50	40	1,5	0,44	0,000047	0,000697
3	7,25	60	1,5	0,35	0,000183	0,000880
1	5,00	2	1,5	0,29	0,000206	0,001085
2	6,00	40	2,0	0,25	0,000516	0,001601
3	7,25	60	1,0	0,19	0,000336	0,001937
2	5,50	40	0,0	0,18	0,001453	0,003390

Hazard Curve

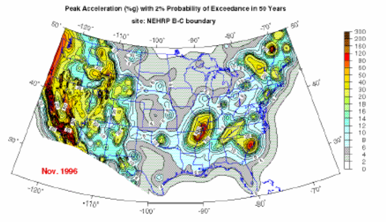


PSHA - Code implications

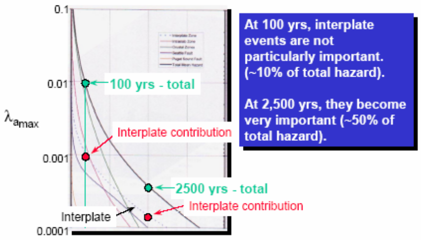
UBC - 10% probability of exceedance in 50 yrs



AASHTO - 2% probability of exceedance in 50 yrs ???



AASHTO - 2% probability of exceedance in 50 yrs ???



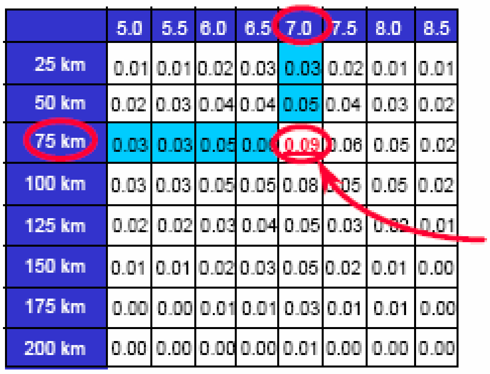
At 100 yrs, interplate events are not particularly important. (~10% of total hazard).

At 2,500 yrs, they become very important (~50% of total hazard).

PSHA Disaggregation (De-aggregation)

Common question:

What magnitude & distance does that a_{max} value correspond to?



	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
25 km	0.01	0.01	0.02	0.03	0.03	0.02	0.01	0.01
50 km	0.02	0.03	0.04	0.04	0.05	0.04	0.03	0.02
75 km	0.03	0.03	0.05	0.0	0.09	0.06	0.05	0.02
100 km	0.03	0.03	0.05	0.05	0.08	05	0.05	0.02
125 km	0.02	0.02	0.03	0.04	0.05	0.03	[illegible]	0.01
150 km	0.01	0.01	0.02	0.03	0.05	0.02	0.01	0.00
175 km	0.00	0.00	0.01	0.01	0.03	0.01	0.01	0.00
200 km	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00

Total hazard includes contributions from all combinations of M & R.

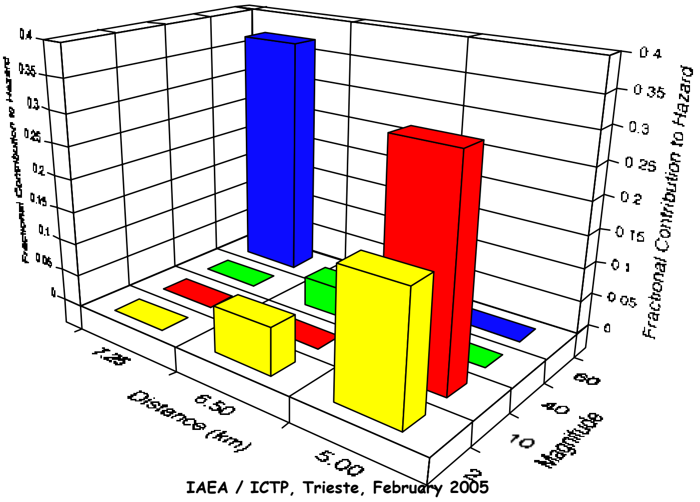
Break hazard down into contributions to "see where hazard is coming from."

M=7.0 at R=75 km

Deaggregation at 10^{-3} Hazard

Source	Mag	R (km)	ε	Sa(g)	Rate	Hazard	Deagg
1	6,50	2	0,5	1,80	0,000038	0,000038	0,035
1	5,00	10	0,0	0,58	0,000355	0,000432	0,327
3	7,25	60	1,0	0,49	0,000218	0,000649	0,201
2	6,50	40	1,5	0,44	0,000047	0,000697	0,044
3	7,25	60	1,5	0,35	0,000183	0,000880	0,169
1	5,00	2	1,5	0,29	0,000206	0,001085	0,190
2	6,00	40	2,0	0,25	0,000516	0,001601	
3	7,25	60	1,0	0,19	0,000336	0,001937	
2	5,50	40	0,0	0,18	0,001453	0,003390	

Group Similar Scenarios for Deaggregation Plots



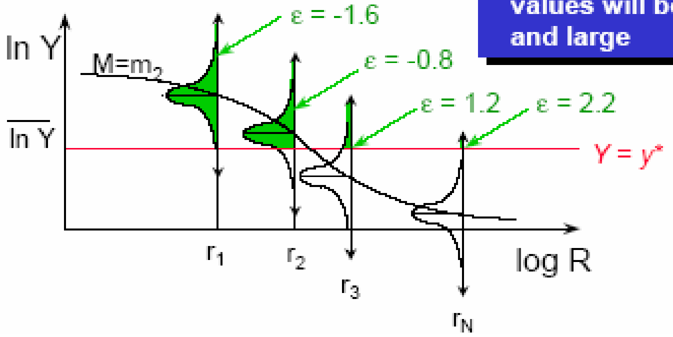
PSHA Disaggregation (De-aggregation)

Another disaggregation parameter

$$\varepsilon = \frac{\ln y^* - \overline{\ln y}}{\sigma_{\ln y}}$$

For low y*, most ε values will be negative

For high y*, most ε values will be positive and large



Overview

Some generalities on hazard assessment
- goals and applications : probability level, ground motion parameter (pga ≠ time history)
- DSHA / PSHA

Dealing with uncertainties in PSHA
- Types of uncertainties
  - Epistemic / Aleatory
- origins of uncertainties
  - data : raw, reprocessed
  - methods : method themselves, parameters
- An example : Ground Motion Predictive Equations
- ? experts ?

Quality requirements / Quality criteria ?
- Personal recommendations

Probability statements reflect a quantitative expression of an individual's state of knowledge

> *To know that we know what we know, and that we do not know what we do not know, that is true knowledge.*
>
> -Confucius

Aleatory Variability and Epistemic Uncertainty

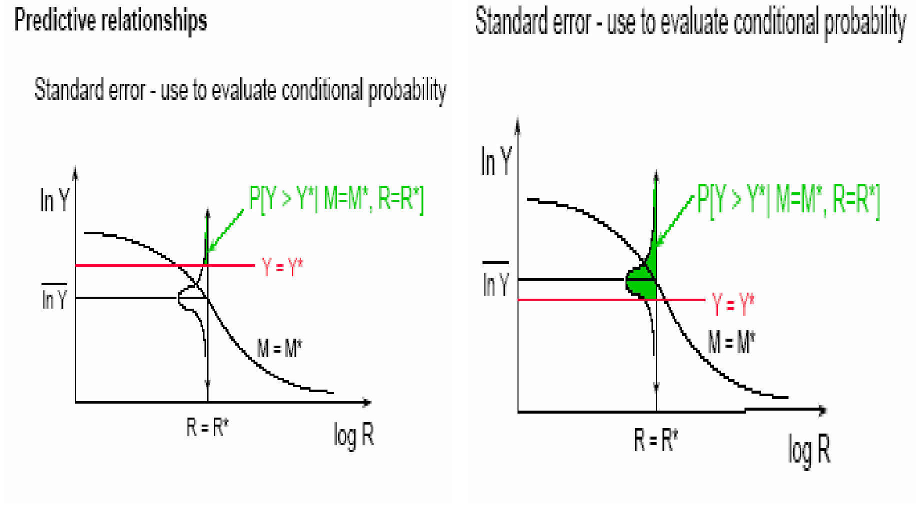
Random Variability (aleatory)

- Randomness in M, location, ground motion (ε)
- Incorporated in hazard calculation directly

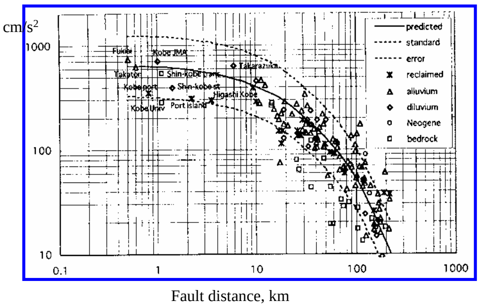
Scientific Uncertainty (epistemic)

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

An example of aleatory variability : GMPE



Empirical attenuation relationships
Ground motion predictive equation



Example Kobé event (17/01/1995) :

Comparison between the observed pga and the values predicted with the Fukushima and Tanaka(1990) relationship

Aleatory Variability

Comparion of different GMPE (Kramer et al., 1997)

Epistemic Uncertainty

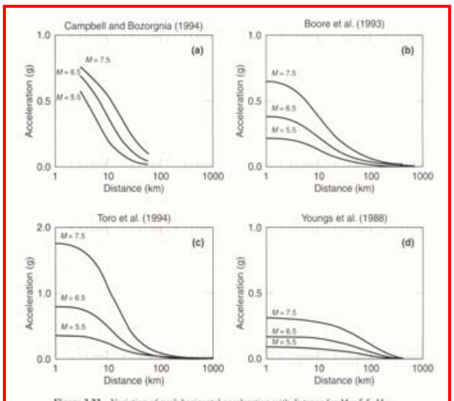


Figure 3.22 Variation of peak horizontal acceleration with distance for *M* = 5.5, *M* = 6.5, and *M* = 7.5 earthquakes according to various attenuation relationships: (a) Campbell and Bozorgnia (1994), soft rock sites and strike-slip faulting; (b) Boore et al. (1993), site class B; (c) Toro et al. (1994); and (d) Youngs et al. (1988), intraslab event.

GMPE : distribution of residuals : ? lognormal ?

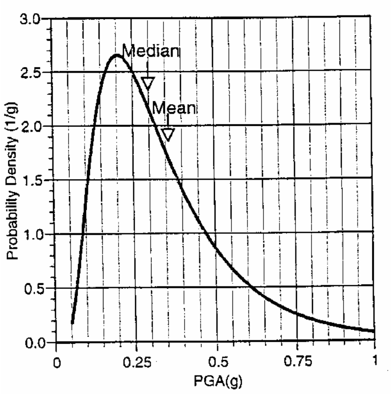


Figure 3. Comparison of the mean and median for a lognormal distribution with a standard deviation of 0.6.

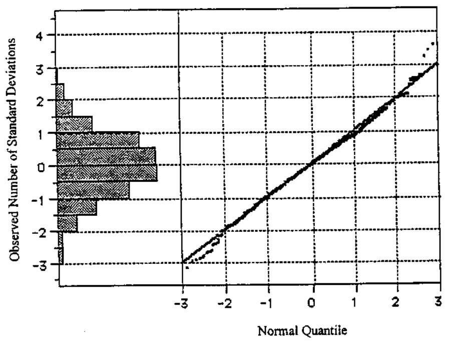


Figure 4. Normal quantile plot comparing the observed distribution of peak accelerations with the assumed lognormal distribution. If the data follow a lognormal distribution, the points would lie on the line.

D'après Abrahamson, 2000

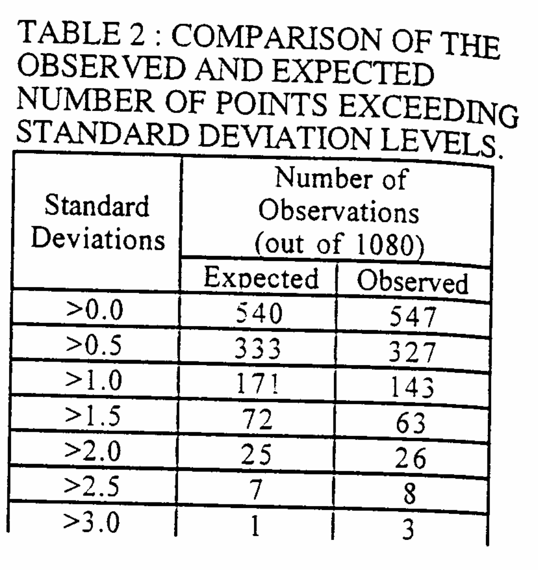


TABLE 2 : COMPARISON OF THE OBSERVED AND EXPECTED NUMBER OF POINTS EXCEEDING STANDARD DEVIATION LEVELS.

Standard Deviations	Number of Observations (out of 1080)	
	Expected	Observed
>0.0	540	547
>0.5	333	327
>1.0	171	143
>1.5	72	63
>2.0	25	26
>2.5	7	8
>3.0	1	3

Epistemic Uncertainty

- Due to lack of data
  - Sparse data implies large uncertainty

- In practice, not always the case

  Estimated using alternative available models/data
  - Few available studies leads to apparent small uncertainty (few alternatives available)
  - Many available studies leads to larger uncertainty (more alternatives available)

Capen's survey

- While a Distinguished Lecturer for the Society of Petroleum Engineers, Ed Capen asked ten questions of the audiences on the meetings circuit in 1974-1975.
- Examples of questions:
  - What is the area of Canada in square miles?
  - How long is the Amazon River in miles?
  - How many earth years does it take the planet Pluto to revolve around the sun?
- He asked participants to estimate, variously, 98, 90, 80, 50, and 30% confidence ranges

Reference: E.C. Capen, 1976, "The Difficulty of Assessing Uncertainty," Journal of Petroleum Technology, August, p. 843-850

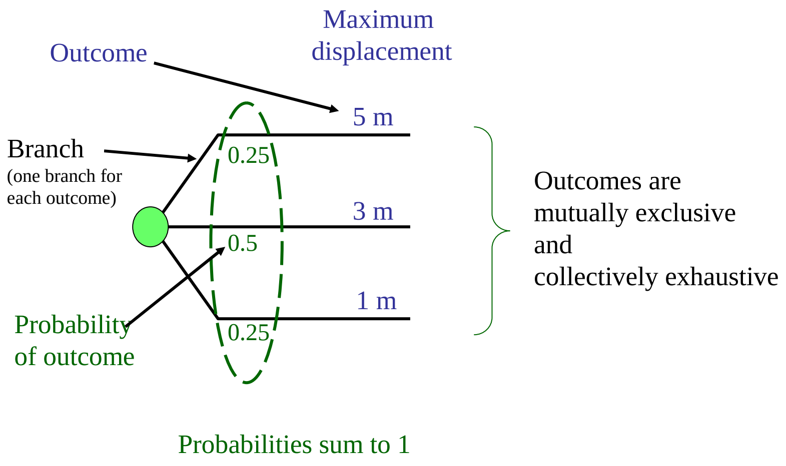
Capen's survey results

Requested Range	Expected # misses	Avg # misses
98%	0.2	6.63
90%	1	6.51
80%	2	7.00
50%	5	6.78
30%	7	7.10

Some of his conclusions:

- People without knowledge of the topic are often unable to differentiate between 30% and 98% confidence intervals.
- The more people know about the general subject (not the specific question), the larger confidence interval they assign. The less they know, the smaller the chance that the interval includes the truth.
- Even when told that most people are overconfident with their intervals, they continue to make the interval too small. Asking for two range estimates helps (e.g., first 90%, then 50% confidence interval).

Representation of discrete uncertain events in probability trees



Maximum displacement

Outcome

5 m

Branch
(one branch for each outcome)

0.25

3 m

0.5

1 m

0.25

Probability of outcome

Outcomes are
mutually exclusive
and
collectively exhaustive

Probabilities sum to 1

Several types of uncertainty may be relevant

Model uncertainty
  - Uncertainty about the fundamental concepts of the hazard and how it should be modeled

Mathematical uncertainty
  - Uncertainty about how well the mathematical implementation of the model represents "reality"

Parameter uncertainty
  - Uncertainty about the values for the inputs to the mathematical model

Most of the discussion and examples today about using probability to represent uncertainty focus on parameter uncertainties

In some cases, one may believe there are several alternative models for a process that are all credible

  In these cases, parameters for each credible model should be assessed

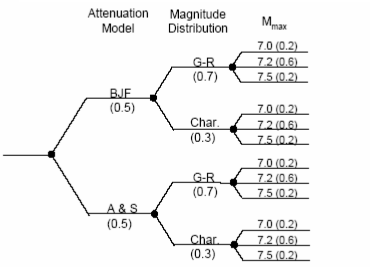
  "Weights" can be assigned to the alternative models, reflecting one's judgement about the relative credibility or usefulness of the predictions or results from each model

PSHA - Logic tree

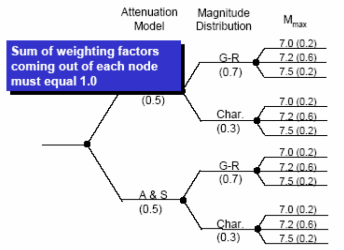
Not all uncertainty can be described by probability distributions

Most appropriate model may not be clear
- Attenuation relationship
- Magnitude distribution
- etc.

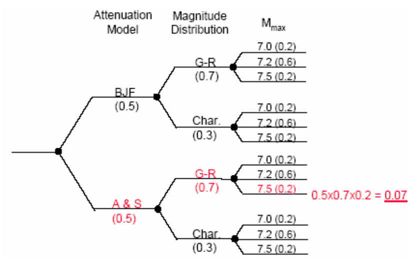
Experts may disagree on model parameters
- Fault segmentation
- Maximum magnitude
- etc.

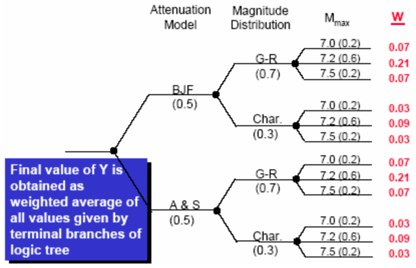


PSHA Logic trees



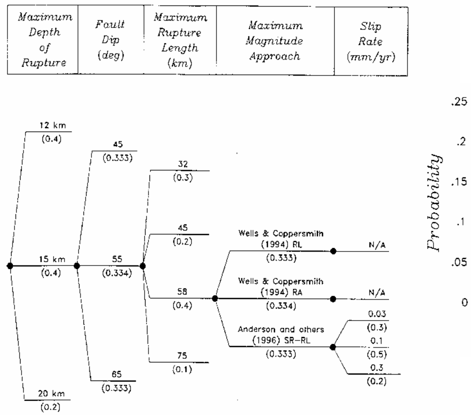
Sum of weighting factors coming out of each node must equal 1.0

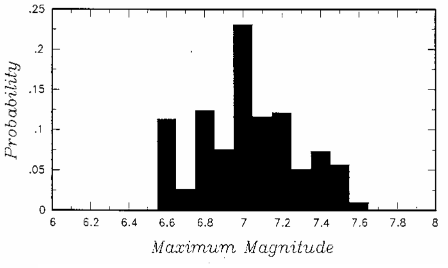




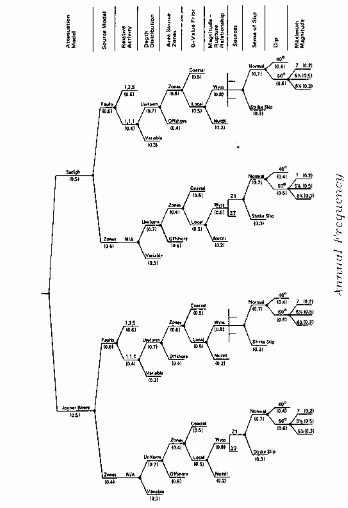
Final value of Y is obtained as weighted average of all values given by terminal branches of logic tree

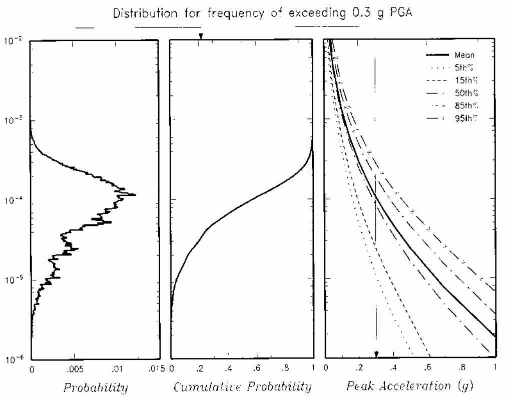
Example logic tree: Typical maximum magnitude assessment for a fault-specific seismic source





Example of a seismic hazard distribution





Overview

- Some generalities on hazard assessment
  - goals and applications : probability level, ground motion parameter (pga ≠ time history)
  - DSHA / PSHA
- dealing with uncertainties in PSHA
  - Types of uncertainties
    - Epistemic / Aleatory
  - origins of uncertainties
    - data : raw, reprocessed
    - methods : method themselves, parameters
  - An example : Ground Motion Predictive Equations
  - ? experts ?
- Quality requirements / Quality criteria ?
  - Personal recommendations

Data

raw data

- seismicity catalogues : x,y, h, magnitudes
  - instrumental / historical / paleo,
  - domestic / foreign
  - fault activity / deformation rate
- attenuation relationships

  (ground motion prediction equations - GMPE) ←
    - standard-deviations, tectonic environment, M-R distribution, M + R definitions, site conditions, ground motion parameter (max, average, random,…)
  - Theoretical / numerical GMPEs
    - crustal + source parameters
- site conditions / site effects
  - different levels :
    - site characteristics : geological, geotechnical, geophysical
    - site effects : measurements (AV, WM, SM)

Data

Reprocessed data

- "homogeneized" seismicity catalogue :
  - keep track of all methods
  - in case of various possible interpretations, include logic tree branches for possible variations
    - (intensity - magnitude)
- seismicity zones
  - geographical limits : explain your choice (many strange examples in DSHA !)
  - seismicity parameters : mmin, Mmax, b, distribution, G-R / characteristic
- ground motion prediction equations
  - M conversion
  - R conversion
  - "rock" corrections
- site conditions / site effects
  - from site characteristics to site model :
    - 1D-2D-3D, detailed layering for computations,
    - parameters (elastic / damping / NL;
    - site effects measurements (AV, WM, SM) : S/N ratio, selection of recordings, methods for deriving amplification curve (Fourier, response, …

Methods

Hazard code

- internal parameters
- ? zone free ?
- truncation / no truncation

Logic tree

- document the weights !

Theoretical GMPE

- stochastic-empirical / wave propagation
- point source vs extended source

Site effects

- Rheology : L / LE / NL
- Geometry : 1D / 2D / 3D
- Input wavefield
  - vertical / oblique / azimuth,
  - SH/SV/P,
  - plane / with source,
- Input motion : sensitivity to accelerograms

The case of GM Predictive Equations

- Y = b0 . f1(M) . f2 (R) . f3(M,R) . f4 (Pi) . ε
  - Y = Ground motion parameter
  - M = measure of magnitude (ML, Ms, Mb, Mw, …)
  - R = measure of distance (Rep, Rh, Rf, …)

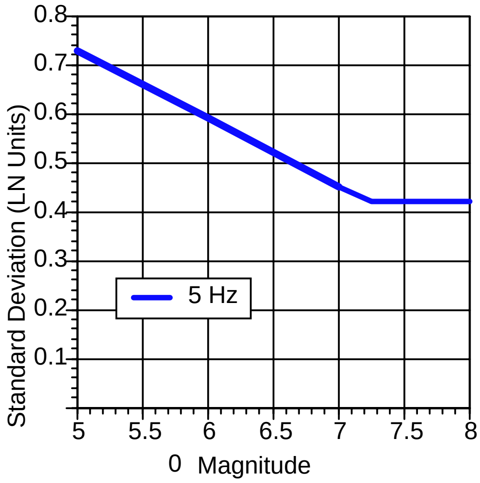
  - f1(M) = exp (b1.M)
  - f2(R) = exp(-b2.R) . $[R^2 + b4]^{-b3/2}$ (0.5 < b3 < 1)
  - f3(M,R) : b4= b5. exp(b6 . M)
  - f4(Pi) : corrective factors
    - site conditions (most often)
    - Fault types (inverse / strike-slip / normal)
    - Directivity …
  - ε : standard-deviation (about 2 : NEVER NEGLECT !)

The case of GM predictive equations

Aleatory variability σ

- larger data sets: equal σ !
- almost no hope of significant reduction of σ in the foreseeable future
  - (complexity of physics, crudeness of models)
- homoskedastic or not ?
  - variability of σ with M, or R, or pga, or site conditions
  - Partial results
    - σ ↘ when M ↗
    - σ ↘ when R ↘
    - σ ↘ when pga ↗
    - σ ↘ when site softness ↗

Standard Deviation of Ground Motion



σ values and upper bounds

PSHA "Achille's heel"

- Low annual probabilities : possibility of unphysical estimates
  - Examples : PEGASOS (10^{-7}), Yucca Flat (10^{-8})
- Origin :
  - M, R always physically possible
  - but
  - tail of Gaussian distribution on GMPE : no upper limits for εσ
    - ε = 1 : 84%; ε = 2 : 97.7%; ε = 3 : 99. %; ε = 4 : 99.%;
  - ⇒ no saturation of hazard estimate
  - ⇒ hazard driven by the tail of the lognormal distribution of residuals
- Common, artificial solution
  - truncating ε to some values (2, 3) : convenient, but not satisfactory
- Challenge : finding physical upper bounds
  - not easy : very high levels (> 5 g) could not be proved to be unphysical!

σ values and upper bounds

Does DSHA provide envelope estimates ?

Pessimistic scenarios (M, R) but

Median : 50 % chances to be exceeded

Median + σ : 16% chances to be exceeded (1 in 6 !)

Answer = NO !

EU in GM prediction equations

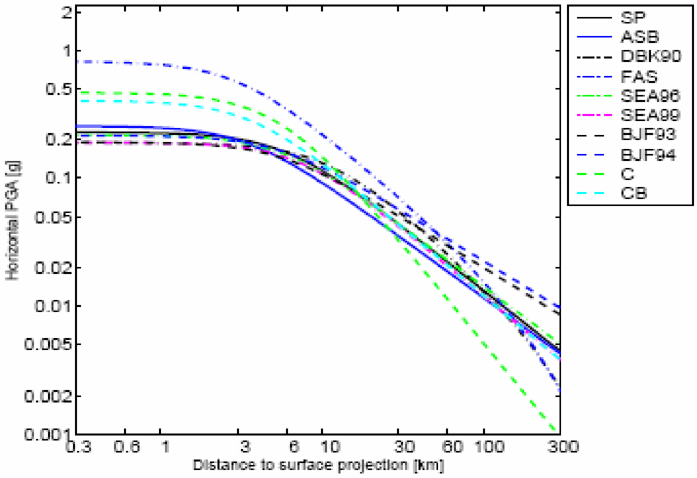
Is all the uncertainty included in σ ?

- would be so only if :
  - GMPE derived very large data set
  - dense and uniformly distributed accelerograph networks
  - triggered by earthquakes with source characteristics spanning the whole range of possible parameter variations
    - such a data set DOES NOT EXIST (yet)
- existing GMPE based on biased data sets
  - source characteristics
  - spatial sampling (distance and azimuth)
- existing GMPE also biased by the formulation
  - same data sets and different formulations result in different median predictions

Consequences

- never use one single GMPE ! use several !
- in areas with few local data, the EU is even larger: extrpolating GMPE from other areas, or from small events
- areas with many events / data : is it necessary to use GMPE from elsewhere ?
  - Yes ! Existing data sets may always be biased !
  - Including by the technology (HF issue !)

Horizontal PGA ($M_w = 5.5$)



Overview of empirical strong-motion attenuation relationships for peak ground acceleration and spectral ordinates – p.9/27

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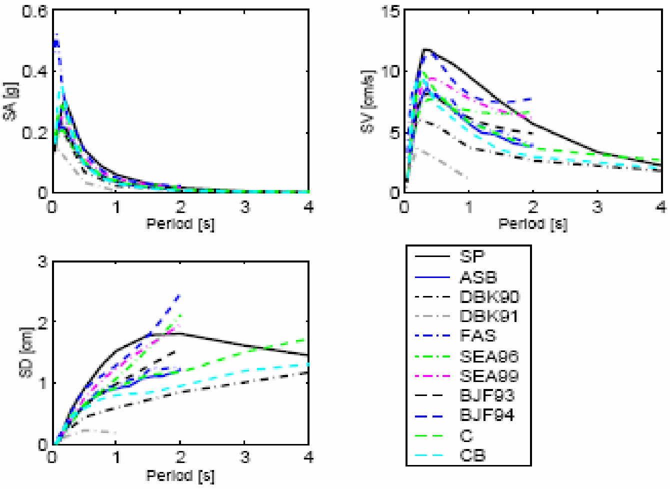
Horizontal spectra ($M_w = 5.5$, $d_f = 10\,\mathrm{km}$)



Overview of empirical strong-motion attenuation relationships for peak ground acceleration and spectral ordinates – p.10/27

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Logic Trees for GM models

Widely used but little guidance !

Branches and weigths

Conversions for parameter compatibility

Adjustments for regional applicability

Uncertainties in conversions and adjustments

Logic Trees for GM models

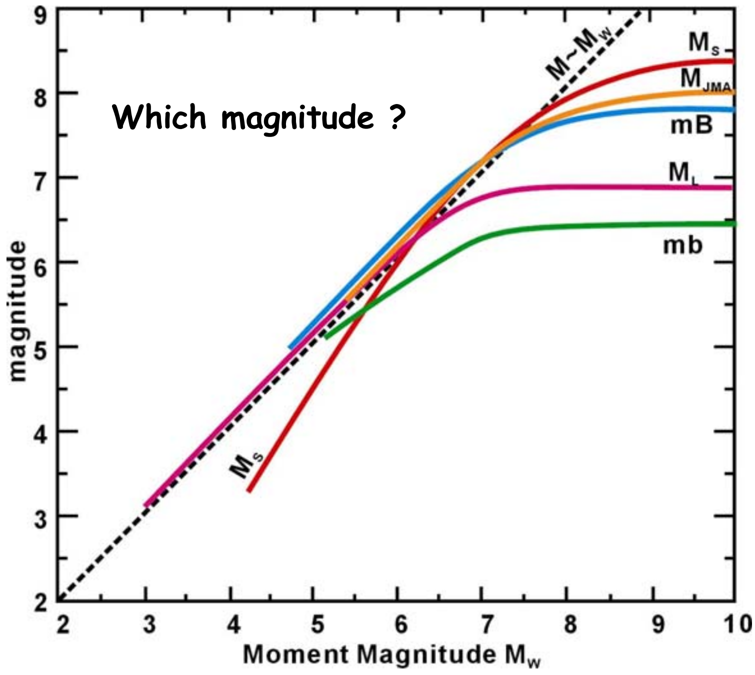
Branches and weigths
- 1 branch fro each GMPE thought relevant for the site / region
- weights reflect relative confidence from the expert
    - may vary from expert to expert…
    - may vary across M-R bins
    - may vary from frequency to frequency
- intrinsic versus application-specific characteristics
    - intrinsic : confidence in the GMPE itself (base data, derivation method, …) regardless of where it is applied
        - weights may bary M-R bins, across frequency
        - allows to take maximum advantage of each GMPE strength, in domains where it is well constrained
        - criteria: M-R distribution, quality of SM data
    - application specific : two kinds
        - related to conversions adopted for hazard calculations
        - related to the region of application

Influence on final results [Sabetta et al., SDEE, 2004]
- if more than 4 GMPE, only small differences in median hazard estimates at exceedance levels 10^{-3}

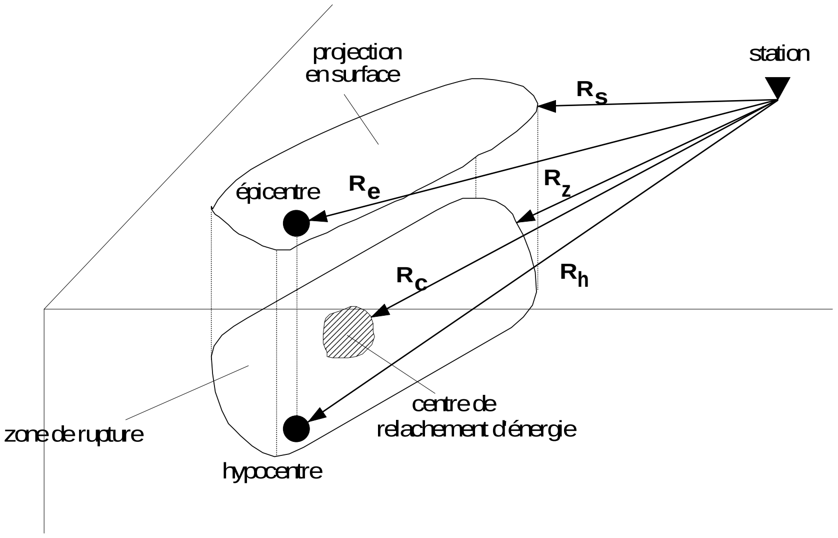
Logic Trees for GM models

Application-specific characteristics : conversions for parameter compatibility

- wide variety of definitions used in GMPE
  - hz component (max 2, max θ, min, average, random, …)
  - magnitude scale
  - measure of source-to-site distance
    - ⇒ suitable adjustments MUST BE MADE to account for different definitions used in the selected GMPEs
- suitable conversions
  - component definition : see Bommer et al., BSSA, 2004/5
  - magnitude scale: see Bommer et al., BSSA, 2004/5
  - distance measure : see Scherbaum et al., BSSA, 2004 (94-3, 1059-1069)
    - ⇒ _greatest impact : distance definition !
- Other sources of incompatibility
  - different predictor variables in different branches (GMPE)
    - example 1 : style of faulting
    - ⇒ possible solution: adding aleatory variability in other GMPEs
    - example 2 : site class definition
      (WNA: rock = Vs30 > 620 m/s, ENA: rock = Vs30 > 2800 m/s)
    - ⇒ possible solution: correcting for site conditions (not so simple - depends on frequency, on soil profile, on near-surface attenuation : includes also AV !)


Which magnitude ?

Distance measure



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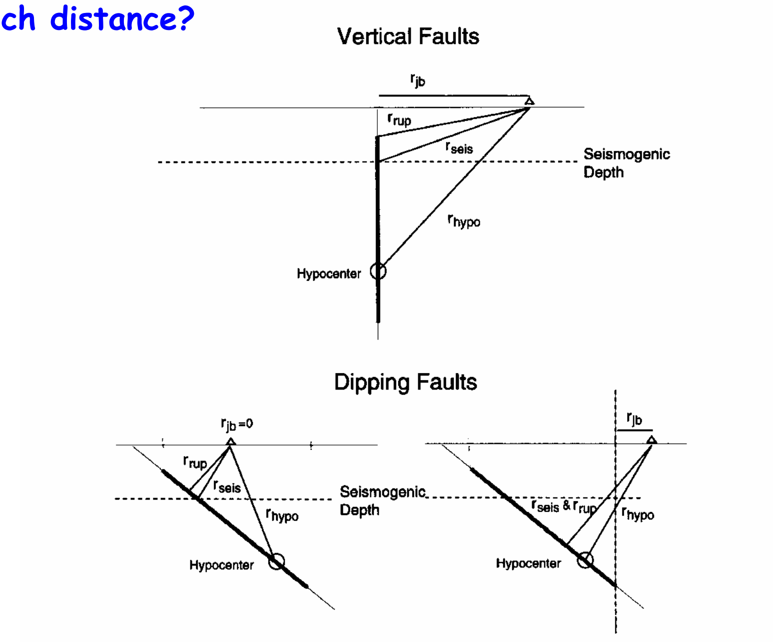
Which distance?

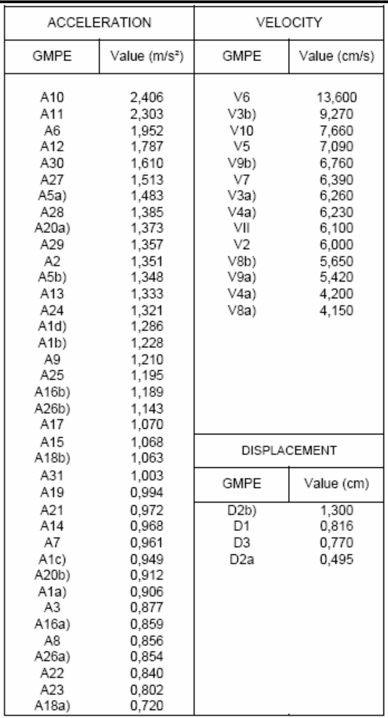


▲ **Figure 1.** Source-to-site distance measures for ground motion atteodels. Seismogenic depth (long dashed line) is the depth of the top omogenic part of the crust. The distance measured by Campbell is the shortest distance to the rupture surface below the seismogenic depth.

	Ambraseys et al. (1996)	Berge-Thierry et al. (2000)	Sabetta and Pugliese (1996)	Lussou et al. (2001)	Abrahamson and Silva (1997)	Boore et al. (1997)	Campbell and Bozorgnia (2002)
Magnitude	Ms	Ms	Ml and Ms	M_{JMA}	Mw	Mw	Mw
Distance	Rjb	Rhypo	Rjb	Rhypo	Rjb	Rjb	Rseis
Motion	larger	random	Larger	random			
Tectonic context	European	European	Italien	Japan	Western US Global	Western US	Global
Site conditions	-	-	-	++	-	++	-
Data quality	-	-	-	++	+	+	+
Mw<5.5	+	+	+	+	+	-	-
5.5<Mw<6.5	+	+	--	+	+	+	+
Mw>6.5	-	-	-	--	++	+	++
D<15km	-	--	-	--	+	+	++
15<D<70km	+	+	+	+	+ (conv)	+	+
>70 km	-	-	-	-	+	-	-
Rock velocity	550 m/s	550 m/s	800 m/s	950 m/s	650 m/s	650 m/s	650 m/s (generic) 950 m/s (hard)

GMPE variability

- Example
  - M=6, R = 25 km
  - pga, pgv, pgd
- Overall variability of median
  - 0.72 to 2.406 m/s² : 3.3
  - 4.15 to 13.6 cm/s : 3.3
  - 0.495 to 1.3 cm : 2.6



ACCELERATION		VELOCITY	
GMPE	Value (m/s²)	GMPE	Value (cm/s)
A10	2,406	V6	13,600
A11	2,303	V3b)	9,270
A6	1,952	V10	7,660
A12	1,787	V5	7,090
A30	1,610	V9b)	6,760
A27	1,513	V7	6,390
A5a)	1,483	V3a)	6,260
A28	1,385	V4a)	6,230
A20a)	1,373	VII	6,100
A29	1,357	V2	6,000
A2	1,351	V8b)	5,650
A5b)	1,348	V9a)	5,420
A13	1,333	V4a)	4,200
A24	1,321	V8a)	4,150
A1d)	1,286		
A1b)	1,228		
A9	1,210		
A25	1,195		
A16b)	1,189		
A26b)	1,143		
A17	1,070		
A15	1,068		
A18b)	1,063		
A31	1,003		
A19	0,994		
A21	0,972		
A14	0,968		
A7	0,961		
A1c)	0,949		
A20b)	0,912		
A1a)	0,906		
A3	0,877		
A16a)	0,859		
A8	0,856		
A26a)	0,854		
A22	0,840		
A23	0,802		
A18a)	0,720		

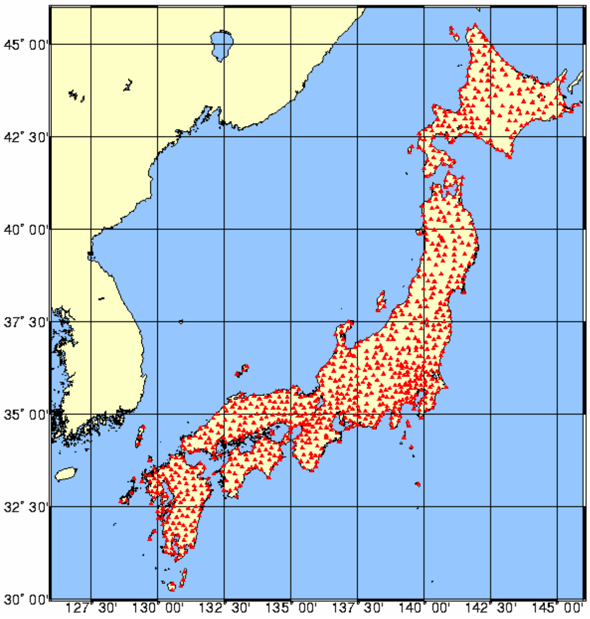
DISPLACEMENT	
GMPE	Value (cm)
D2b)	1,300
D1	0,816
D3	0,770
D2a	0,495

Use / choice of GMPE

- Several hundreds are available !
  - possibility to "cheat" : choosing the one best corresponding to one's own interests
- Advice
  - Never use one single GMPE
  - Similar seismotectonic context
    (as much as possible)
  - As much as possible, try to keep the same site / fault configuration
  - Go back to the original publications
    - validity domains, exact parameter definitions
    - prefer GMPE from peer reviewed international journals
  - Site conditions : very often basic / oversimplistic and badly constrained :
    - consequences : underestimation bias for some sites, overestimation bias for some other
    - exception : KNET et KIKNET Japanese networks
  - Do account for standard deviations
    - NEVER USE GMPE which do not report on σ !

1000
accelerometres

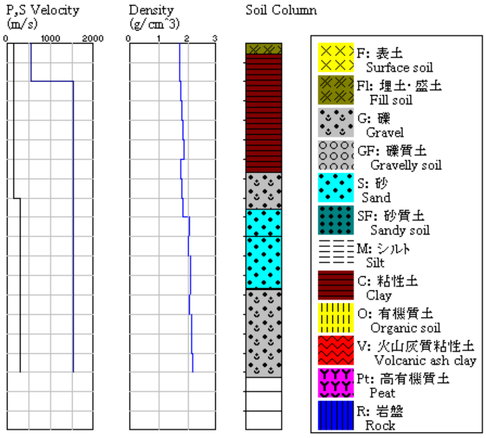
mesh = 25 km



Kyoshin Net

K-NET : Geotechnical data for each station

- penetrometer test
- P, S velocities
- density
- geological log



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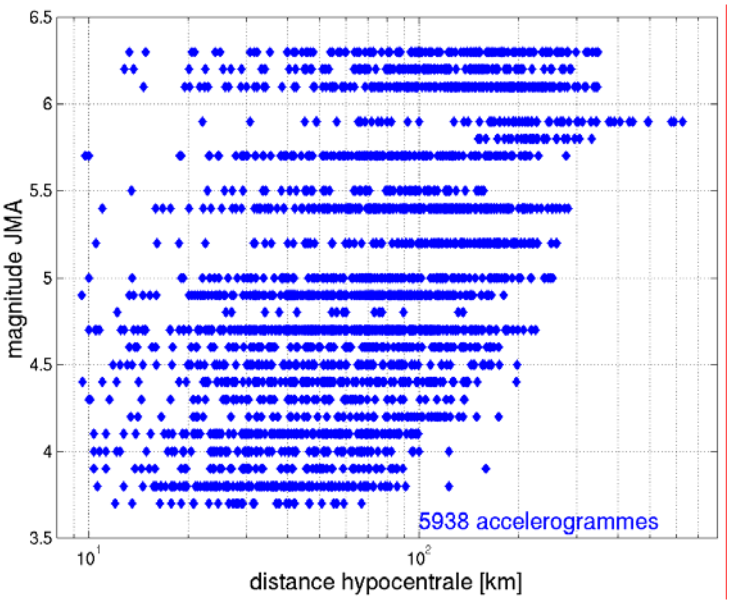
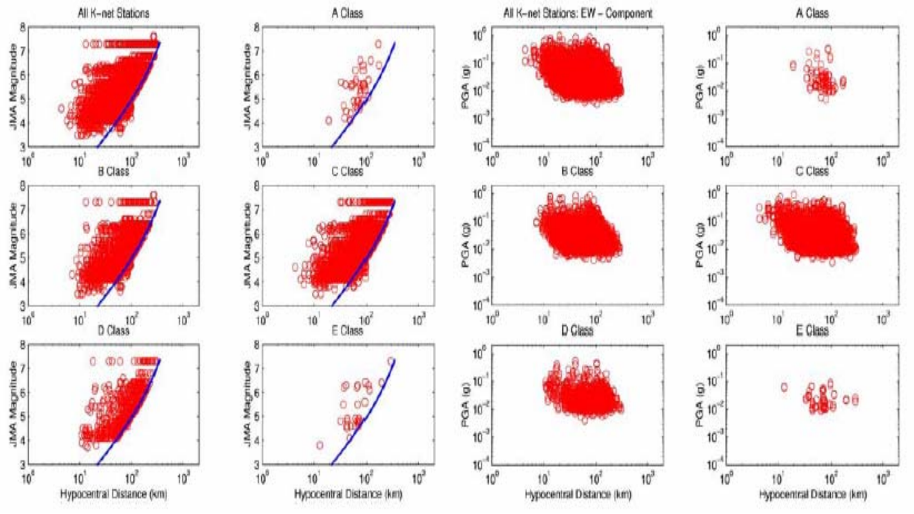
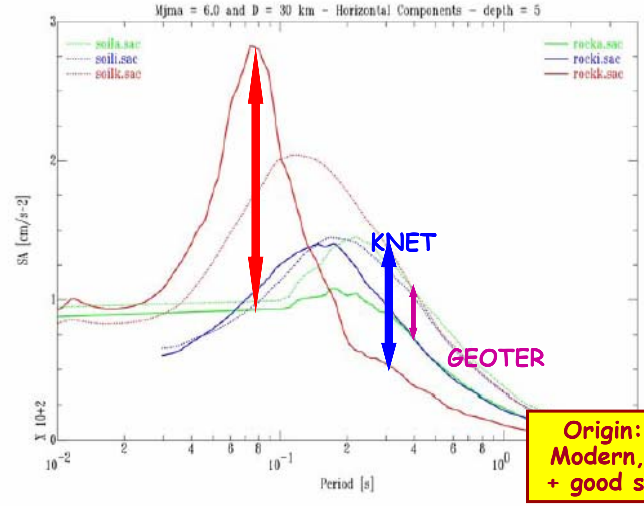
3 year data...



KNET 6 year data



Comparison with 2 other GMPE for M=6.0 - D=30 km



Larger short period content

Larger site-to-site differences at intermediate and long pariods

Origin: Japanese context ?
Modern, digital instruments ?
+ good site characterization ?

Concluding comments on uncertainties

- Uncertainties in GMPE
  - will remain large for decades !
- essential goal
  - identify, quantify, capture
  - demonstrate its impact on the hazard results
  - inform risk-based decisions regarding eq-resistant design
- Distinction Epistemic / Aleatory
  - sometimes ambiguous
  - needed for rational treatment
    - aleatory: measured and included in hazard integral
    - epistemic : managed through logic trees
      - may be used in PSHA and DSHA

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    - data : raw, reprocessed
    - methods : method themselves, parameters
  - ? experts ?
- Quality requirements / Quality criteria ?
  - Personal recommendations

Experts
? any expert-related bias

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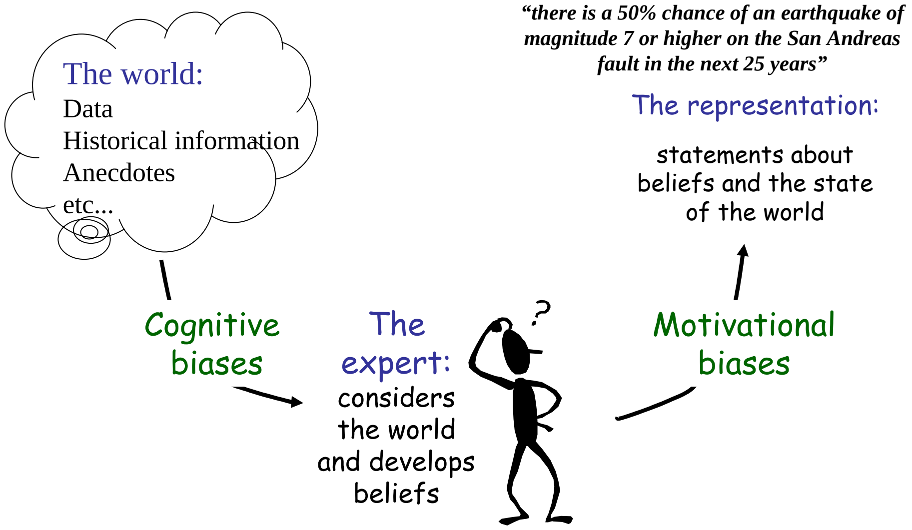
Cognitive and motivational biases



"there is a 50% chance of an earthquake of magnitude 7 or higher on the San Andreas fault in the next 25 years"

The world:
Data
Historical information
Anecdotes
etc...

The representation:

statements about
beliefs and the state
of the world

Cognitive
biases

The
expert:
considers
the world
and develops
beliefs

Motivational
biases

Be aware of the most common cognitive biases

- Anchoring:
  - focusing on a specific number and not adjusting it sufficiently
- Availability
  - focusing on a specific, dramatic or recent event
    - examples : tsunamis; near-field terms
- Overconfidence
  - overestimating what is known
- Coherence/vividness
  - overestimating the likelihood of an event because there is a good “story”
- Ignoring conditioning events

Anchoring and Availability biases are related

- Anchoring is the tendency to focus on an initial estimate and then fail to adjust sufficiently to account for uncertainty or when new information becomes available
- Often experts anchor on a recent (“available”) event
- “Available” information can be
  - Recent (it’s in the news)
  - Dramatic (unexpected but noticeable)
  - Vivid (easily pictured)
  - Official

Countering cognitive biases

- Awareness is the first defense !
- Avoid anchoring by starting with extreme values in assessments
- Minimize overconfidence by actively looking for ways in which the value could be outside your assessed distribution
- Minimize implicit conditioning by clearly stating all your assumptions

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Motivational bias results from personal involvement

Examples of motivational bias include:

- "Expert bias"
    - Reluctance to express true beliefs about uncertainty in order to appear more expert
- "Wishful thinking"
    - managers often overestimate the likelihood of success for their projects
- Reluctance to depart from "approved" numbers
- Estimating "conservatively"
    - underestimating one's own performance
    - overestimating a hazard or risk
- "Business bias"
    - keeping good relations with "clients"
        - client = nuclear authority : conservative bias
        - client = utility owners : optimistic bias
        - client = media : conservative bias

Overview

- Some generalities on hazard assessment
  - goals and applications : probability level, ground motion parameter (pga ≠ time history)
  - DSHA / PSHA
- dealing with uncertainties in PSHA
  - Types of uncertainties
    - Epistemic / Aleatory
  - origins of uncertainties
    - data : raw, reprocessed
    - methods : method themselves, parameters
  - An example : Ground Motion Predictive Equations
  - ? experts ?
- Quality requirements / Quality criteria ?
  - Personal recommendations

IAEA / ICTP, Trieste, February 2005

Quality criteria

! Uneasy !

Main issue : possibility of critical reviews

- reproducibility of analyses and results
  - archived and well-documented data and "pre-processing"
  - methods / models :
    - proper referencing of the used existing methods
    - detailed documentation of new methods, whenever developed and used
      - » better if it is "validated" by a publication
    - adequate description and documentation on meaning and values of internal parameters
  - logic trees
    - document the weights
- ? at least 2 independent similar studies
  - allows cross-checking and thus checks the reproducibility
- possibility of rapid updates in case of new results in one specific field
    - proper justification of the choices at each step
      - » models, logic tree structure, weights

Quality criteria (cont.)

Main issue : possibility of critical reviews

- consistency in each step
  - Source / Propagation / site
  - basic data / interpretation / models
  - adapt the resources on the uncertainty level
- choice of experts / companies
  - "quality"
    - reference studies
    - recognition by peers (publications, conferences, …)
    - should be ready to discuss / justify his choices
  - "variety" (different / opposite biases)
- competence also on the ordering side (should not be a black box)
  - setting up a review committee

Very low probability levels

- special attention to aleatory variability
- physical bounds ?

Decisions on acceptable / accepted hazard levels

Should be done only at the end !

- not the job of earth scientists
  - ⇒ neither conservative bias nor self-censure on possible events / effects
- not the job of structural engineers
  - ⇒ should not interfere with earth scientists to reduce the estimates, arguing that …
    - the experience tells that a well designed structure for a given level can withstand 50%, or twice more than that level
    - too high hazard values result in technical impossibility or unaffordable costs
- the job of the informed owner and controller

A personal recommendation

Value of instrumentation

- More sensitive than SMA-1 !
  (10^{-5} g / 0.01 g)
- free-field
  - EGF tests
  - GMPE
  - site effects (WM, SM)
  - checking values for short return periods
- structure
  - validate structural models
  - may help in detecting / quantifying changes
- negligible cost (compared to utilities)
- will raise of quality and reliability of all hazard, vulnerability and risk assessments
  - in the long run
  - medium term also

Should a study end up with a consensus ?

(is quality associated with consensus on hazard mean value ?)

- There is no one correct model, interpretation, or answer
  - This is not a competition for the “best model”
  - Goal is to understand uncertainty, not eliminate it
- Purpose is not to achieve consensus
  - Diversity is expected
  - Disagreement is acceptable