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

14 - 25 February 2005

Overview of Seismic PHSA Approaches with Emphasis on the Management of Uncertainties

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IAEA/ICTP Workshop on
Earthquake Engineering for Nuclear Facilities - Uncertainties in Seismic Hazard Assessment

"Overview of Seismic PSHA Approaches With Emphasis on the Management of Uncertainties"

Trieste, Italy, 14 – 25 February 2005

Unit 22 - K. Campbell, USA

Contents of the Presentation

- Introduction
- Uncertainties
- PSHA components
- Seismic hazard calculation
- Seismic hazard results
- Lessons learned and conclusions
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Introduction

Seismic Hazard Analysis (SHA)

- Deterministic SHA (DSHA)
  - No consideration of earthquake recurrence rate
- Probabilistic SHA (PSHA)
  - Explicit inclusion of earthquake recurrence rate

DSHA Methodology

- Select *finite set* of earthquake scenarios (M,R)
- Select site where hazard is to be estimated
- Estimate median ground motion for each scenario ($y'|m,r$)
- Select largest value of y' (y_{max})
- Select desired exceedance probability of y_{max}:

  $P[Y>y_{\text{max}}|m,r]$
- Calculate fractile (percentile) of y_{max}: $x = 1 – P[Y>y_{\text{max}}|m,r]$
- Determine standard normal variate of x (z_{x})
- Compute x*th*-percentile value of y_{max}:

  $\log y_{\text{max,x}} = \log y_{\text{max}} + z_{\text{x}}\sigma^{\text{a}}_{\text{logY}}$
- Repeat for all sites of interest

PSHA Methodology

- Select *all possible* earthquake scenarios (M,R)
- Select site where hazard is to be estimated
- Estimate median ground motion for each scenario ($y'|m,r$)
- Specify recurrence frequency of each scenario ($\nu|m,r$)
- Specify ground-motion value of interest (y)
- Calculate value of z_x associated with y:

  $$z_x = (\log y - \log y') / \sigma^a_{\log Y}$$
- Calculate ground-motion probability of y: $P[Y>y|m,r] = 1 - x$
- Calculate exceedance frequency of y: $\nu \times P[Y>y|m,r]$
- Sum exceedance frequencies over all scenarios (M,R)
- Repeat for different values of y and for all sites of interest

Seismic Hazard Equation

$$\nu(Y>y) = \Sigma_{\mathrm{src}} \int_M \int_R \nu \times \mathrm{P}[Y>y|m,r]\, \mathrm{f}_R(r|m)\, \mathrm{f}_M(m)\, \mathrm{d}r\, \mathrm{d}m$$

where,

- $\nu(Y>y)$ = annual exceedance frequency
- $\nu = \nu|m,r$ = recurrence frequency of m, r
- M,m = earthquake magnitude
- R,r = source-to-site distance
- $\mathrm{f}_M(m)$ = probability that $M = m$
- $\mathrm{f}_R(r|m)$ = probability that $R = r$ given m
- $\mathrm{P}[Y>y|m,r]$ = probability of $Y>y$ given m,r

Uncertainties

Types of Uncertainties

- Aleatory
  - Generally modeled using standard error of individual relationships or random (stochastic distribution of a parameter
- Epistemic
  - Generally modeled using multiple relationships or error in median or mean value of a parameter

Aleatory Uncertainties

- They are random in nature
- For all practical purposes, they cannot be known in detail or cannot be reduced
- They are susceptible to analysis concerning their origin, their magnitude, and their role in PSHA
- They are used to calculate a single estimate of annual exceedance frequency (seismic hazard) using the seismic hazard equation

Epistemic Uncertainties

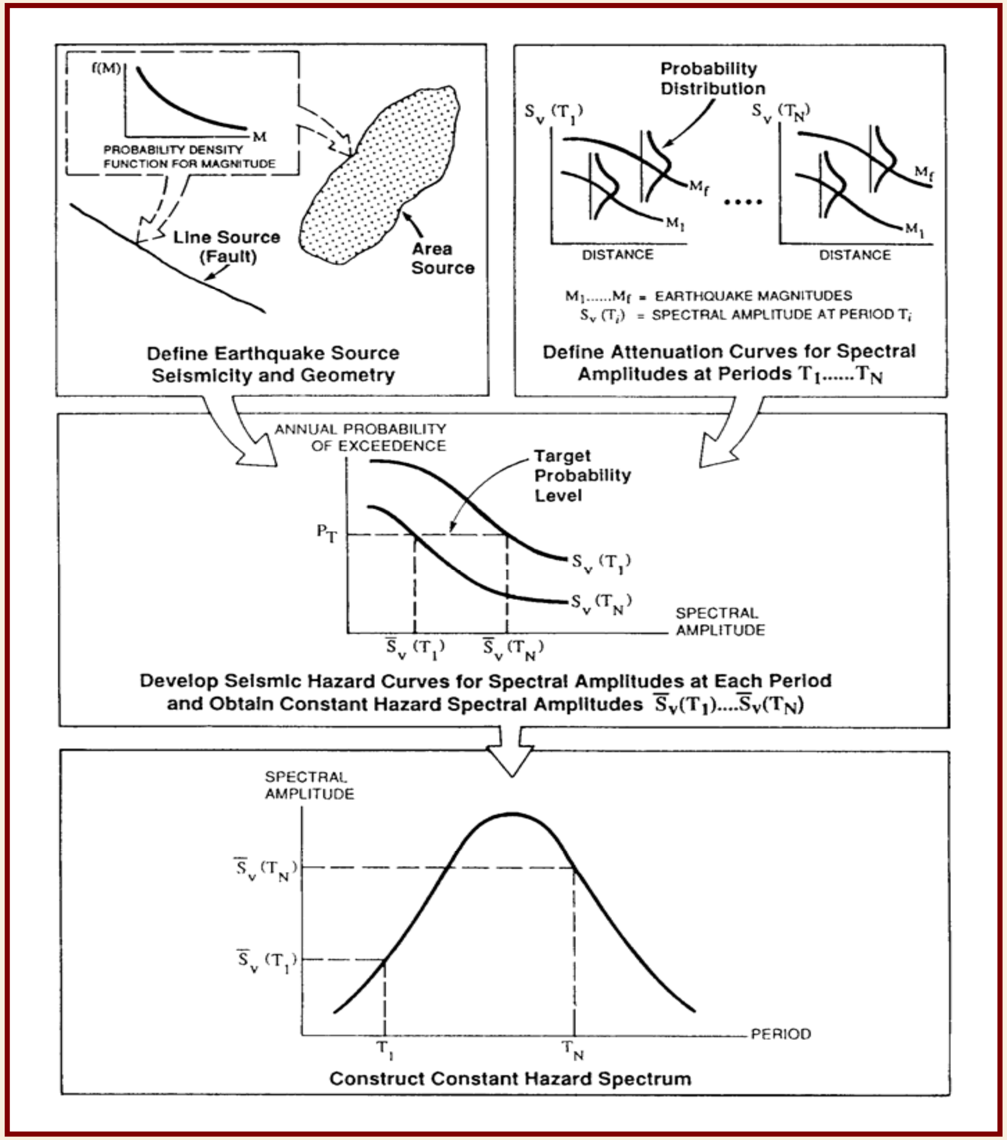
- The quantify the lack-of-knowledge arising because our scientific understanding is imperfect *for the present*
- They are of a character that in principle are reducible through further research and gathering of more and better earthquake data
- They are used to calculate the “mean” and “fractiles” (statistics) of seismic hazard

PSHA Components

Model Components

- Seismotectonic model
  - Source zonation
  - Earthquake recurrence
- Ground-motion model
  - Attenuation law
  - Site amplification
- PSHA calculation

Schematic of PSHA Components

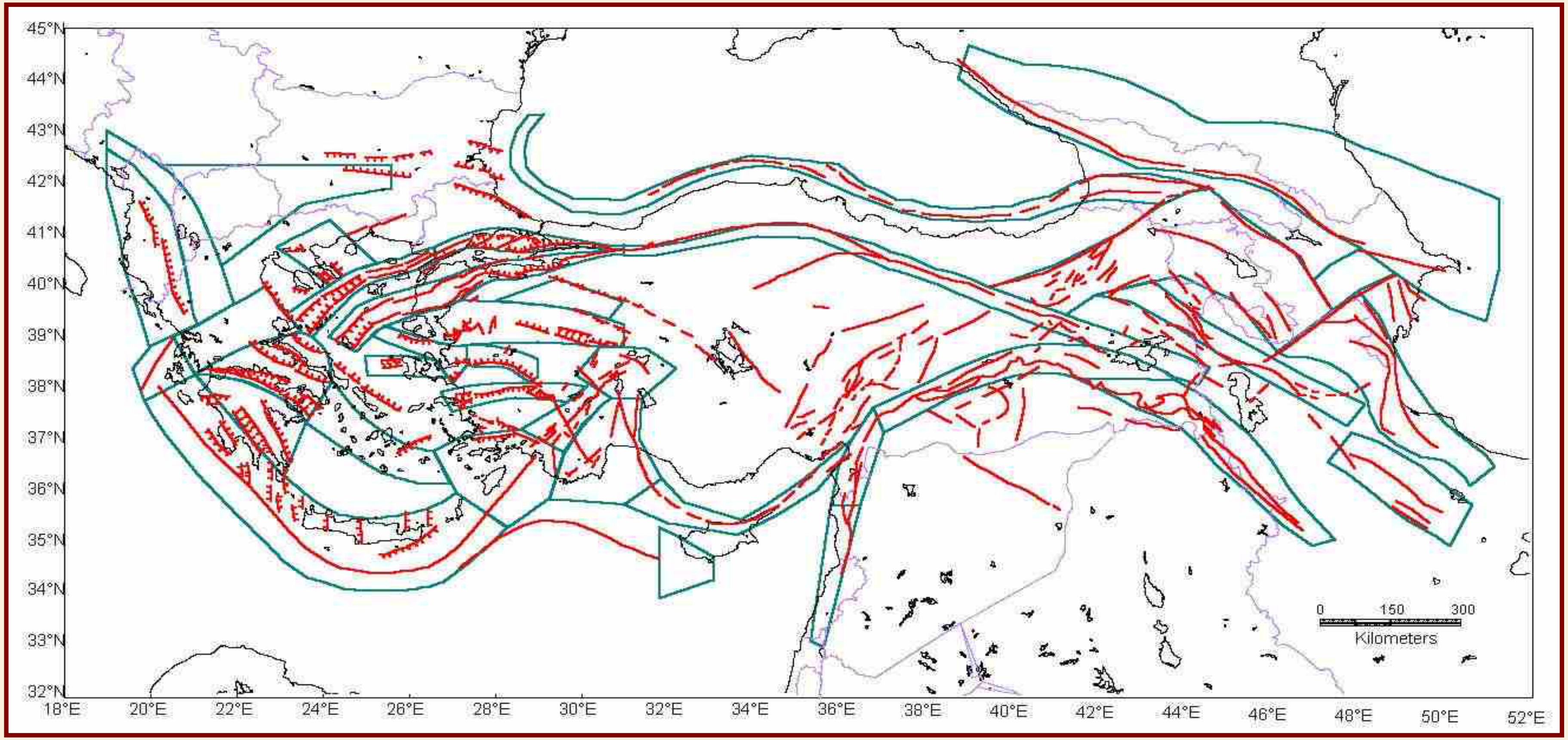


Source Zonation

- Faults
- Area sources
- Gridded seismicity

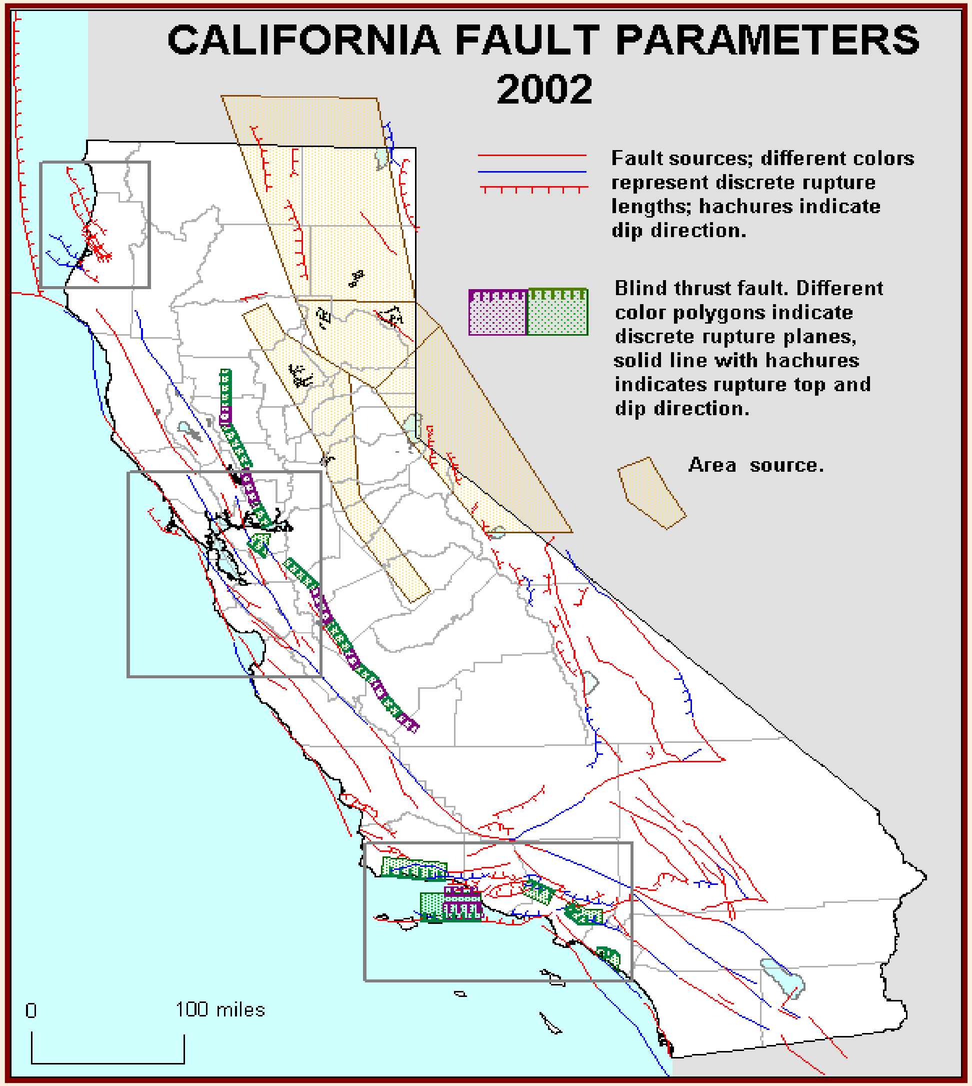
Example Source Zonation Model

Turkey



Example Source Zonation Model

California

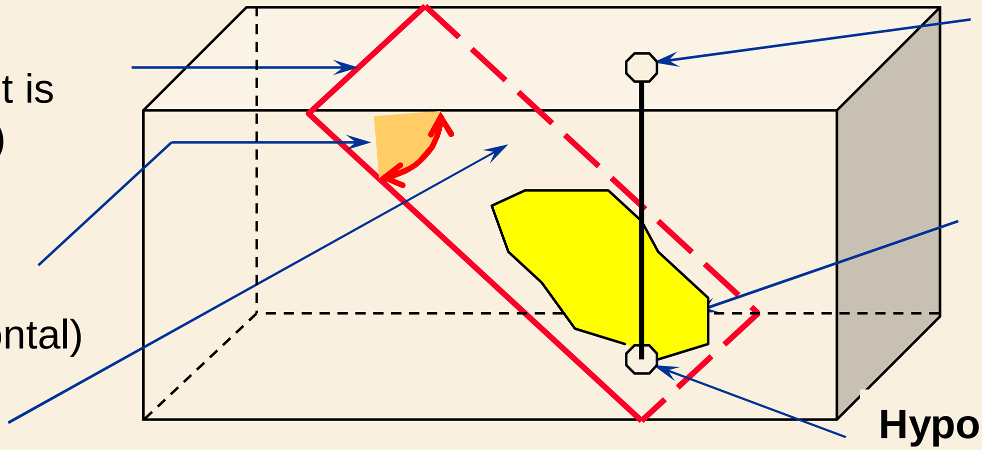


Source Zonation

- Aleatory Uncertainties
  - Location of epicenters within an area source or in a zone of gridded seismicity
  - Location of hypocenters on a fault
  - Location of rupture centroids on a fault
  - Rupture dimensions (random part)
  - Distribution of focal depths

Fault Rupture Model

A 3D model enables proper calculation of distance & ground motion



Surface Fault Trace
(The orientation of fault is known as the Azimuth)

Fault Dip
(The angle from horizontal)

Fault Plane
(Defines fault surface)

Epicenter (Point on the surface directly above the hypocenter)

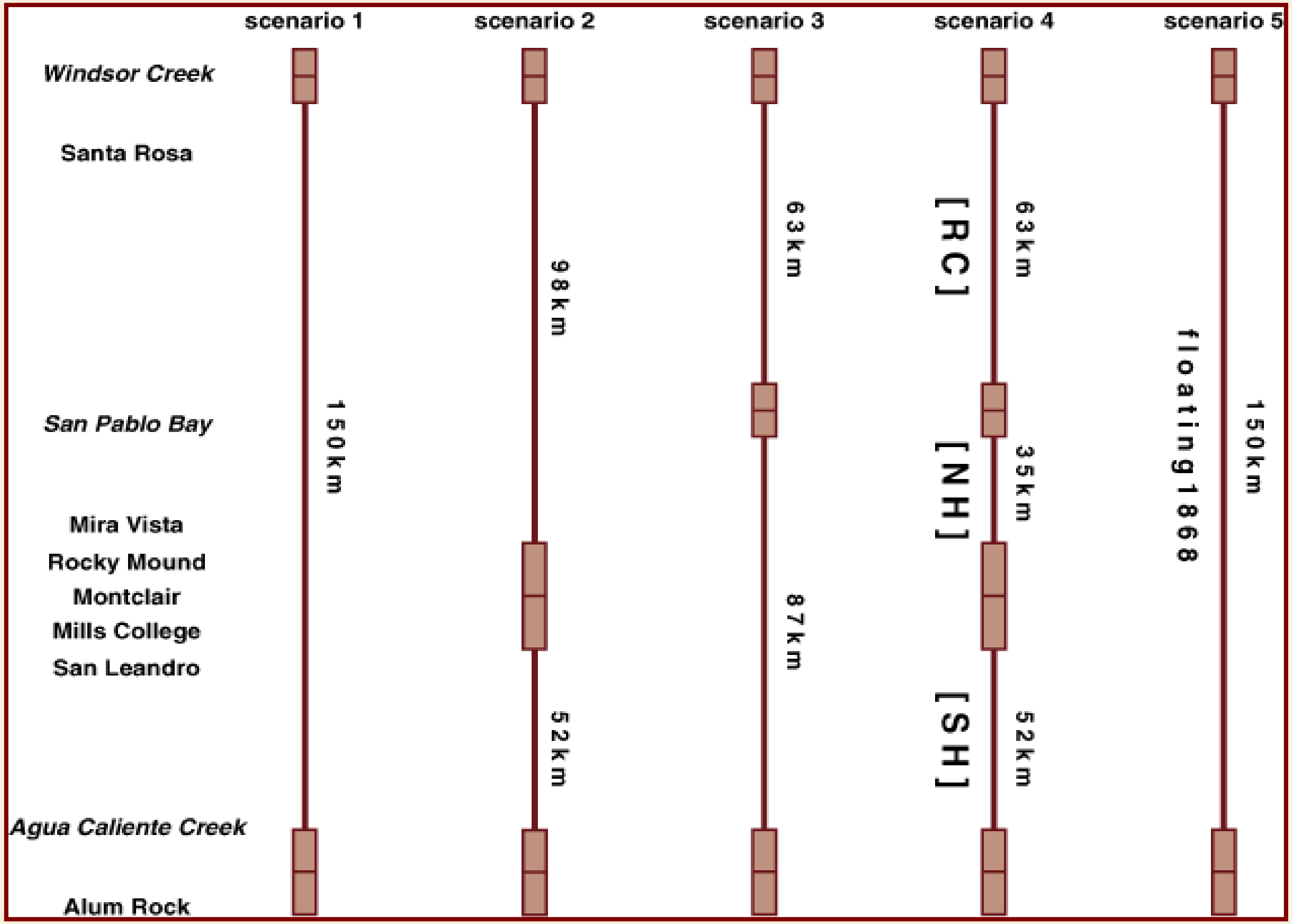
Rupture Surface
(Area that moves in EQ)

Hypocenter
(Point at which rupture starts)

Source Zonation

- Epistemic Uncertainties
  - Type of source (fault, area, grids)
  - Size and configuration of sources
    - Location, shape and size of area sources
    - Fault length, width, depth and dip
    - Segment or multi-segment ruptures (fault cascading)
  - Rupture dimensions (epistemic part)
  - Style of faulting
    - Strike slip, reverse or thrust
  - Source activity

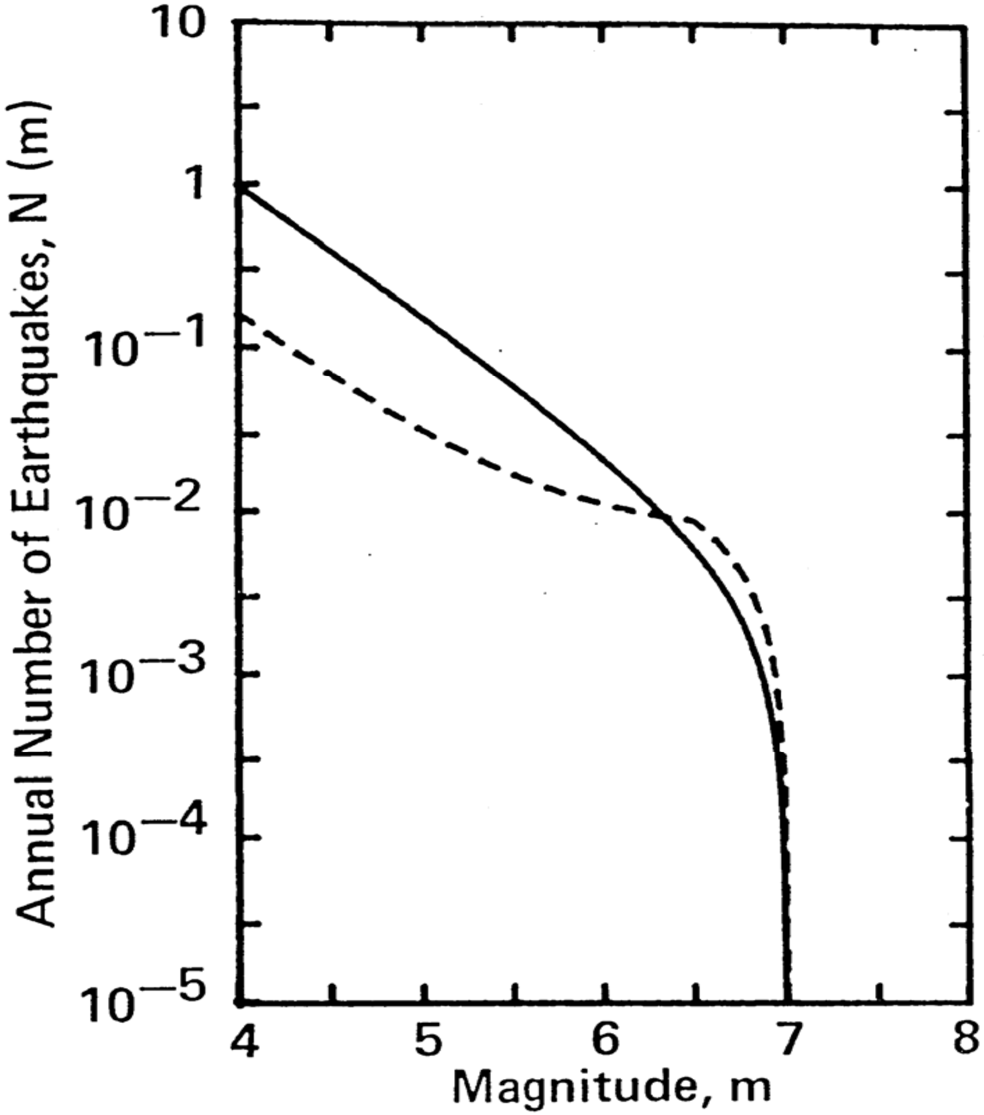
Fault cascading



Earthquake Recurrence

- Characteristic earthquake relation
  - Gaussian magnitude-frequency distribution
  - Uniform magnitude-frequency distribution
- Gutenberg-Richter law
  - Exponential magnitude-frequency distribution
  - $\log N = a - bM; \quad m_{\min} \leq M \leq m_{\max}$
- Characteristic recurrence relation
  - Combination of characteristic and exponential
  - Could also be treated as epistemic uncertainty

Example EQ Recurrence Relations



Earthquake Recurrence

- Aleatory Uncertainties
  - Selected magnitude-frequency distribution
  - Maximum magnitude (random part)
  - Characteristic magnitude (random part)

Earthquake Recurrence

- Epistemic Uncertainties
  - Type of recurrence relation
  - Minimum magnitude
  - Maximum magnitude (epistemic part)
  - Gutenberg-Richter a- and b-values (correlated)
  - Fault slip rate or seismic moment rate
  - Other fault parameters
    - Area
    - Shear rigidity

Ground Motion (Attenuation)

- Attenuation laws
- Uniform site condition
- Uniform tectonic environment
- Ground-motion parameter
  - Intensity (MSK, MMI)
  - Peak ground acceleration (PGA)
  - Spectral acceleration (S_a)

Ground Motion (Attenuation)

- Aleatory Uncertainties
  - Standard error of relationship (sigma)
  - Lognormal distribution (Gaussian on log Y)
  - Parameter conversion (random part)
    - Dispersion in Intensity to PGA relationship
    - Dispersion in PGA to S_a relationship

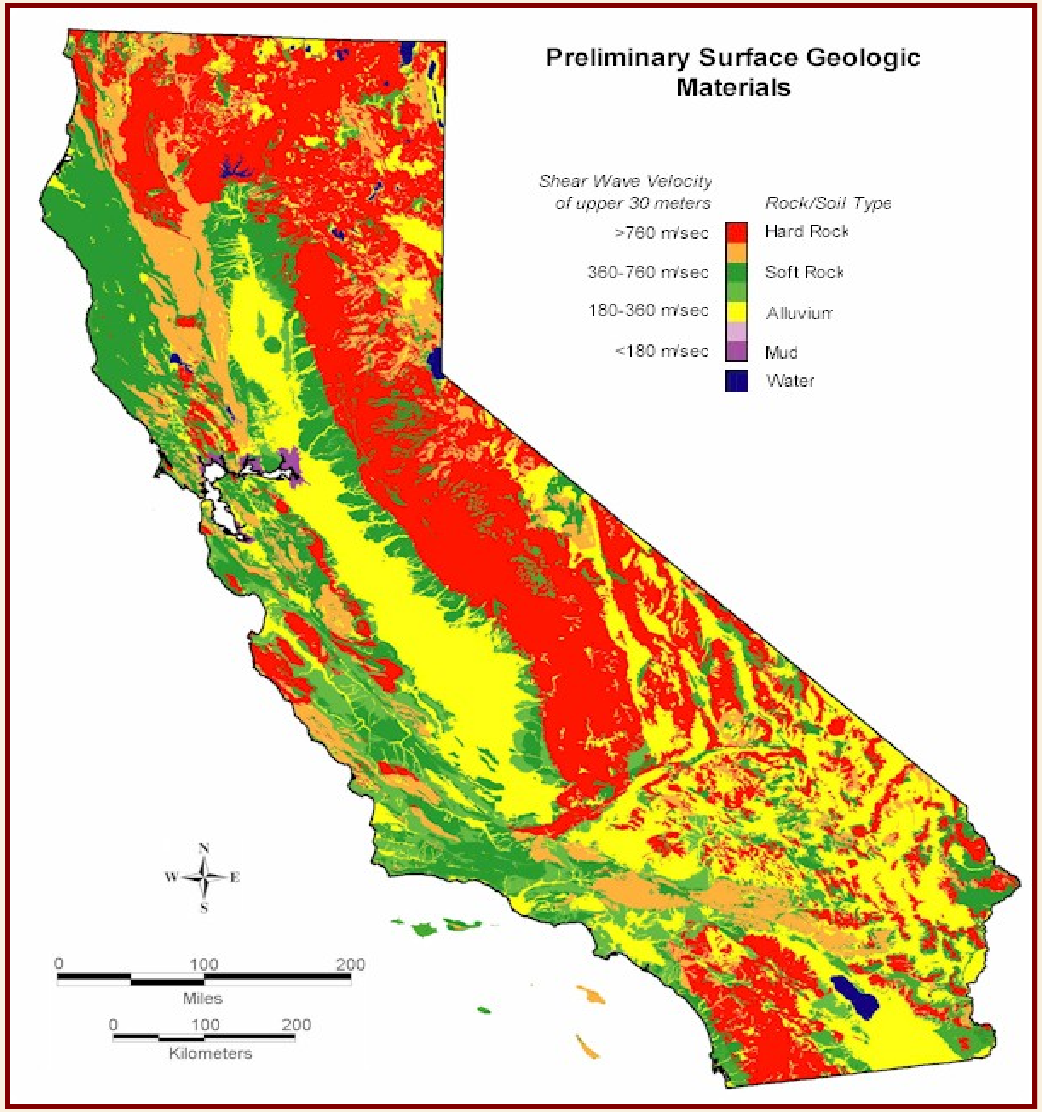
Ground Motion (Attenuation)

- Epistemic Uncertainties
  - Type of tectonic environment
  - Attenuation law (epistemic part)
    - Functional form
    - Database selection criteria
    - Characterization of site conditions
    - Method of analysis
  - Parameter conversion (epistemic part)
    - Multiple Intensity to PGA relationships
    - Multiple PGA to S_a relationships

Site Amplification

- Site classification criteria
  - Geological site categories
  - NEHRP site categories (V_{s30})
  - Shear-wave velocity (V_{s30})
  - Shear-wave velocity (1/4 wavelength)
- Site amplification factors
  - Intensity
  - PGA
  - S_a

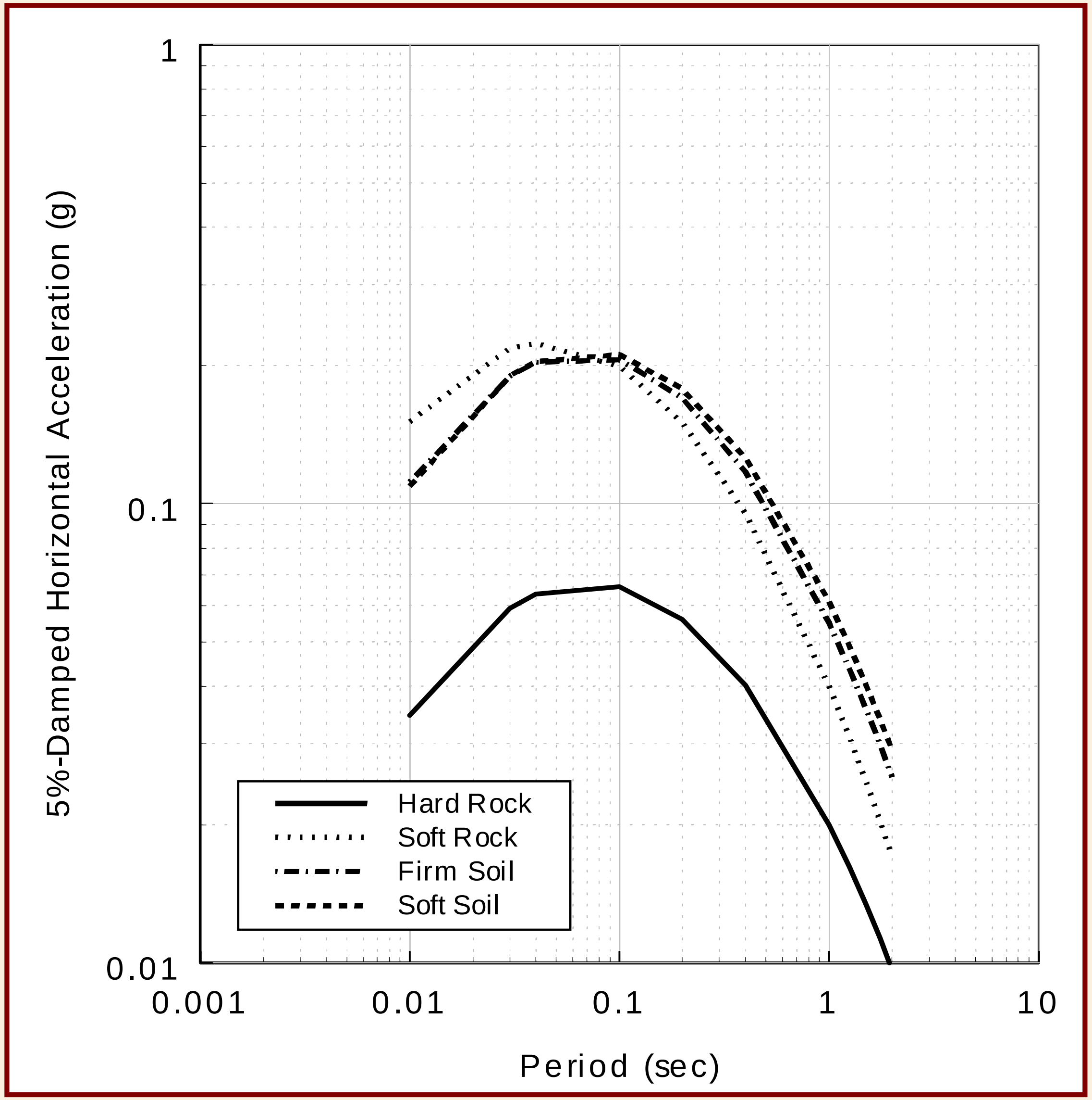
Example NEHRP Site Map



Site Amplification

- Aleatory Uncertainties
  - Typically considered as part of attenuation law
  - Additional uncertainty might be needed
- Epistemic Uncertainties
  - Site classification criteria
  - Site category
  - Conversion factors
    - Reference site condition (e.g., V_{s30}=760 m/s)
    - Reference ground-motion parameter

Effect of Site Amplification on S_a



Seismic Hazard Calculation

Hazard Calculation Components

- Aleatory component
- Epistemic component
  - Logic tree
  - Epistemic calculation
- PSHA results

Aleatory Component

$$\nu(Y>y) = \Sigma_{\mathrm{src}} \int_M \int_R \nu \times \mathrm{P}[Y>y|m,r]\ \mathrm{f}_R(r|m)\ \mathrm{f}_M(m)\ \mathrm{d}r\ \mathrm{d}m$$

where,

- $\nu(Y>y)$ = annual exceedance frequency
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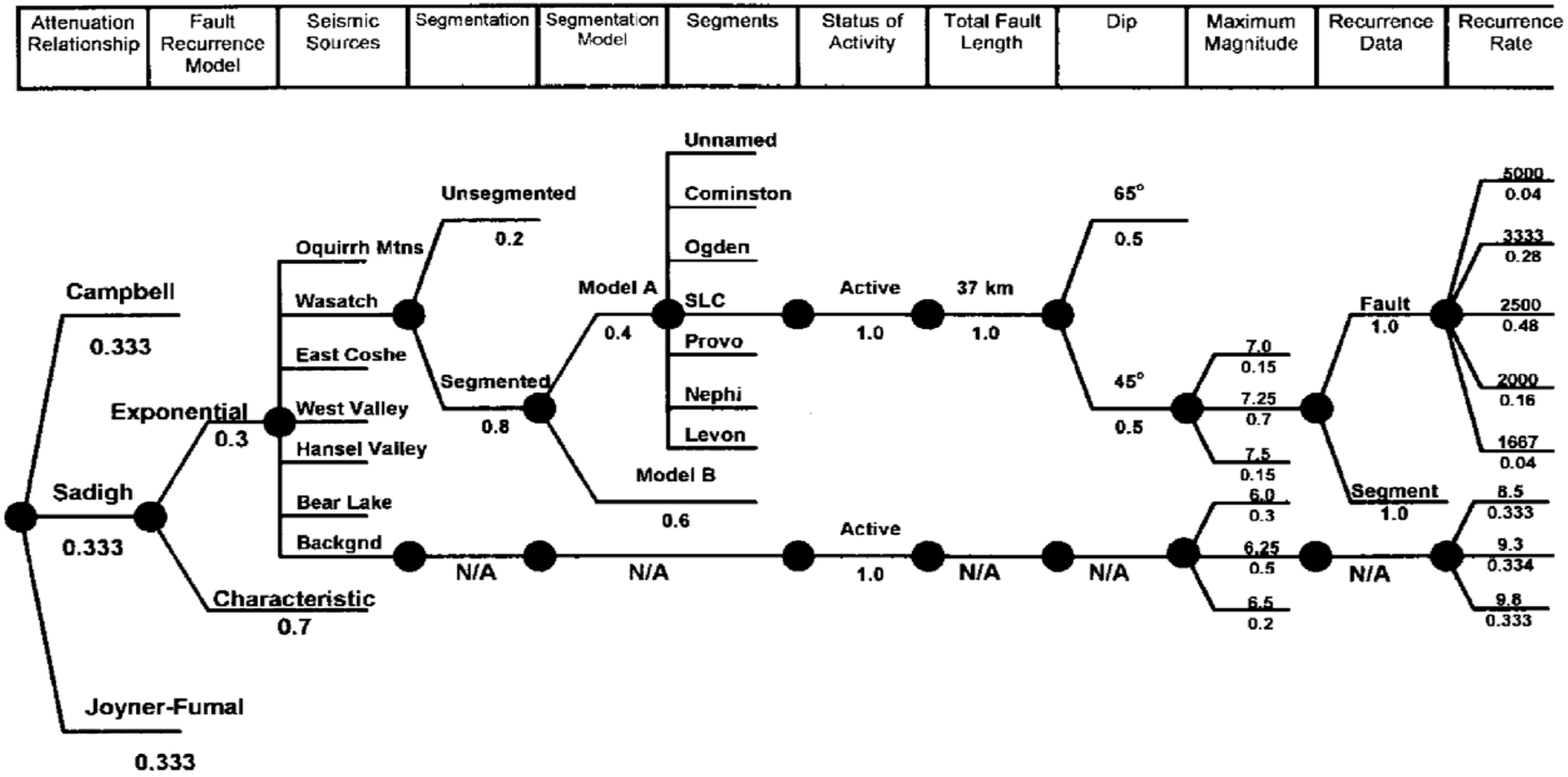
Epistemic Component

- Logic tree
  - Modeled as a decision tree structure of epistemic uncertainties
  - Each path through logic tree (branch) represents one possible combination of models/parameters
  - A sub-branch is selected at each node of logic tree along with is assigned probability (weight)
  - Each branch is assigned a probability equal to the product of the probabilities (weights) of the various sub-branches

Example Logic Tree



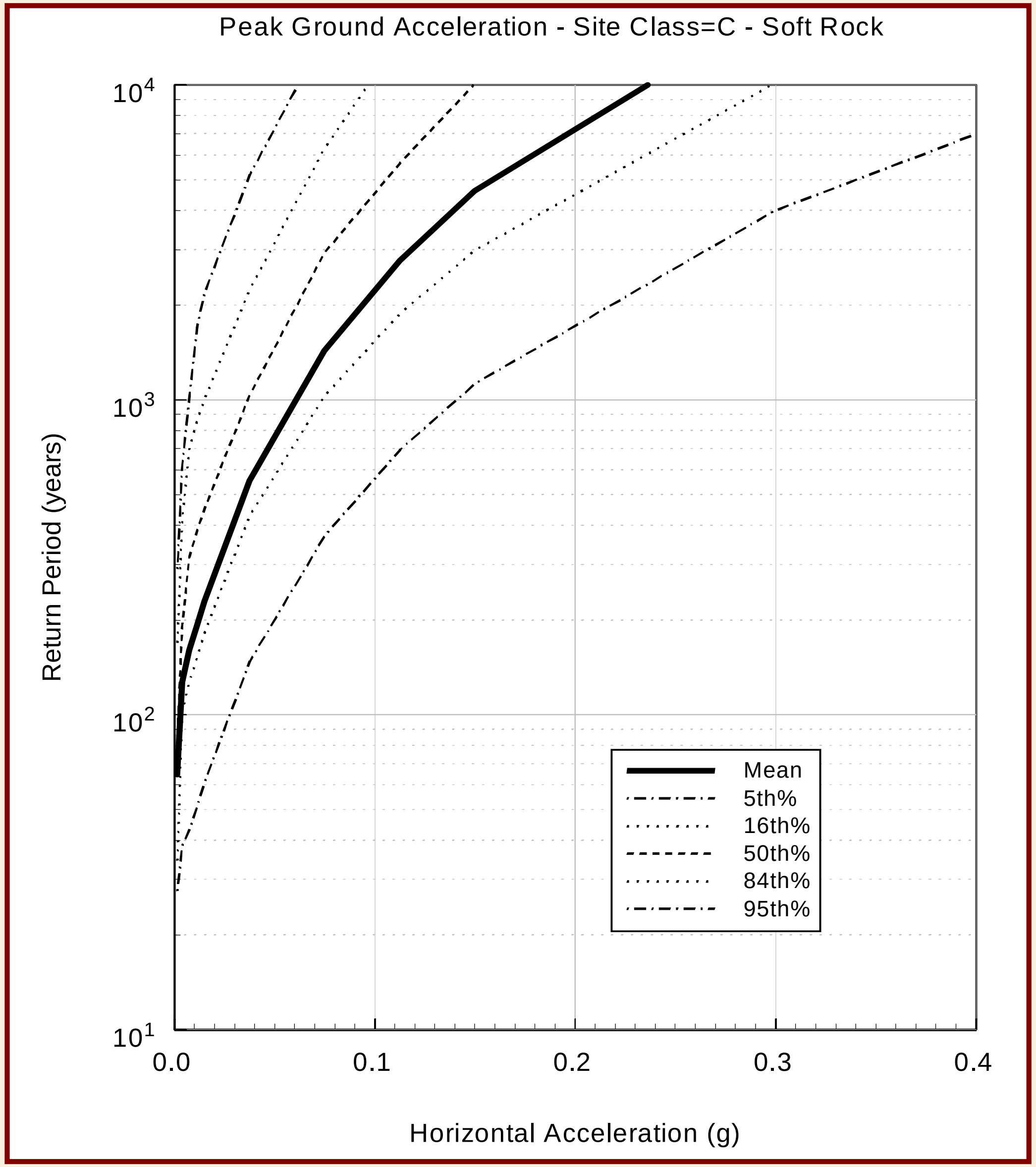
Epistemic Calculation

- Evaluate logic tree using seismic hazard equation
  - Full enumeration (evaluate every possible branch)
  - Monte Carlo simulation (*N*-trials)
    - $N_{min} = 10 / (1 - x)$
    - For $x = 0.05$, $N_{min} = 200$
- Rank by decreasing exceedance frequencies
- Calculate weighted mean exceedance frequency
  - Weight by branch probabilities (full enumeration method)
  - Weight by 1 / *N*-trials (Monte Carlo method)
- Calculate desired fractals exceedance frequencies
  - Typically 5*th*-, 15*th*-, 50*th*-, 85*th*- and 90*th*-percentile

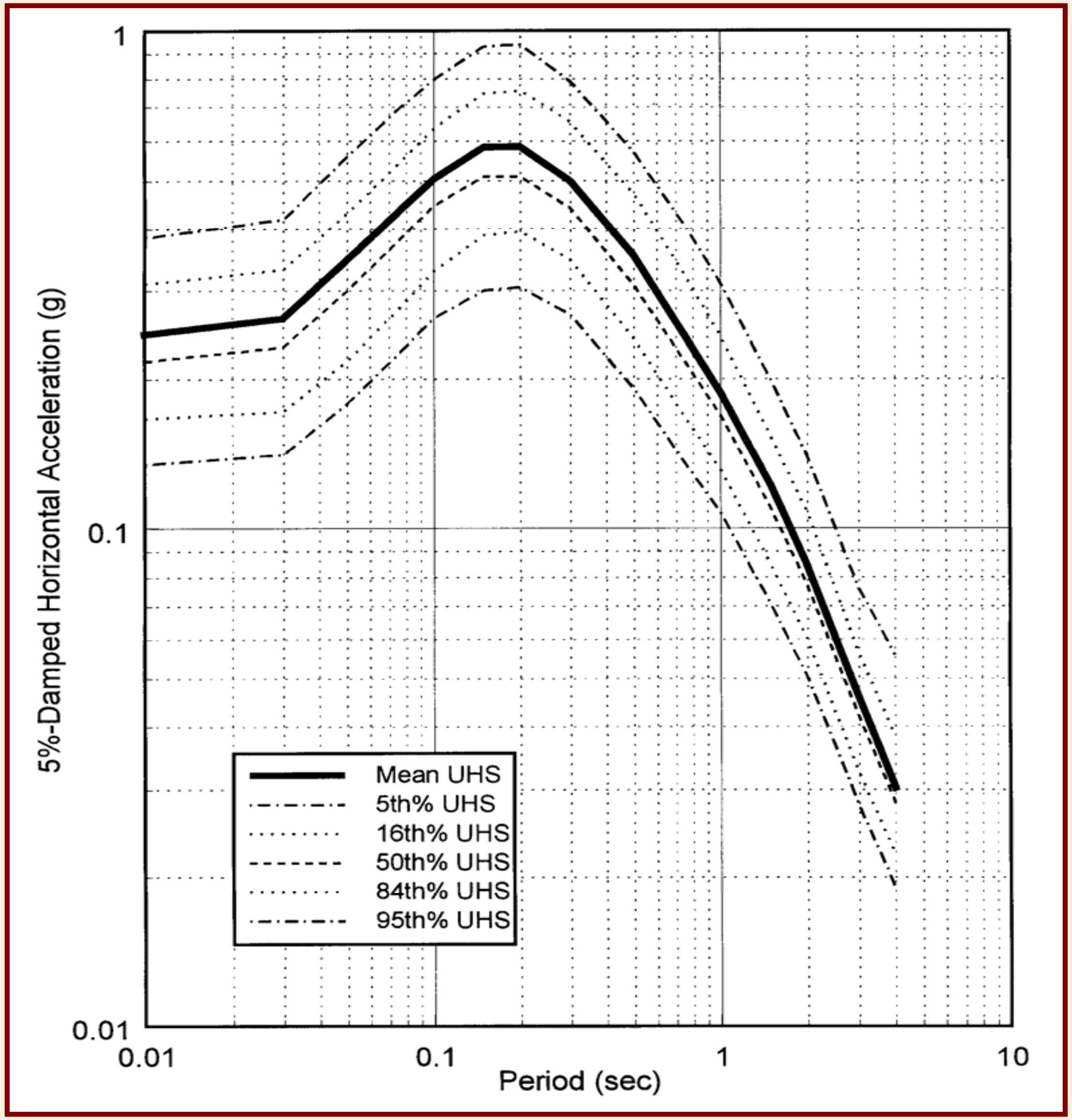
Seismic Hazard Results

- Seismic hazard
  - Annual exceedance frequency: $\nu(Y>y)$
  - Return period (RP): $1 / \nu(Y>y)$
  - Exceedance probability: $1 - \exp[-\nu(Y>y) \times t]$
    (t = time period of interest; can be 1 year)
- Seismic hazard curve
  - Plot of seismic hazard vs. ground-motion parameter (y)
- Uniform hazard response spectra (UHRS, UHS)
  - Plot of spectral response, S_a, vs. period for specified value of seismic hazard (e.g., 10,000-year mean RP)

Example PGA Seismic Hazard Curve



Example 5%-Damped UHRS



Lessons Learned and Conclusions

- Uncertainty is a **critical** element in PSHA
- Uncertainty is composed of *aleatory* (randomness) and *epistemic* (knowledge) uncertainties
- All appropriate and relevant aleatory and epistemic uncertainties should be included in the PSHA calculation
- Aleatory and epistemic uncertainties are modeled using different methods

Summary of the Presentation

- Aleatory uncertainty is incorporated using the seismic hazard equation
- Epistemic uncertainty is incorporated using full enumeration or Monte Carlo sampling of logic tree
- Seismic hazard is calculated based on aleatory uncertainties and is typically displayed as a seismic hazard curve (e.g., RP vs. ground motion)
- Mean and fractile seismic hazard is calculated based on epistemic uncertainties and is displayed as a series of hazard curves for the mean and selected fractiles of seismic hazard (e.g., RP)

References and Glossary

McGuire, R.K. (2004). *Seismic hazard and risk analysis*, Engineering Monographs on Miscellaneous Earthquake Engineering Topics, MNO-10, Earthquake Engineering Research Institute, Oakland, California, 221 p.

Kramer, S.L. (1996). Seismic hazard analysis, In *Geotechnical Earthquake Engineering*, Chap. 4, Prentice-Hall, Inc., Upper Saddle River, New Jersey, p. 106–142.

Reiter, L. (1990). *Earthquake hazard analysis: Issues and insights*. Columbia University Press, New York, 254 p.

Somerville, P. and Moriwaki, Y. (2003). Seismic risk and risk assessment in engineering practice. In *International Handbook of Earthquake and Engineering Seismology*, Part B, Chap. 65, Ed. W.H.K. Lee, H. Kanamori, P.C. Jennings and K. Kisslinger, Academic Press, San Diego, p. 1065–1080.

References and Glossary

Senior Seismic Hazard Analysis Committee (SSHAC) (1997). Recommendations for probabilistic seismic hazard analysis: Guidance on uncertainty and use of experts. Prepared by Lawrence Livermore National Laboratory, NUREG/CR-6372, U.S. Nuclear Regulatory Commission, Washington, D.C.

Thenhaus, P.C. and Campbell, K.W. (2003). Seismic hazard analysis. In *Earthquake Engineering Handbook*, Chap. 8, Ed. W.F. Chen and C. Scawthorn, CRC Press, Boca Raton, Florida, 50 p.