Seismic Hazard Assessment: Problems with Current Practice and Future Developments

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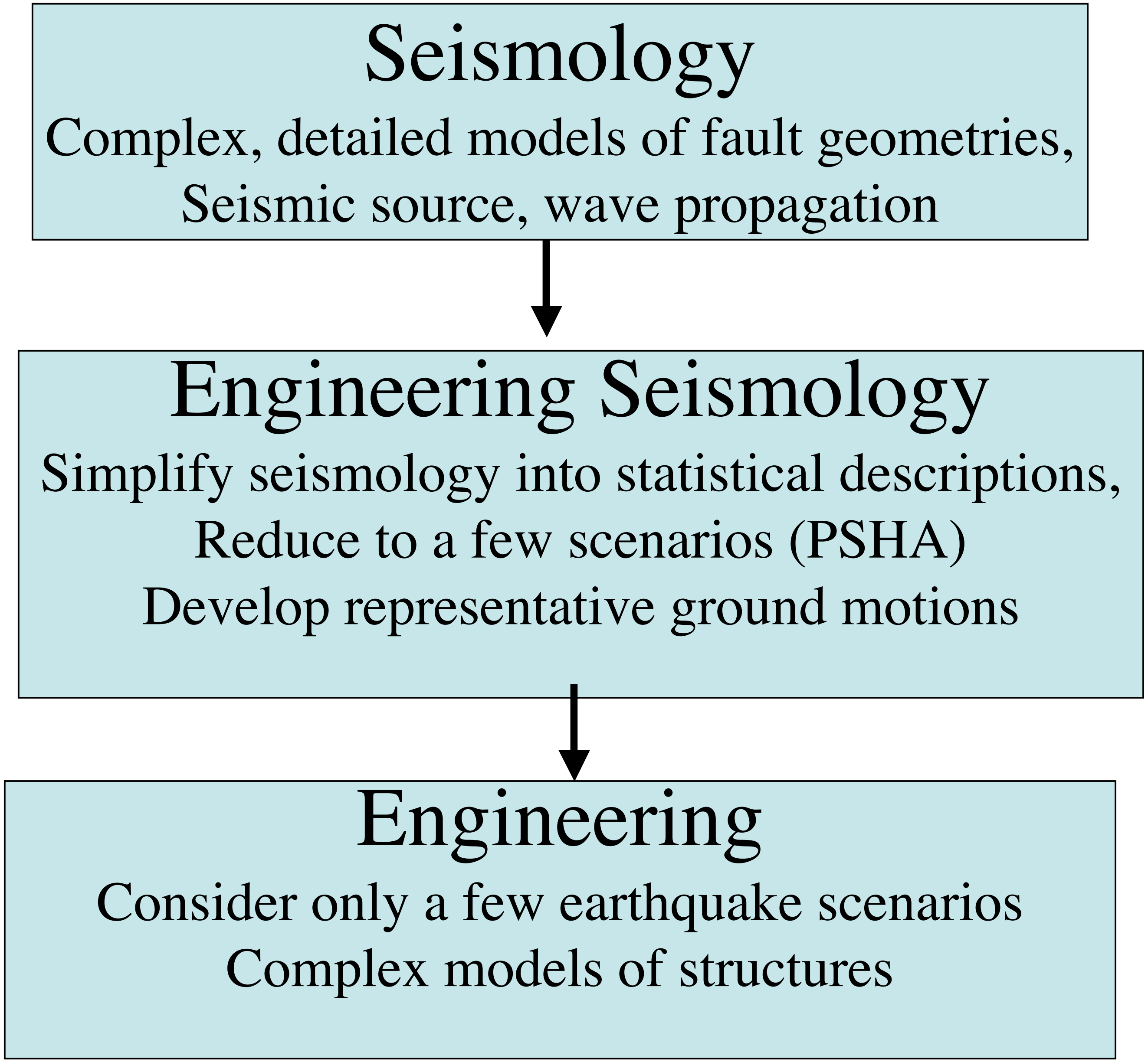

Seismology
Complex, detailed models of fault geometries,
Seismic source, wave propagation
Engineering Seismology
Simplify seismology into statistical descriptions,
Reduce to a few scenarios (PSHA)
Develop representative ground motions
Engineering
Consider only a few earthquake scenarios
Complex models of structures

Example: Dam Site in Eastern CA

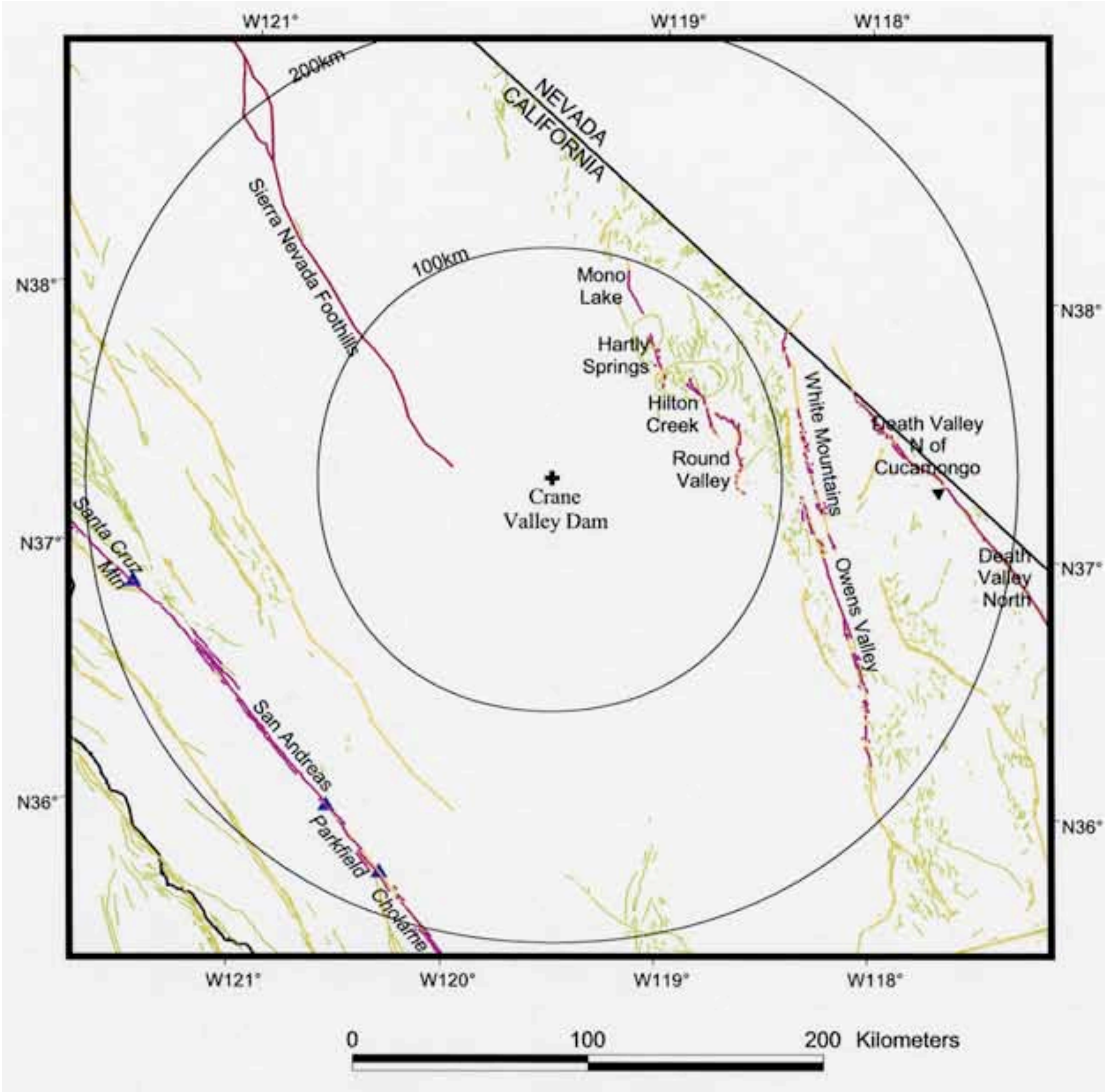
Design Earthquakes:

San Andreas Flt

$M_{max} = 8$,

Distance = 170 km

Also, consider other flts



Need to consider earthquakes not on faults

Design Earthquakes:

San Andreas Flt

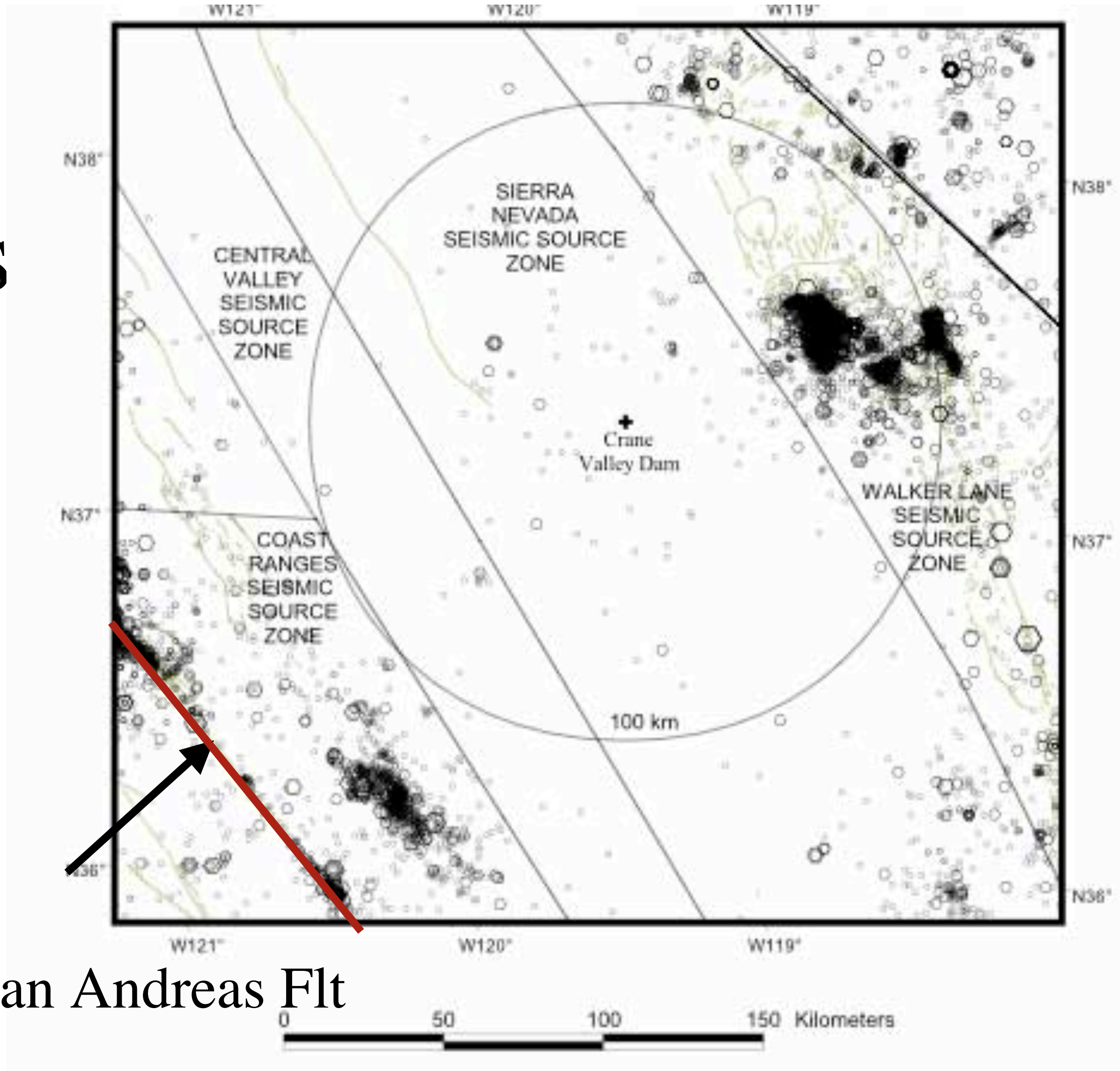
M_{max} = 8,

Distance = 170 km

Sierra Nevada Zone

M_{max} = 6.5

Distance = ?



Background Earthquakes

- What should we use for design?
- Option 1: treat same as faults
  - Largest magnitude at closest location
    - M=6.5, Distance = 0
    - Not “reasonable”
- Option 2: pick some less severe earthquake
  - M=5.5, distance=5 km?
  - M=6.0, distance=10 km?
  - M=6.25, distance = 17 km?
  - What is reasonable? - Depends on seismic activity
- Difficulties in selecting a “reasonable” background earthquake is what lead to the development of PSHA

Deterministic vs Probabilistic

- Deterministic
  - Consider of small number of scenarios (Mag, dist, number of standard deviation of ground motion)
  - Choose the largest ground motion from cases considered
- Probabilistic
  - Consider all possible scenarios: all mag-dist combinations, and number of std dev of ground motion (ε)
  - Compute the rate of each scenario (M,R, ε)
  - Identify the subset of (M,R, ε) scenarios with ground motion above a some threshold (e.g. Sa(T=1 sec) of 0.5g)
  - Sum the rates of the scenarios in the subset of to determine rate of "exceedance"

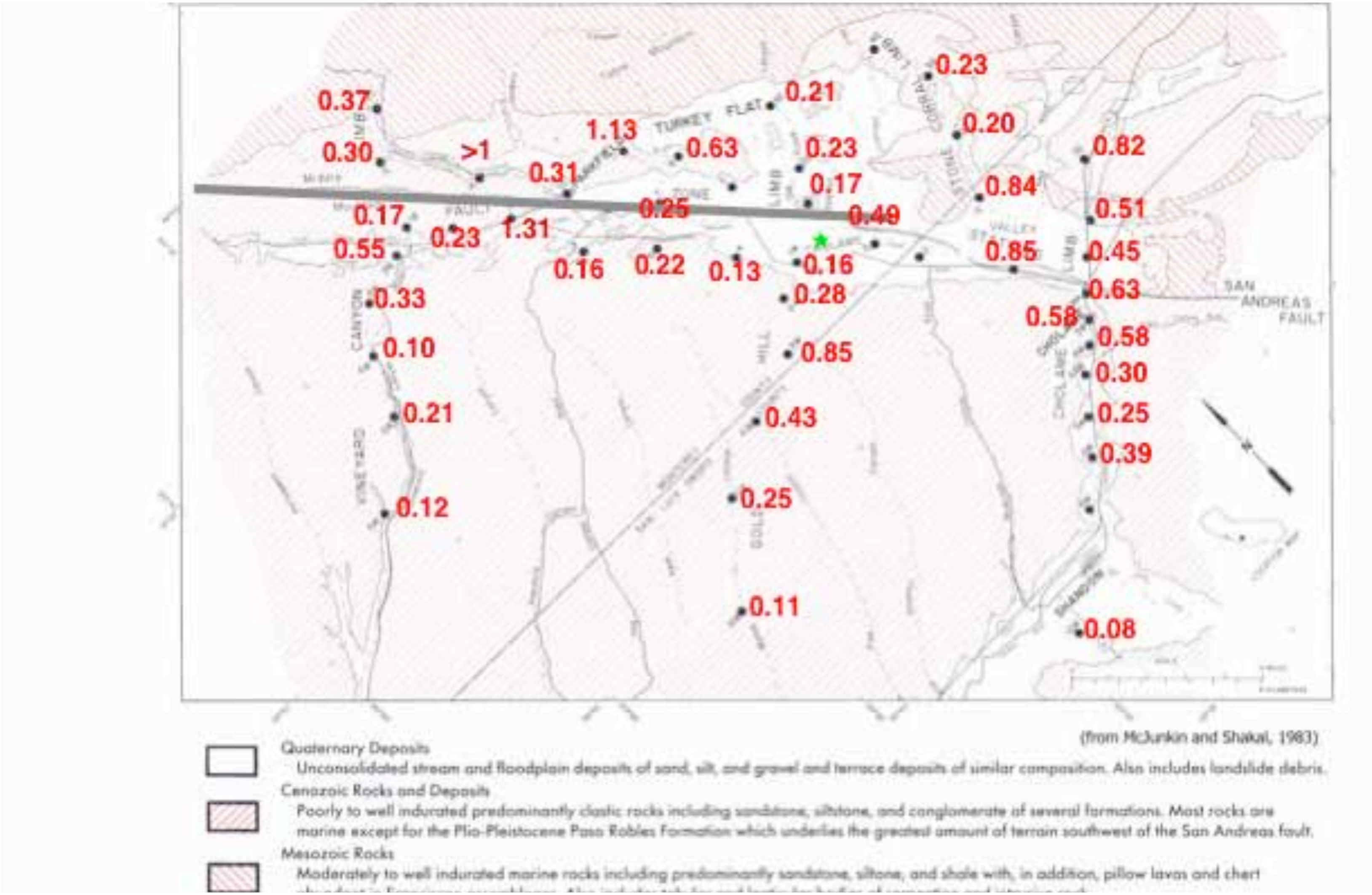
Terminology

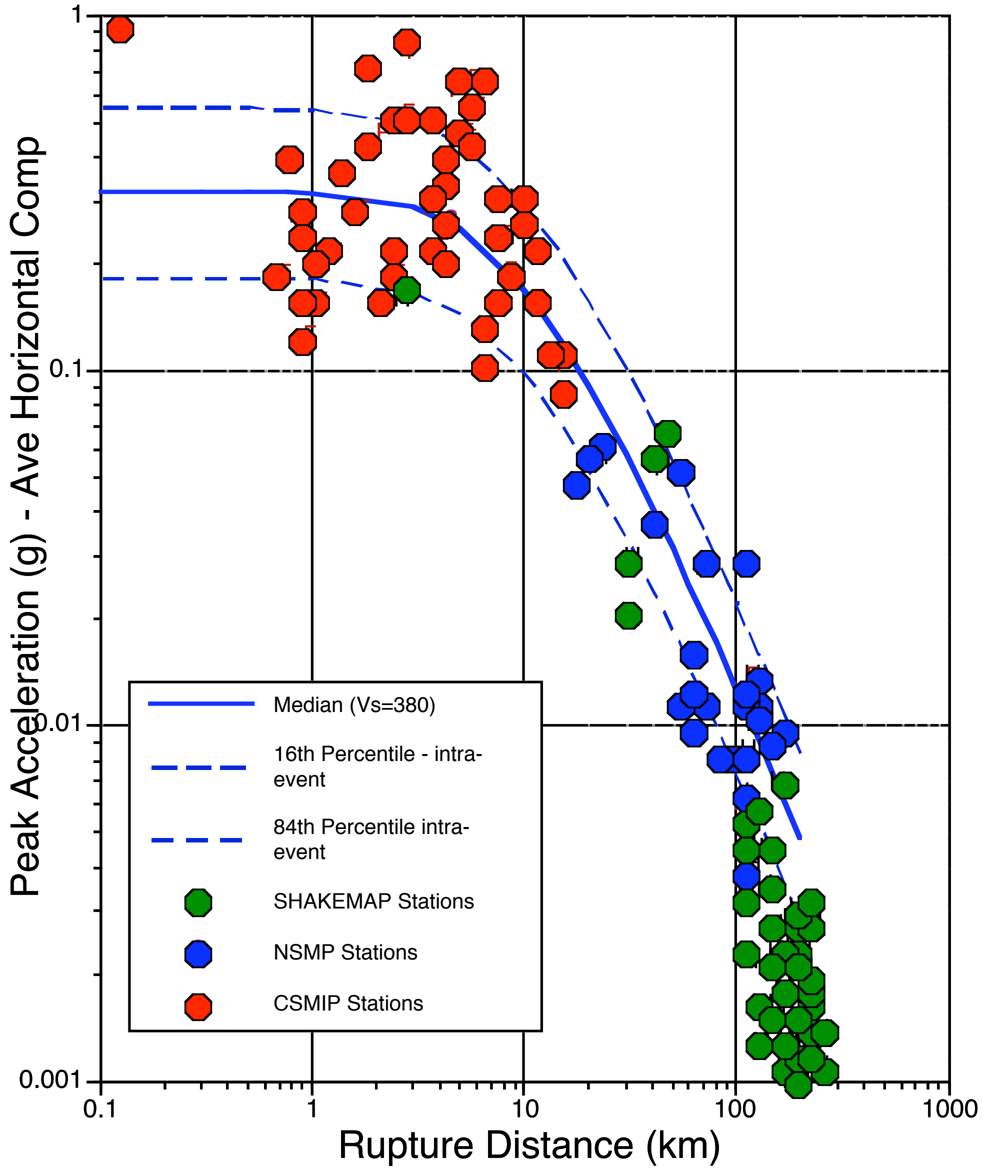
- Aleatory Variability (random)
  – Randomness in M, location, ground motion (ε)
- Incorporated in hazard calculation directly Epistemic Uncertainty (scientific)
  – Due to lack of information
  – Incorporated in PSHA using logic trees (leads to alternative hazard curves)

Deterministic Approach

- Select a specific magnitude and distance (location) for each source
  - Typically, use the largest earthquake at the closest distance (except for background zone with site)
- Design for ground motion, not earthquakes
  - Ground motion has large variability for a given magnitude, distance, and site condition
  - Key issue: What ground motion level do we select?

2004 Parkfield
Near Fault PGA Values

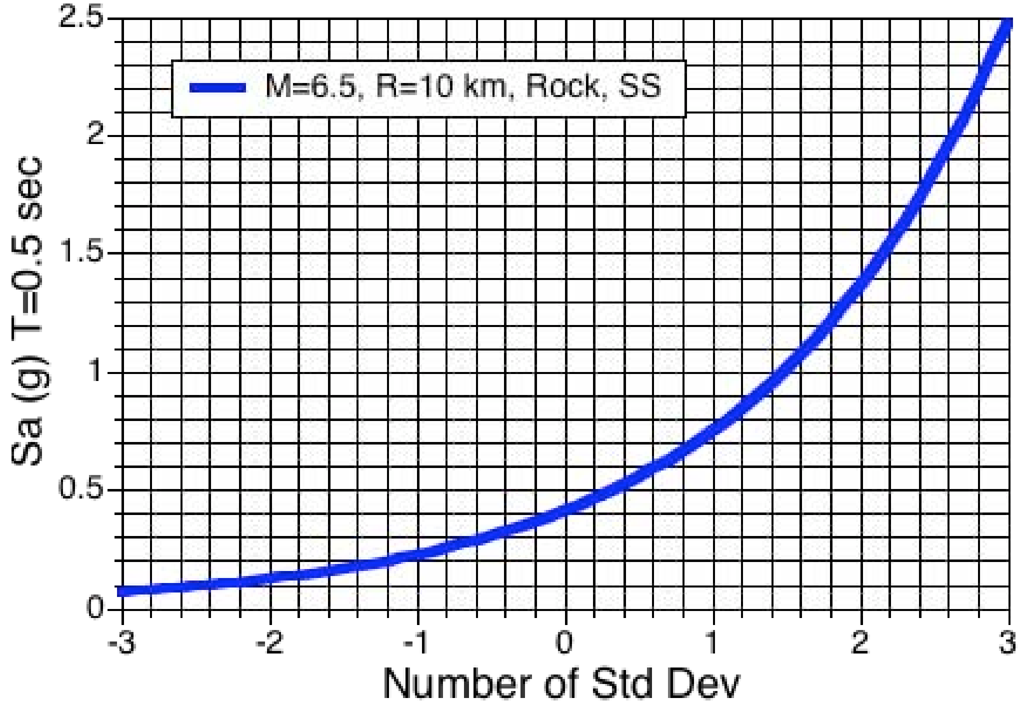




2004 Parkfield PGA Attenuation

Ground Motion Levels

- By tradition, select median or 84th percentile
- Worst-case ground motion is much higher



Worst-Case Ground Motion is Not Selected in Deterministic Approach

- Combing largest earthquake with the worst-case ground motion is too unlikely a case
  - The occurrence of the maximum earthquake is rare, so it is not "reasonable" to use a worst-case ground motion for this earthquake
  - Chose something smaller than the worst-case ground motion that is "reasonable".

What is “Reasonable”

- The same number of standard deviation of ground motion may not be “reasonable” for all sources
  - Median may be reasonable for low activity sources, but higher value may be needed for high activity sources
- Need to consider both the rate of the earthquake and the chance of the ground motion

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
- 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)
  - Compute the probability of each ground motion for each scenario

Probabilistic Approach (cont)

- Hazard Calculation
  - Rank scenarios (M,R, ε) in order of decreasing severity of shaking (Here, use Sa)
  - Result: Table of ranked scenarios with ground motions and rates
  - Sum up rates of scenarios with ground motion above a specified level (hazard curve)
- Select a ground motion for the design hazard level
  - Back off from worst case ground motion until either:
    - The ground motion is does not lead to excessive costs, <u>or</u>
    - The hazard level is not too small (e.g. not too rare) to ignore (e.g. the design hazard level)
    - "Not too rare" hazard should be determined based on risk calculations

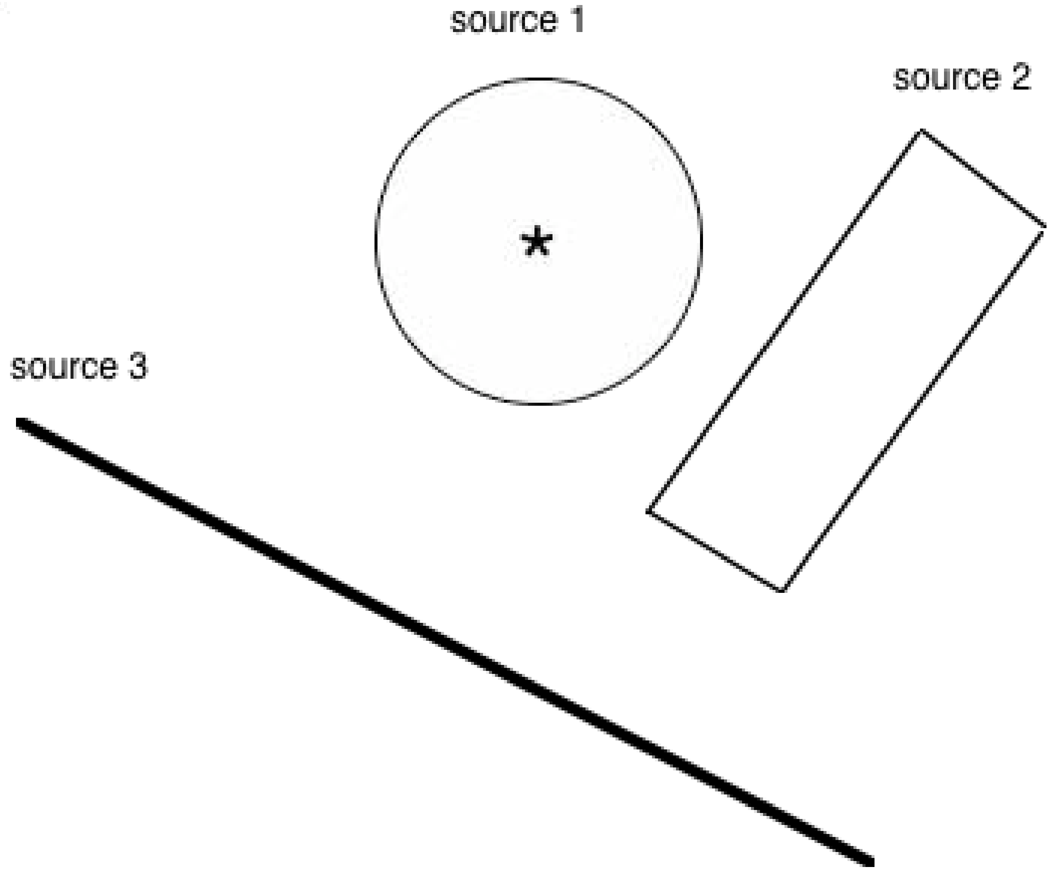
Use of PHSA

- Input for probabilistic risk calculation
  - Uses the full hazard curve (and deaggreation)
- Selection of design ground motion
  - Purpose of PHSA is to provide a method to select "reasonable" deterministic earthquake scenarios (M, R, ε) from the complete set of all scenarios
  - Select the most severe scenarios that is either not too rare <u>or</u> not too costly

Design Ground Motions

- Not using worst-case ground motions
  - "reasonable" ground motions should have acceptably small risk of failure
- Risk calculation
  - Direct computation of probability of failure for a given design
- Probabilistic
  - Selection of a return period for design ground motions is a simplified risk calculation.
    - If we design for certain return period, then the probability of failure is smaller than the hazard
      - How much smaller? Factor of 2? 10?
- Deterministic
  - Simplified PHSA
    - If we choose a deterministic event and ground motion level, then assume that the probability of exceeding the ground motion is small enough to lead to acceptable risk

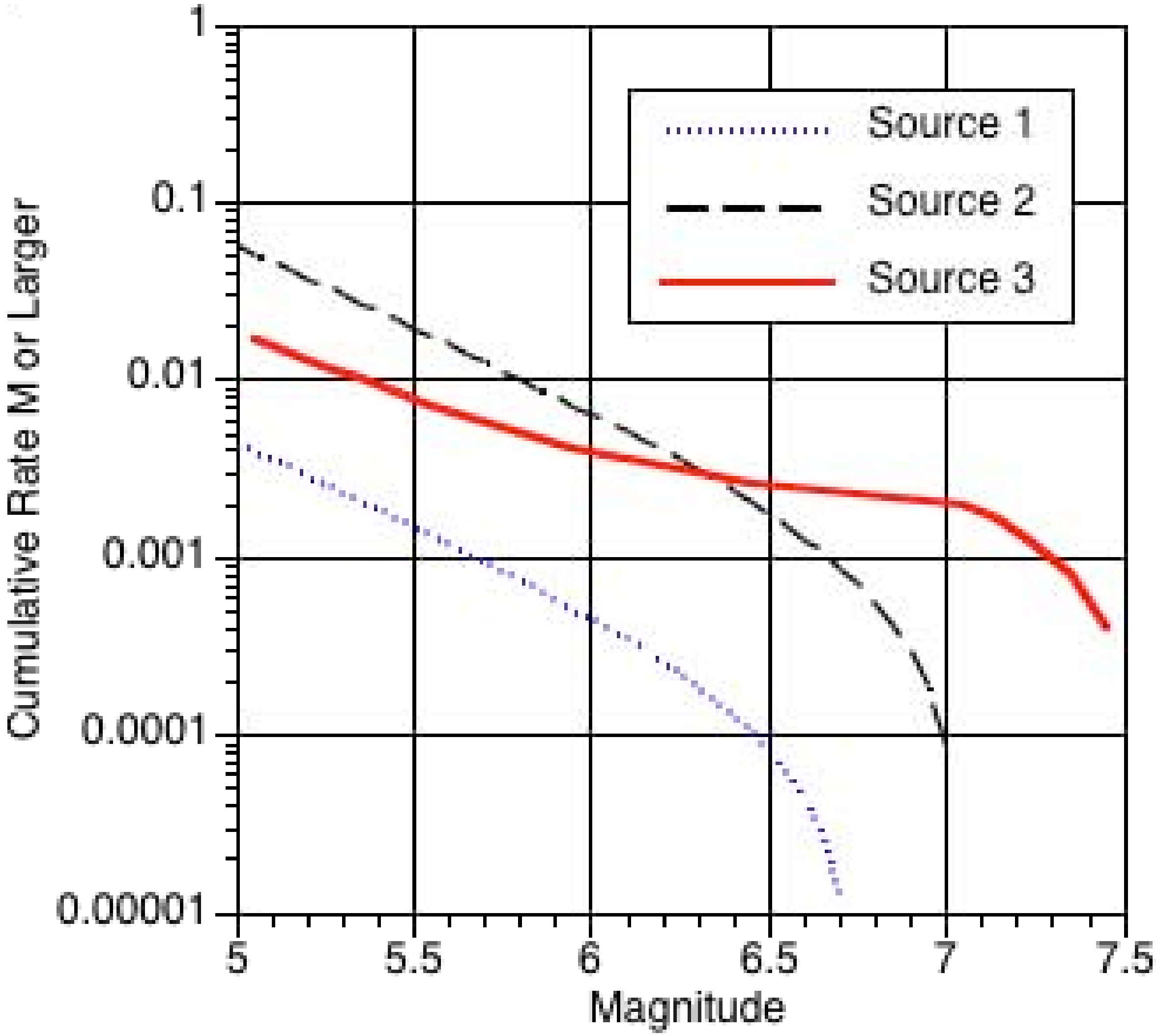
Example Hazard Calculation
w/o equations



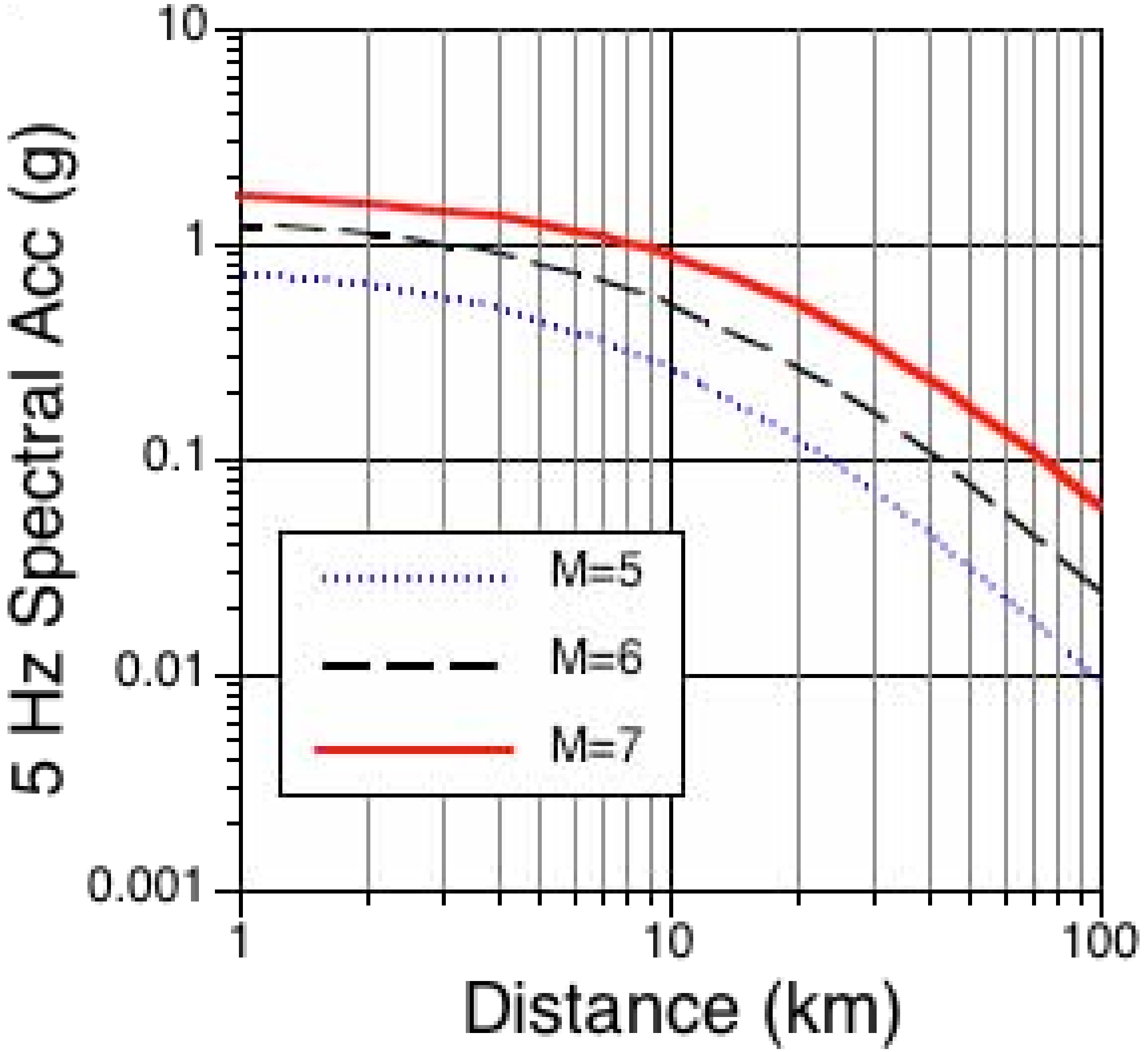
Terminology

- Recurrence Interval
  - Refers to earthquakes on specific sources
  - From magnitude-recurrence curve
  - 1/(Rate of given M or larger)
- Return Period
  - Refers to the ground motion at a specific site
  - From hazard curve
  - 1/(Rate of given Sa or larger)

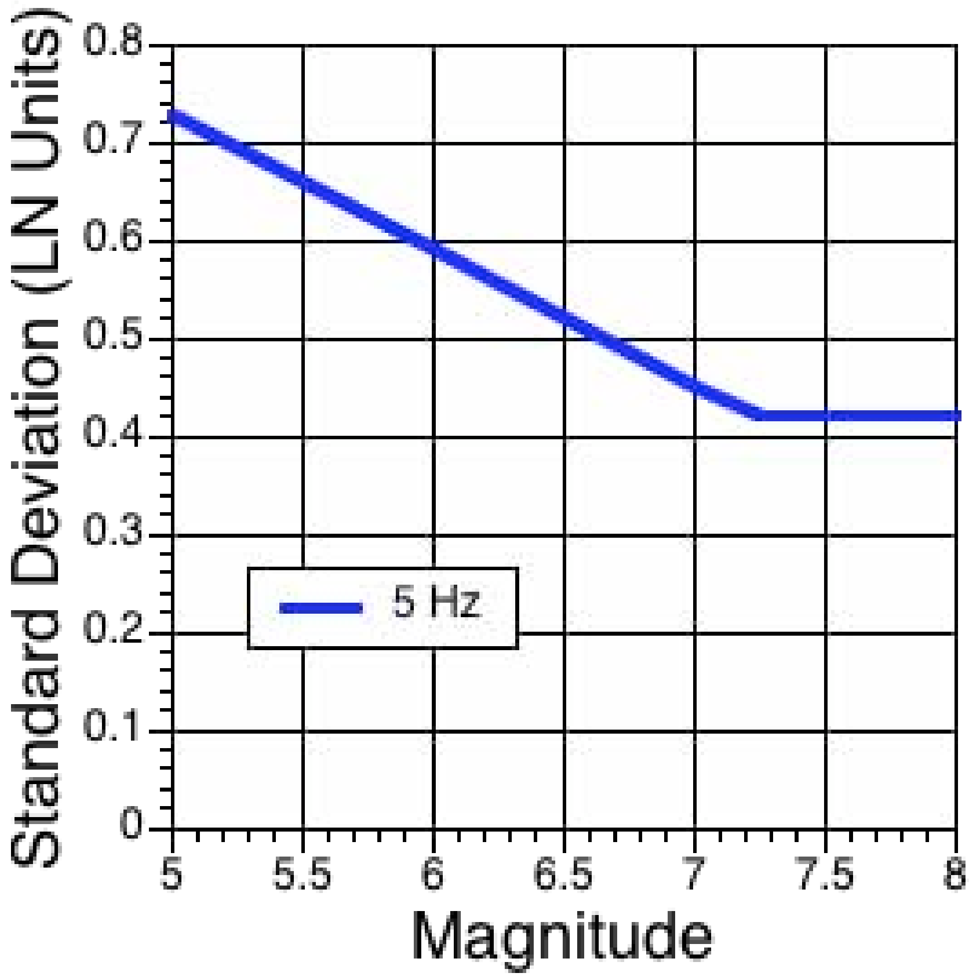
Example Source Characterization



Median Ground Motion



Standard Deviation of Ground Motion



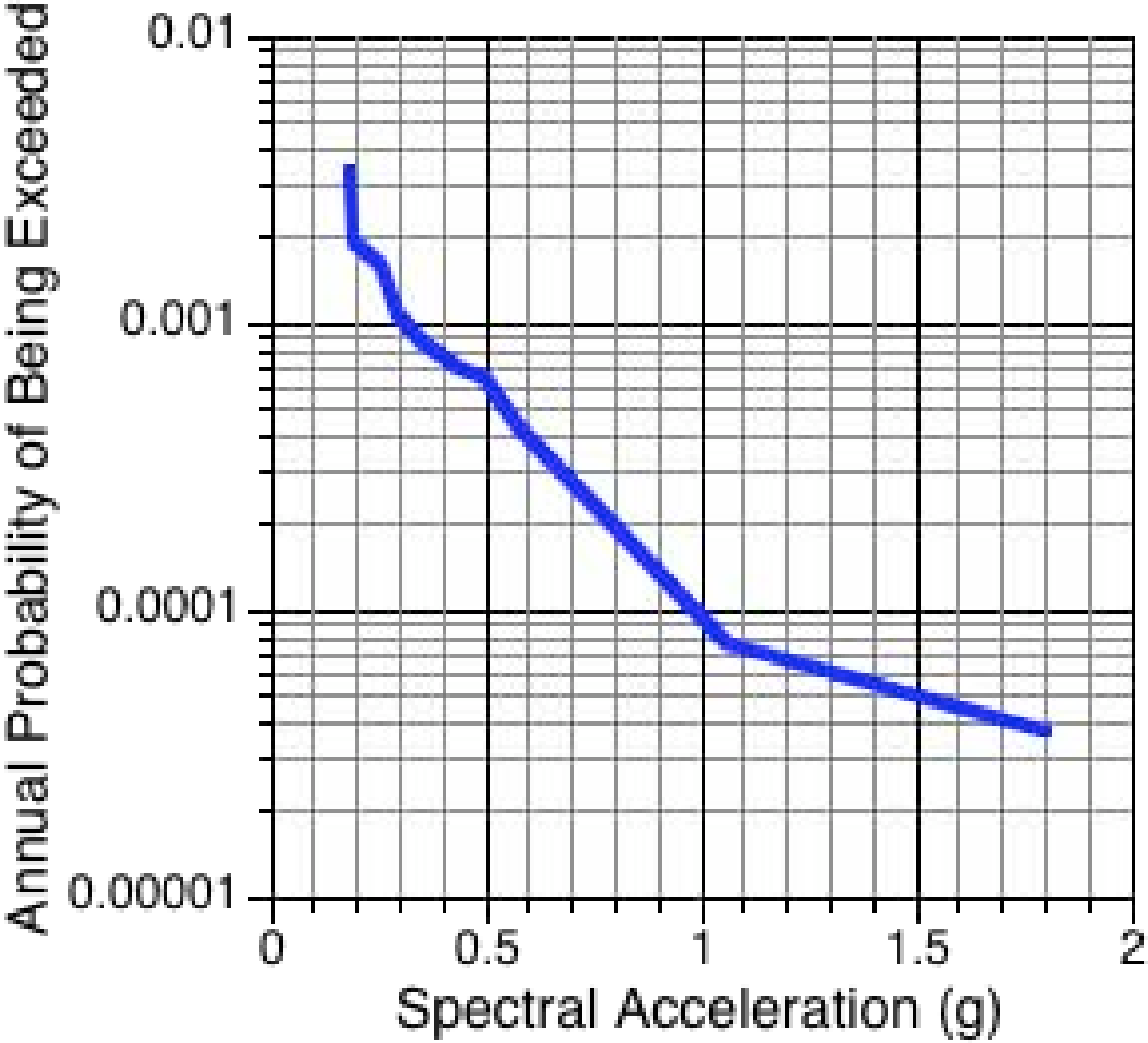
Partial List of Scenarios

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	6.50	2	0.00022	1.38	0.53	-0.5	0.175	1.06	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	6.50	2	-0.5	1.06	0.000038	0.000076
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

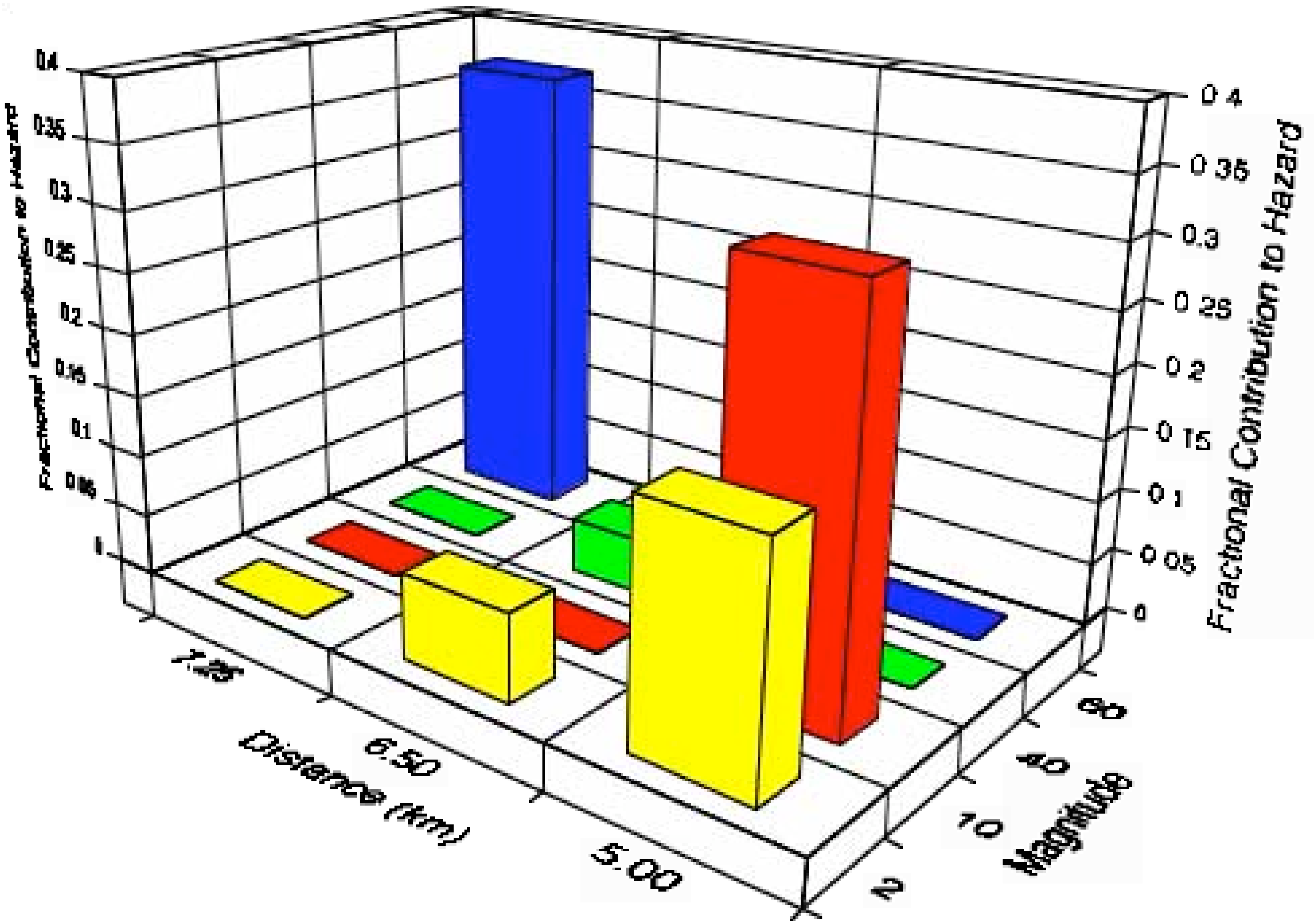
Hazard Curve



Deaggregation at 10^{-3} Hazard

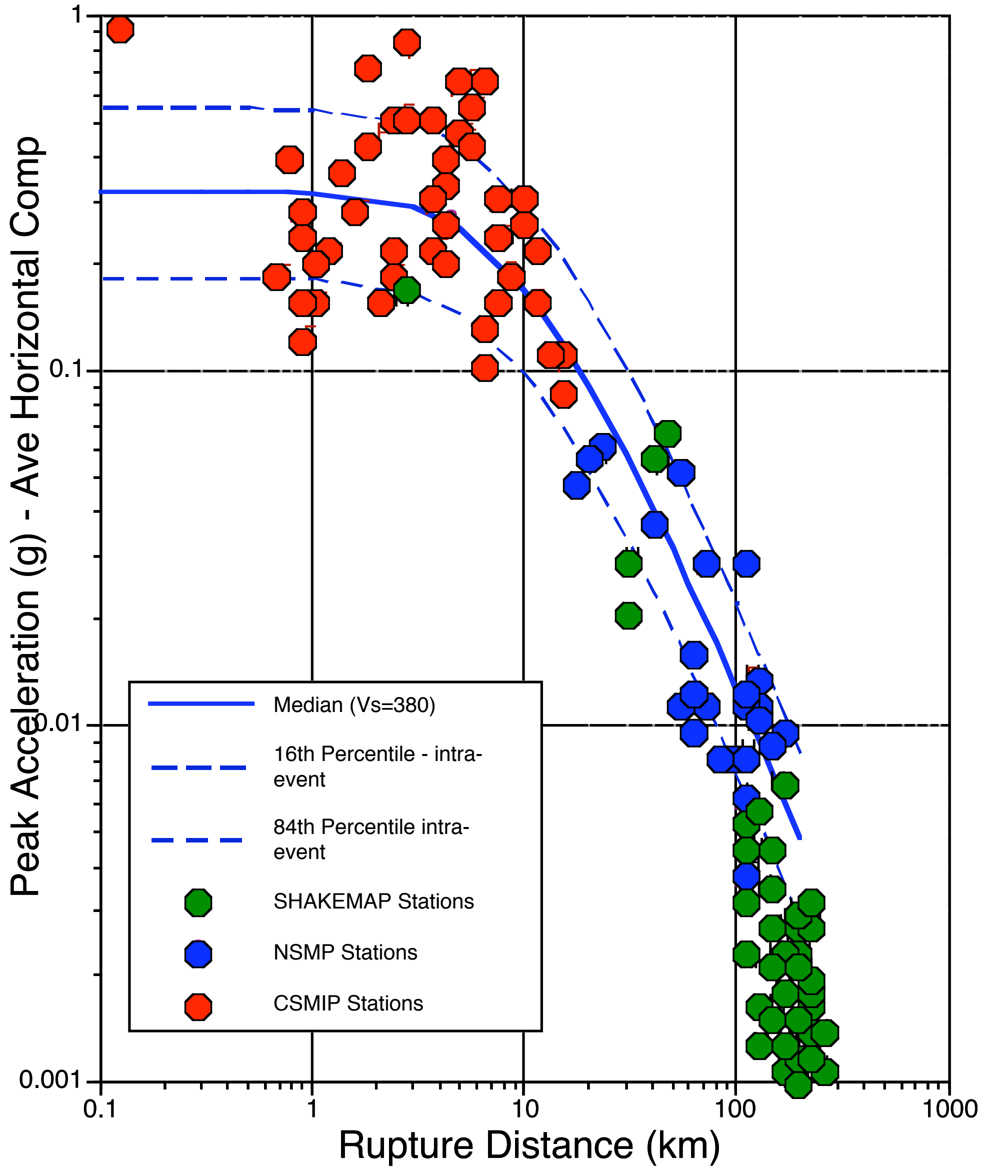
Source	Mag	R (km)	ε	Sa(g)	Rate	Hazard	Deagg
1	6.50	2	0.5	1.80	0.000038	0.000038	0.035
1	6.50	2	-0.5	1.06	0.000038	0.000076	0.035
1	5.00	10	0.0	0.58	0.000355	0.000432	0.327
3	7.25	60	1.0	0.49	0.000218	0.000649	0.201
2	6.50	40	1.5	0.44	0.000047	0.000697	0.044
3	7.25	60	1.5	0.35	0.000183	0.000880	0.169
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



Problems with Current Practice

- Major problems are related to the ground motion variability
  - Ignoring the ground motion variability
    - Assumes $\sigma=0$ for ground motion
    - This is simply wrong. Stop doing it.
  - Applying severe truncation to the ground motion distribution
    - e.g. Distribution truncated at $+1\sigma$
    - Wishful thinking
    - No empirical basis for truncation at less than 3σ.
    - Physical limits of material will truncate the distribution

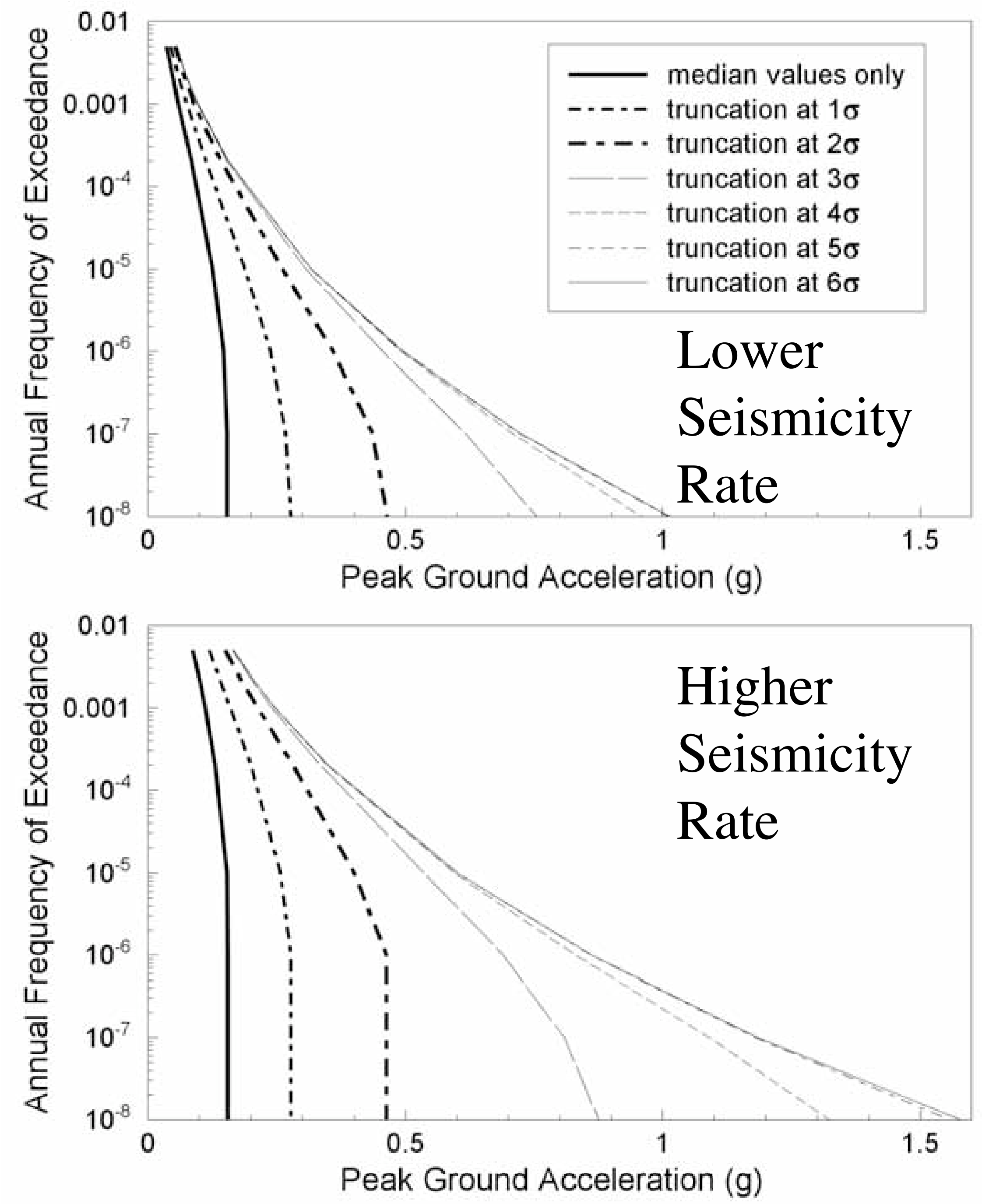


2004 Parkfield PGA Attenuation

Example:

Effect of ignoring σ, or truncating the ground motion distribution

(from Bommer, 2004)



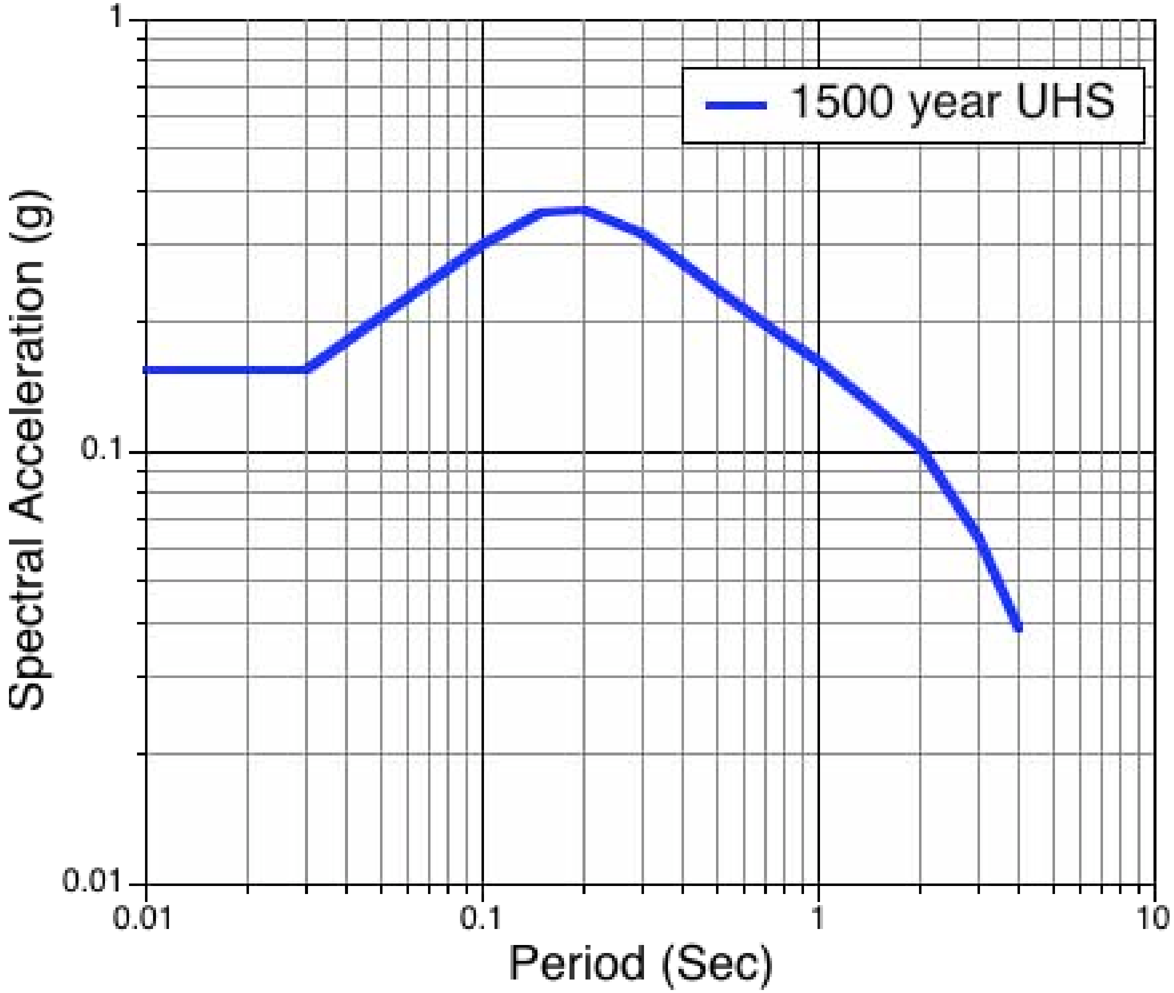
Improvements to Current Practice

- Scenario Spectra for UHS
- Deaggregation bin size
- Spatial smoothing of seismicity
- Lower bound magnitude for hazard calculation
- Underestimation of epistemic uncertainties

Uniform Hazard Spectrum

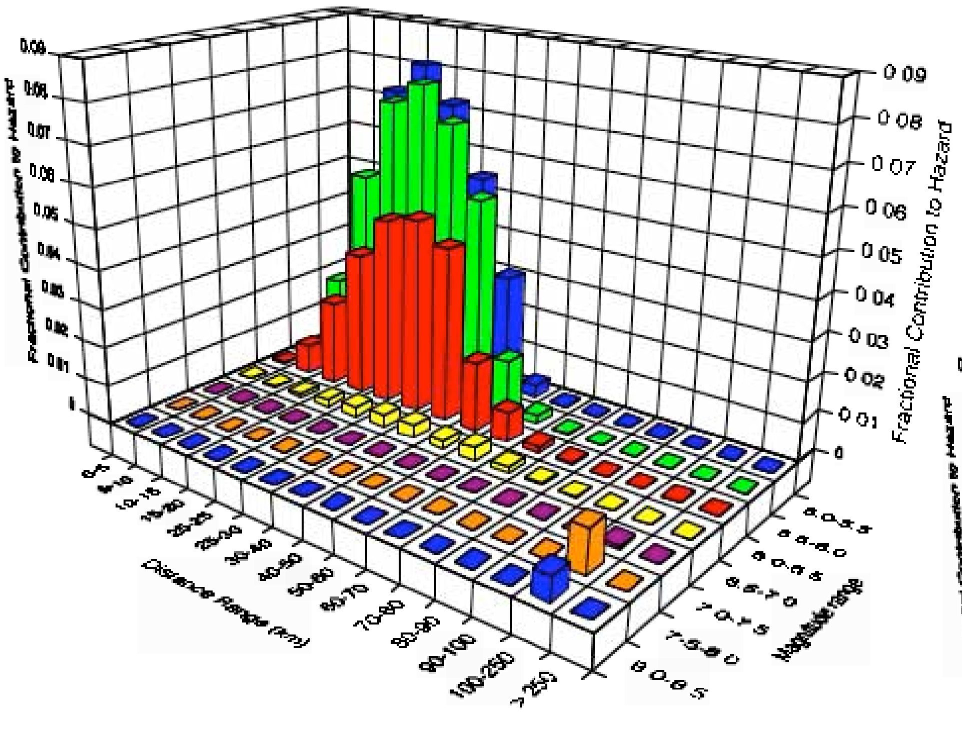
- This is the usual hand-off between the hazard analyst and the engineer. A hazard report includes:
  - UHS at a range of return periods gives the level of the ground motion
  - Deaggregation at several spectral periods for each return period identifies the controlling M,R
- The UHS is not the proper hand-off
  - The UHS is an envelope of the spectra from a suite of earthquakes
  - In addition to the UHS and deaggreagtion, the hazard analyst needs to provide deterministic scenario spectra that make up the UHS.

Crane Valley Dam Example

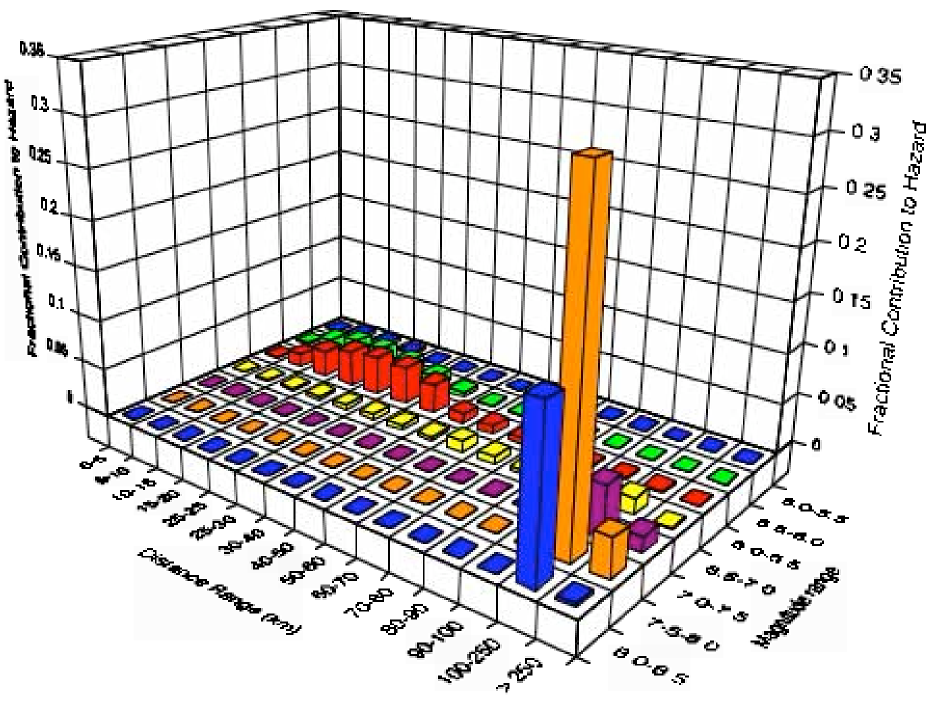


Deaggregation: 1500 yrs

PGA



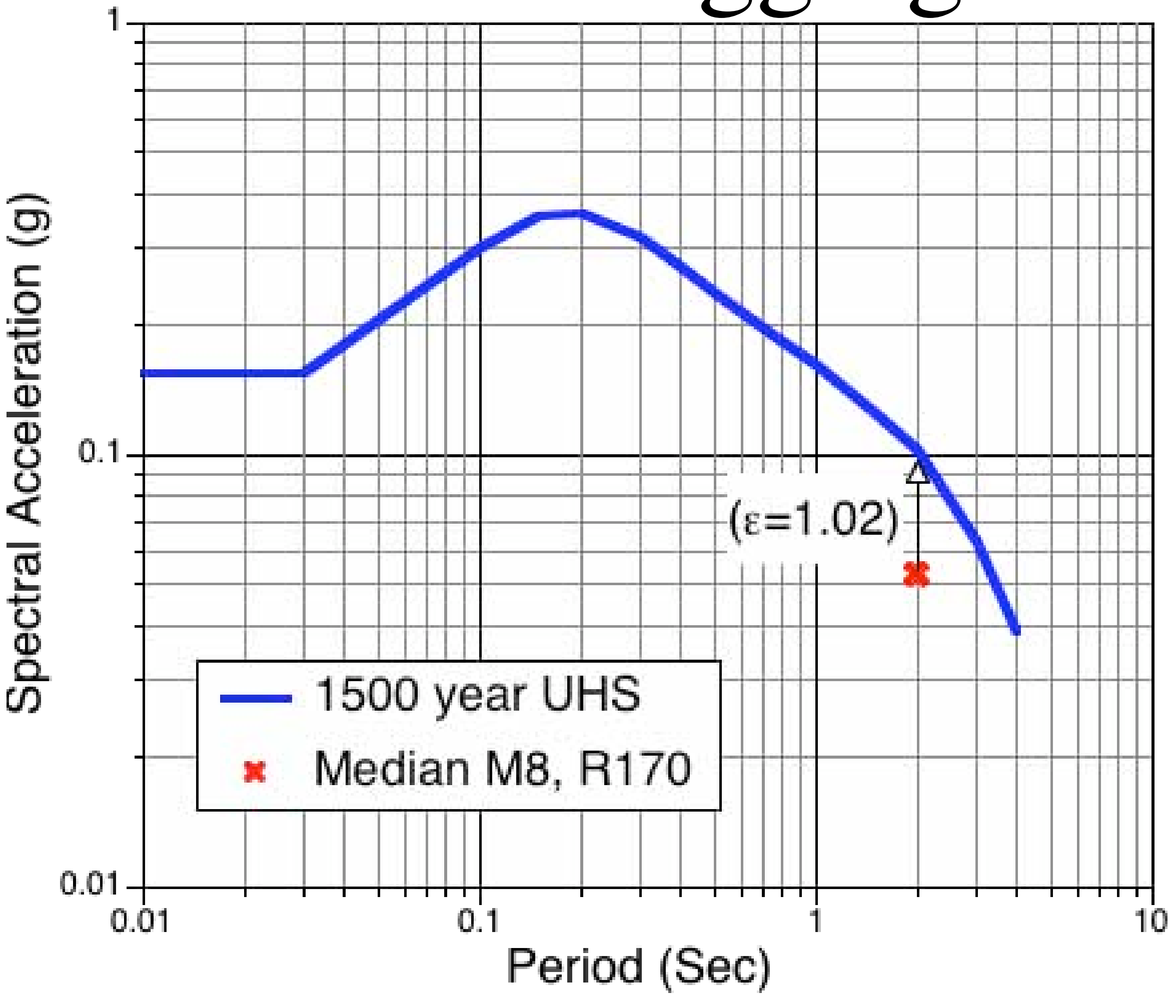
T=2.0 sec



Controlling Scenarios

- For return period = 1500 years:
  - SA(T=0.2): M=5.5-6.0, R=20-30 km
  - Sa(T=2): M=7.5-8.0, R=170 km

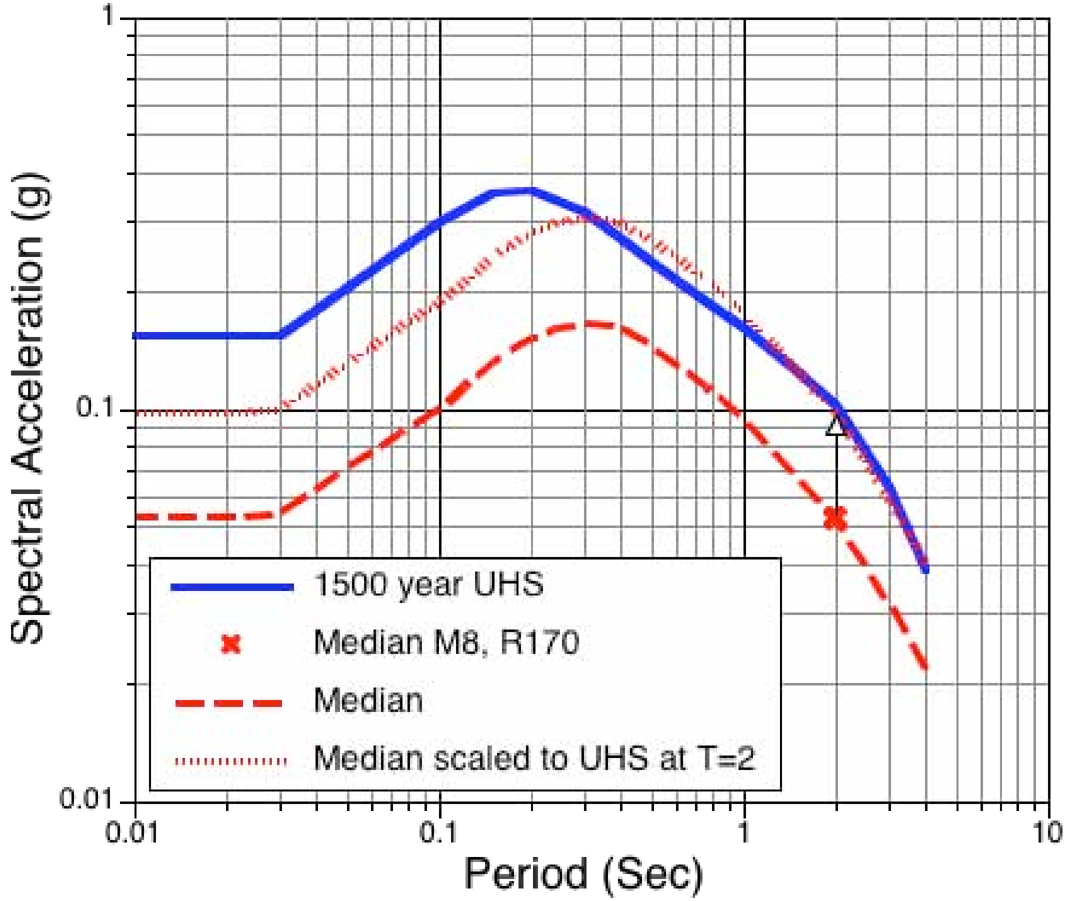
Scenario Ground Motions from Deaggregation



Find number of standard deviations needed to reach UHS

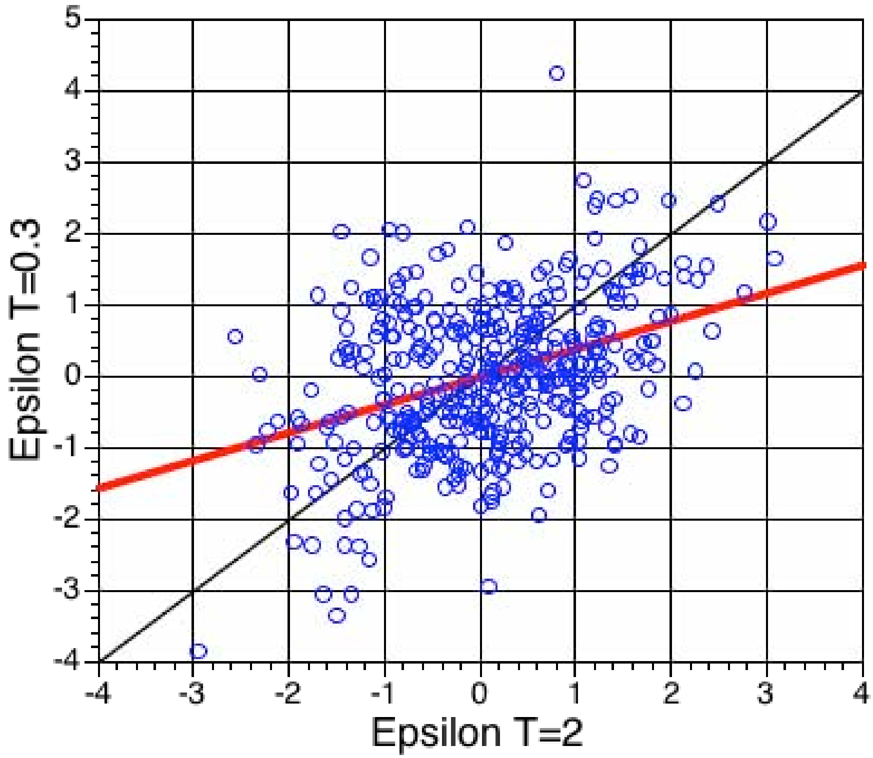
Next,
Construct the rest of the spectrum

Construct Scenario Spectrum



- Most common approach uses the median spectral shape, scaled to the UHS
- This approach assumes full correlation between periods

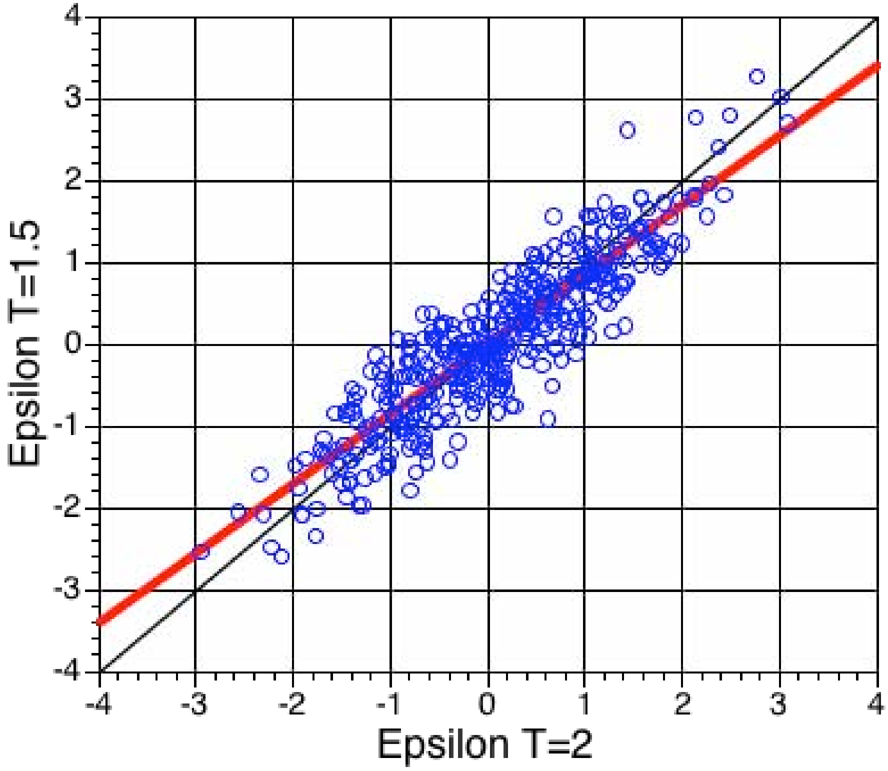
Expected Spectral Shape



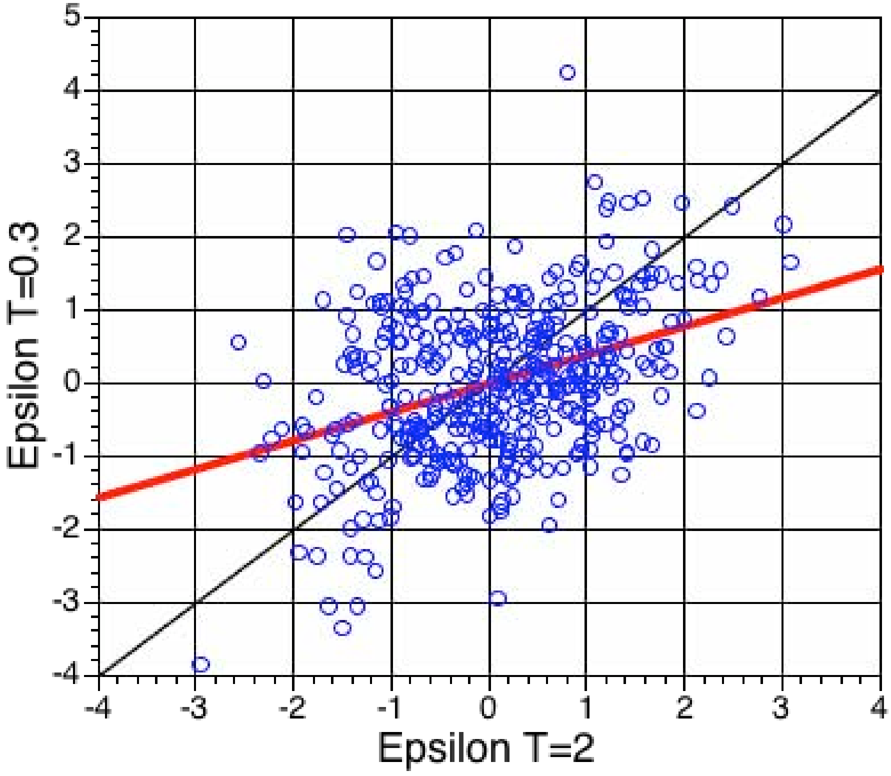
- Depends on the correlation of the epsilon values for different period.
- Find the expected ε (T) given ε(To)
- This approached used by Baker and Cornell for scaling time histories

Correlation of Epsilons is period dependent: $\varepsilon(T)=c\varepsilon(T_o)$

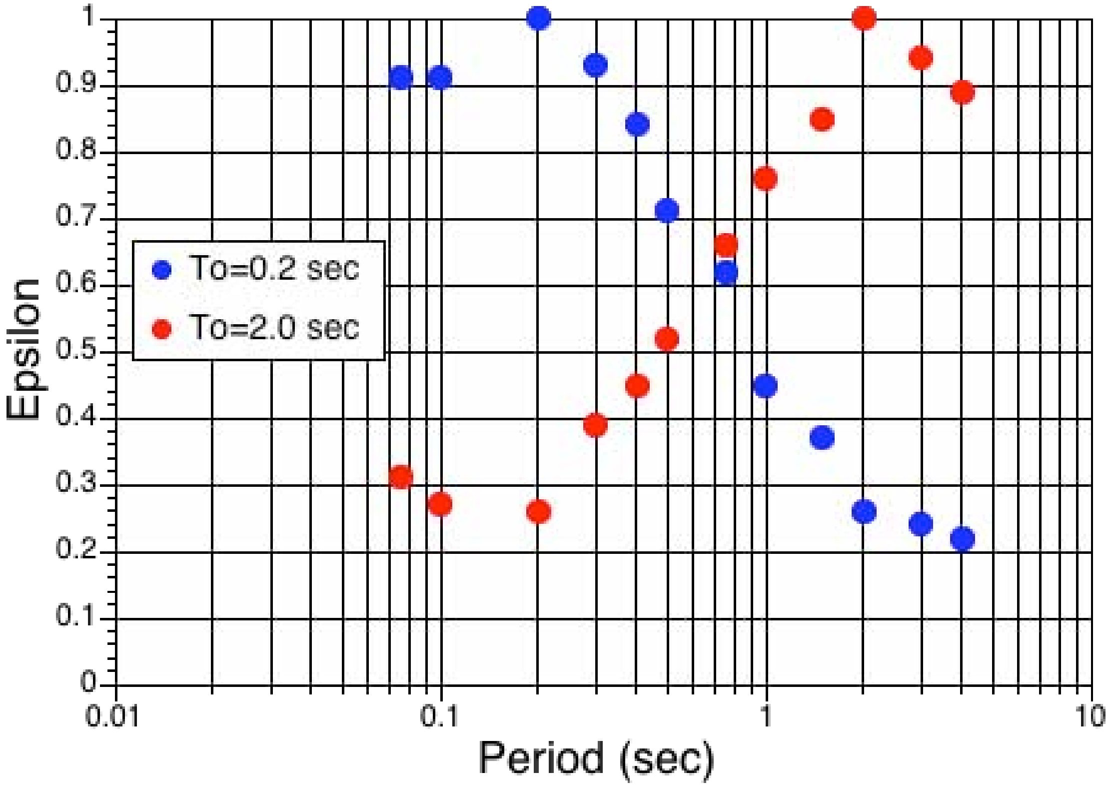
T=1.5



T=0.3

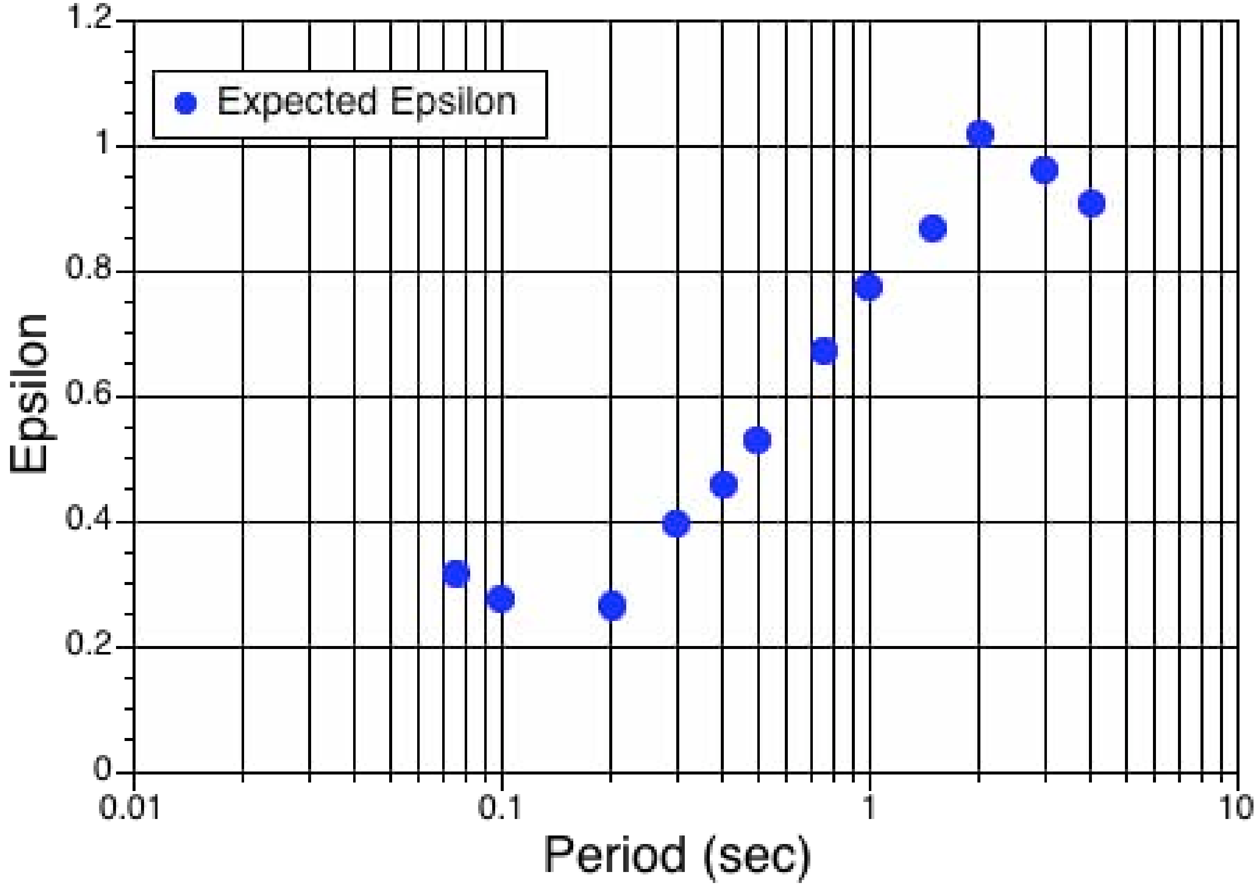


Correlation of Variability Epsilon(T) with Epsilon (T_o)

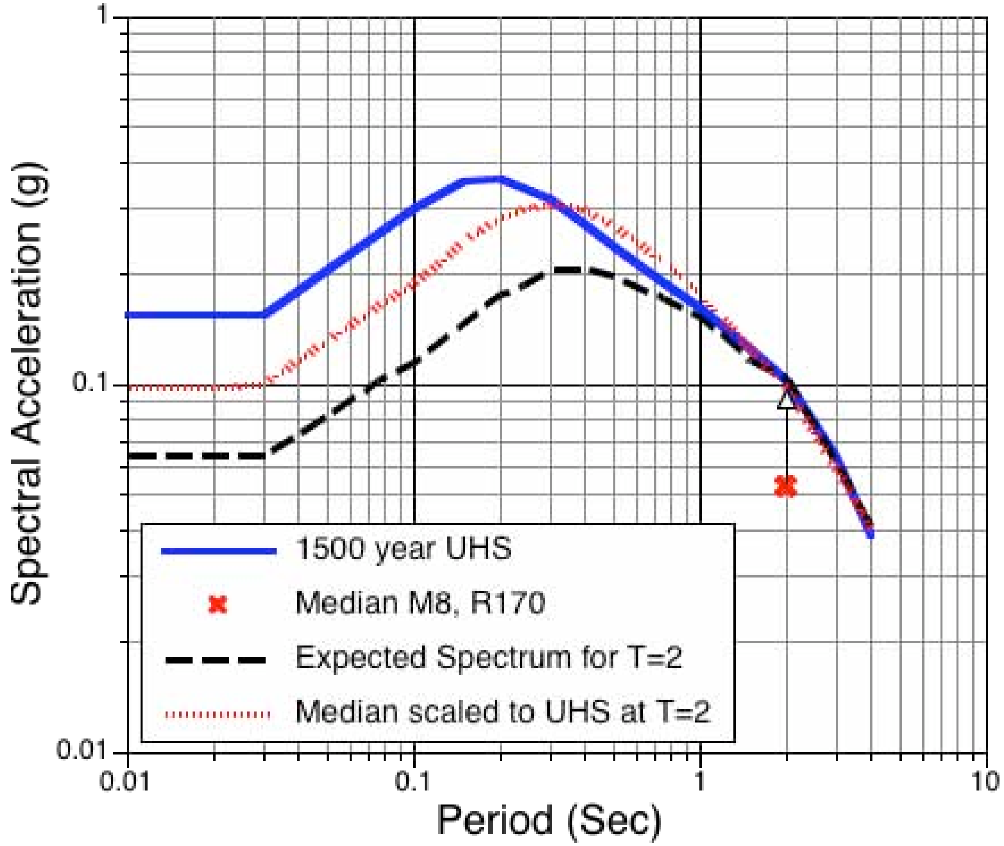


- Correlation decreases away from reference period
- Increase at short period results from nature of Sa

Mean Epsilon for 1500 yr RP, T=2 sec

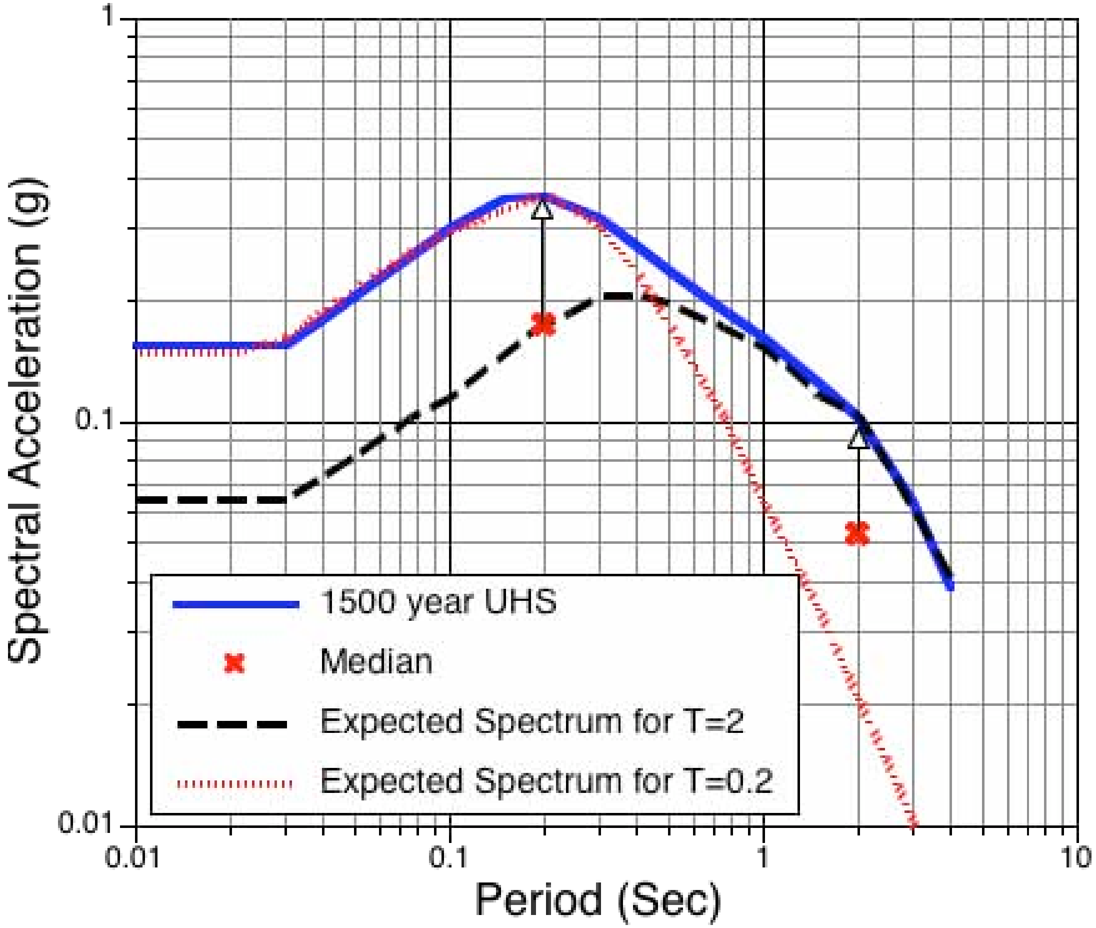


Scenario Spectrum for 1500 yr RP, T=2 sec



- Realistic scenario
- M=8, R=170 km
- Expected spectrum, if the UHS T=2 sec value occurs
  - $Sa(T)=Sa_{med}(T)\exp(\varepsilon(T)\sigma(T))$

Scenario Spectra for UHS



- Repeat process for other spectral periods
- Develop a suite of deterministic scenarios that comprise the UHS
- Time histories should be matched to the scenarios individually, not to the entire UHS

Improvements to PHSA Practice

- At the seismology/engineering interface, we need to pass spectra for realistic scenarios that correspond the hazard level
  - This will require suites of scenarios, even if there is a single controlling earthquake
- The decision to envelope the scenarios to reduce the number of engineering analyses required should be made on the engineering side based on the structure, not on the seismology side.

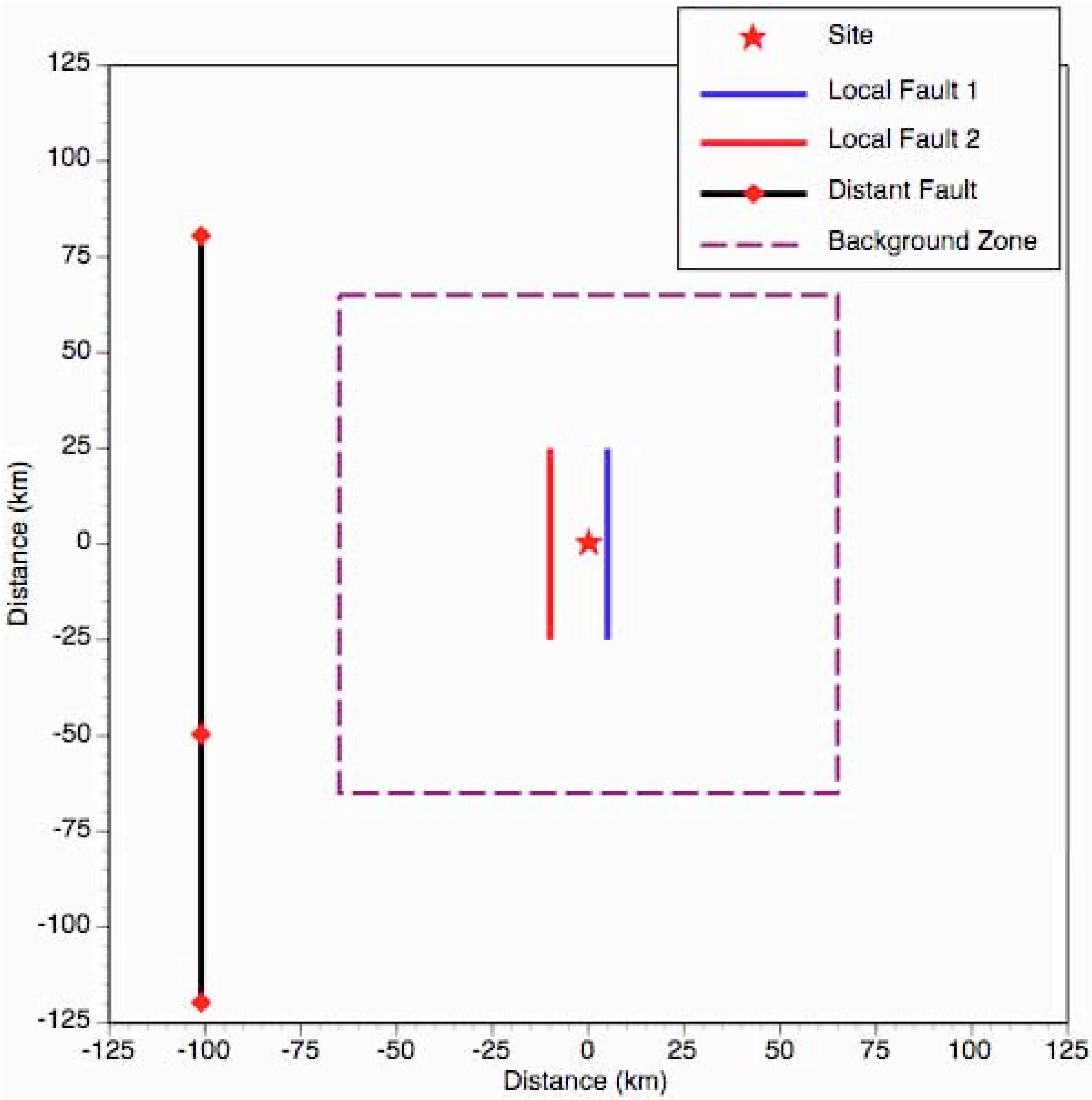
Deaggregation Bin Size

- Common practice to use the mode of the deaggregation in M-R space
  - This avoids the potential problem of finding a non-physical earthquake that can occur using the mean M-R
- Issue:
  - The computed mode depends on the size of the M-R bins used in the deaggreation
  - In current practice, the bin size is set without consideration of the use of the results

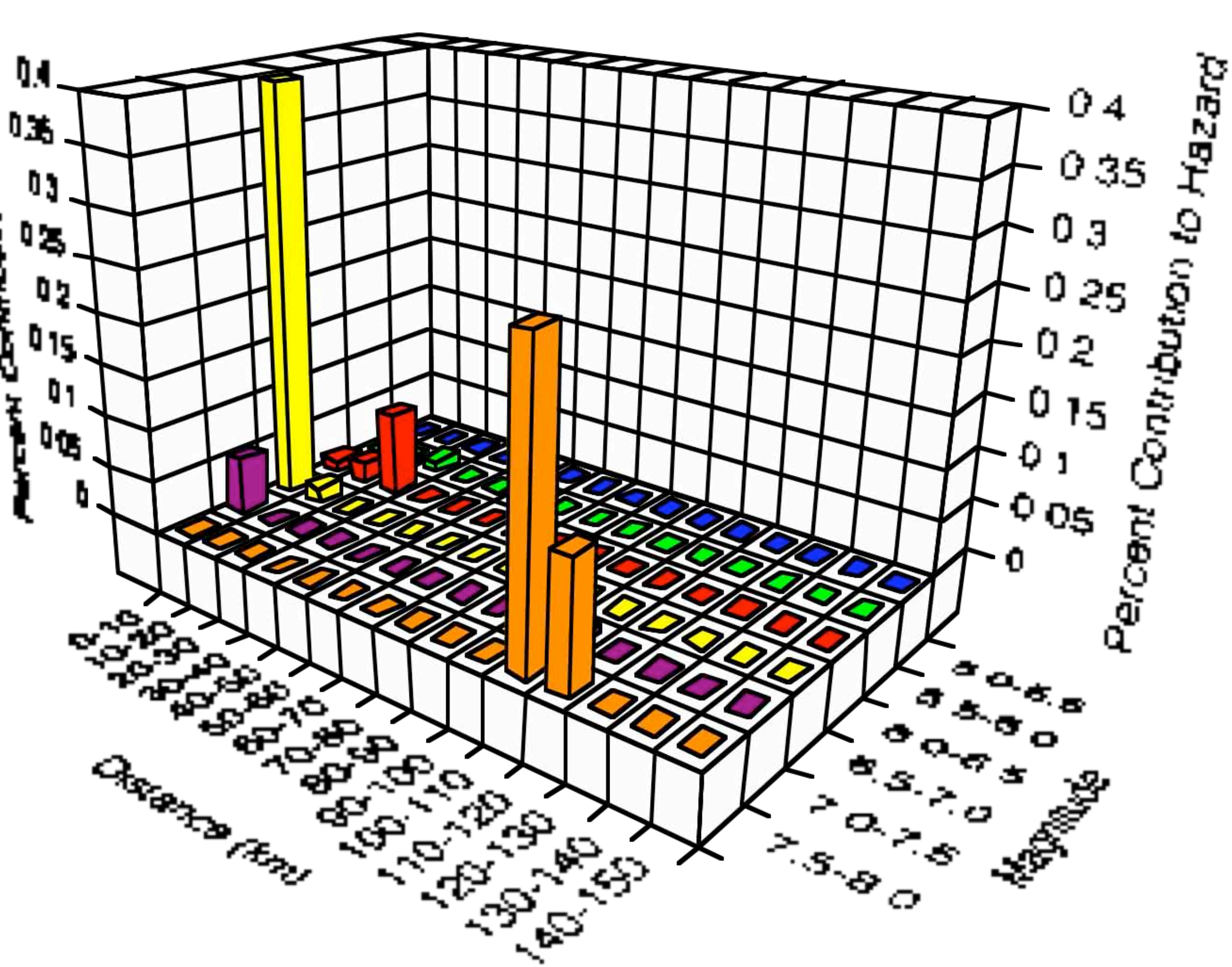
Deaggregation Bin Size

Example

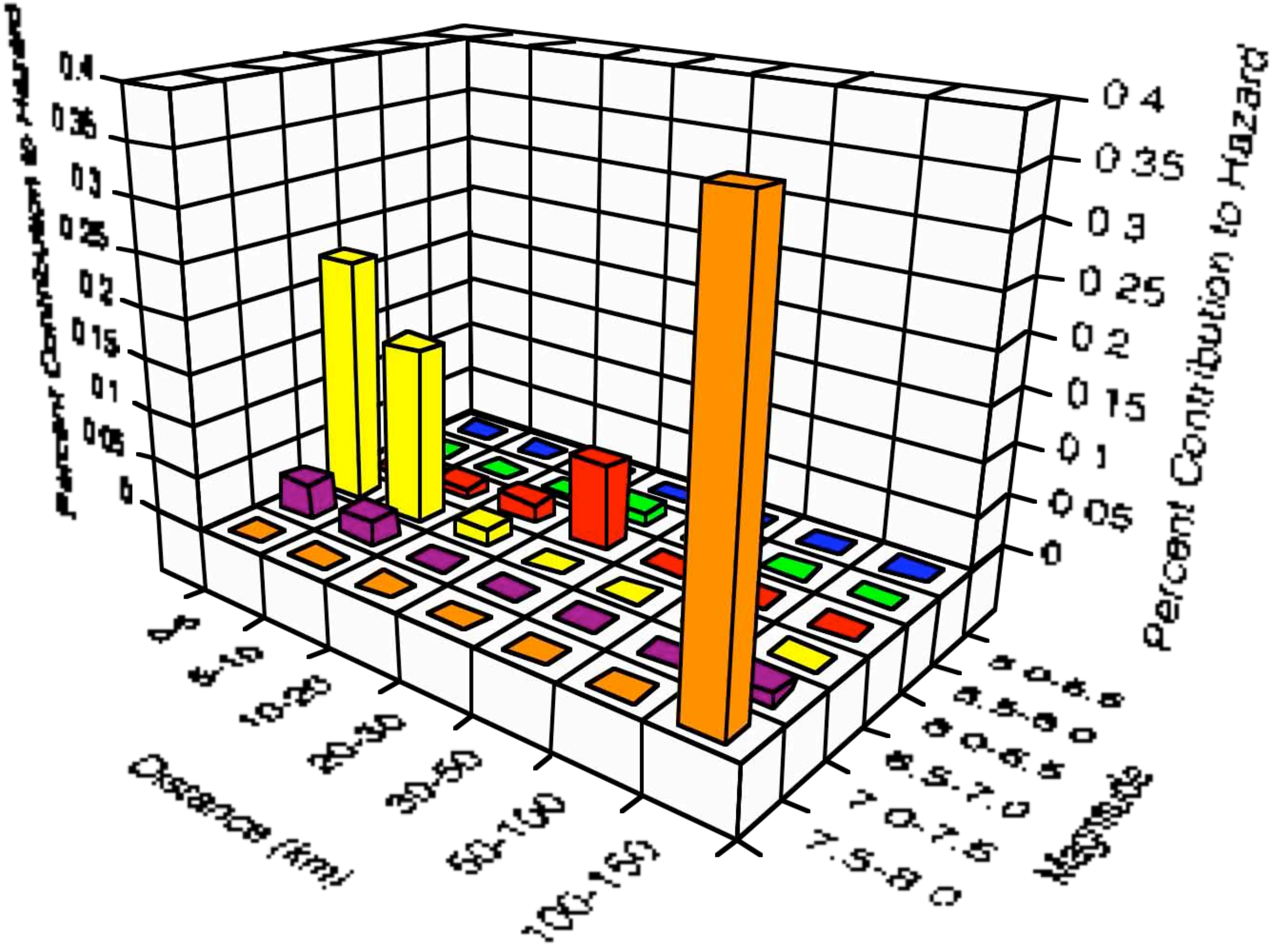
Source Model



Deaggregation: Equal Bin Size in R



Deaggregation: Unequal Bin Size in R



Deaggregation Bin Size

- Just using equal bin size is not necessarily the best approach for finding the mode
- The best bin size will depend on how the results are to be used
  - e.g. If deaggregation is used for selecting time histories, then unequal spacing in distance should be used.
  - The bin size may be different for different types of structures
  - Should be input from the engineer as to bin sizes.

Future Developments in PSHA:

- Incorporate site-specific amplification
  - Compute non-linear amplification factors outside of PHSA
- Vector hazard
  - Joint probability of multiple ground motion parameters
- Inelastic spectra
  - Needs vector hazard

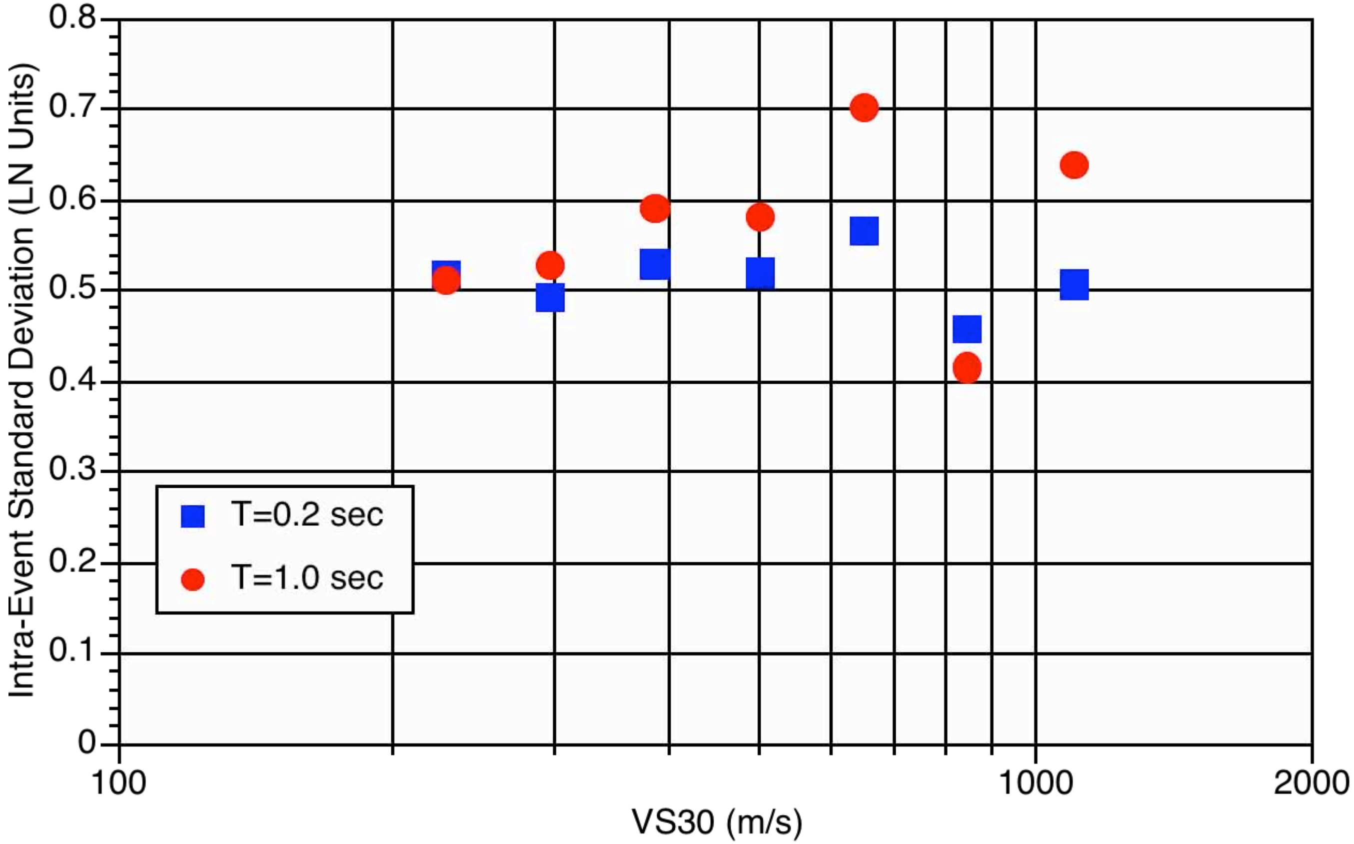
Incorporating Site-Specific Response in PSHA

- Two Approaches
  - Put the site response inside the hazard integral
    - Requires modification of the PSHA software
  - Compute the hazard using standard PSHA and apply the site response effects in a post-process
- Site Response Models
  - Need to be applicable to all cases relevant to the hazard
    - e.g. range of magnitudes and ground motion levels

Site Amplification Models

- Median amplification
  - Function of M, Sa
- Variability of amplification
  - If linear, then standard deviation on soil will be larger than on rock
  - Not observed

Standard Deviation from A&S NGA Model by VS30



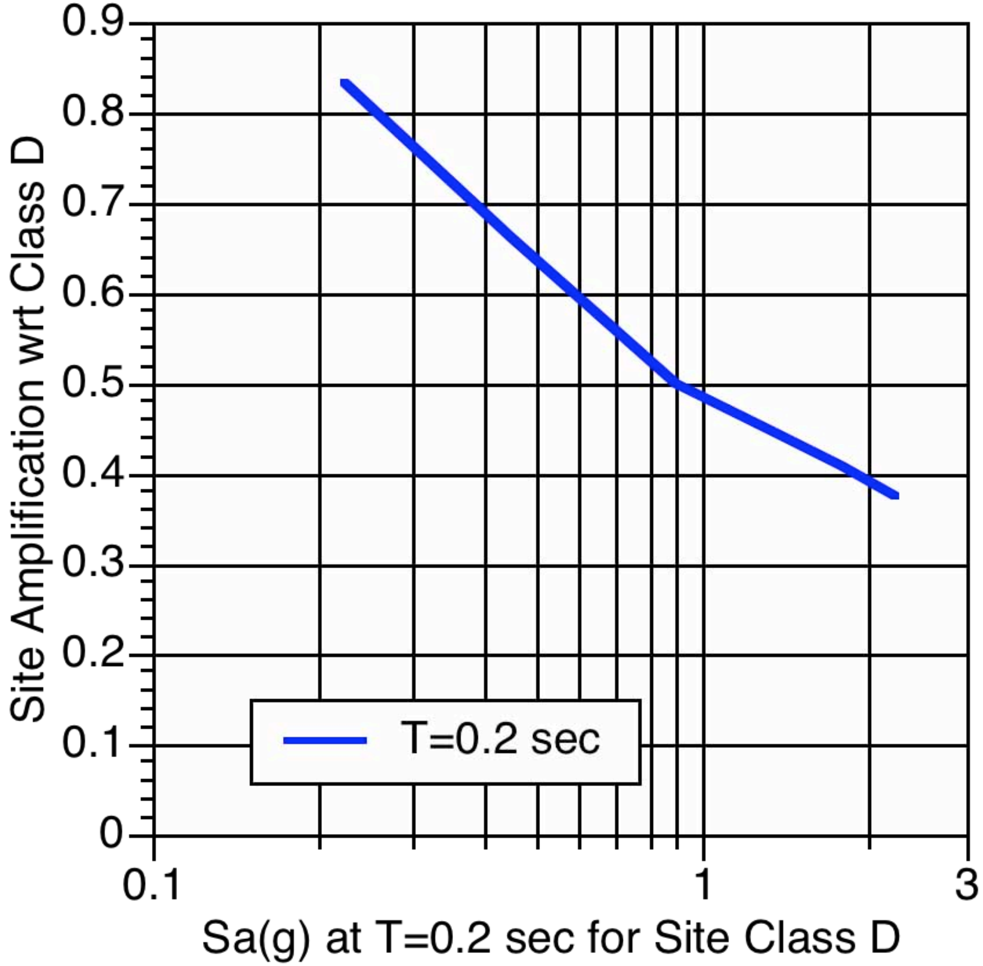
Approaches to this Problem

- Use the variability of the amplification and live with the over-estimation of the total variability
- Use only the median amplification and assume that the standard deviation used for the input rock motion is applicable to the soil

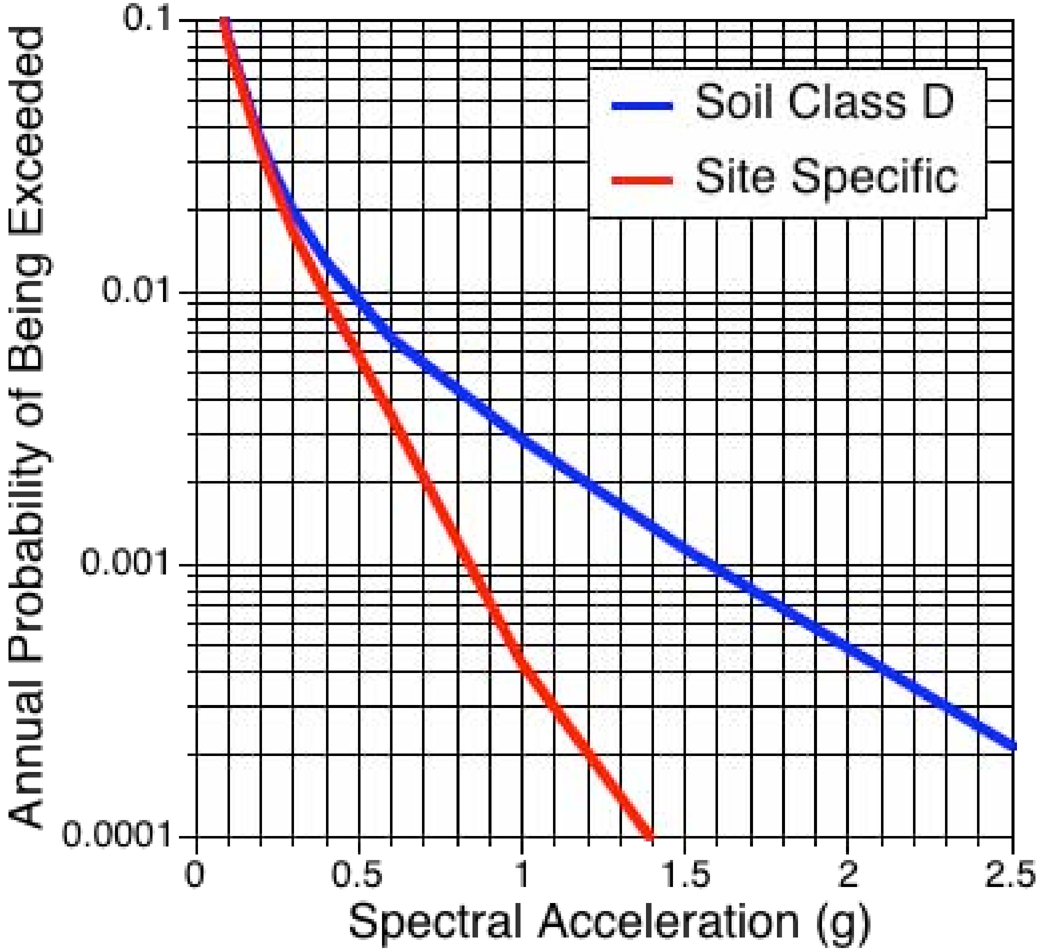
Hazard Example

- Site with engineered fill over class D soil in Los Angeles Region
- Site response computed using SHAKE
  - Magnitudes 6.0, 6.5, 7.0, 7.5
  - PGA (soil D): 0.1, 0.2, 0.4, 0.6, 0.8, 1.0g
  - 7 spectrum compatible time histories used for each case
  - 3 profiles used
  - Total of 504 site response calculations
- Median site amplification used, w/o variability

Median Amplification
T=0.2 sec, M=6



Hazard for T=0.2 sec



Vector Hazard

- Compute the rate of two or more parameters occurring in the same ground motion
  - $Sa(T_1)$ and $S(2T_1)$
  - PGV and duration,
  - Arias intensity, duration, PGV…
- More likely to lead to significant improvements in predicting structural response than looking for an improved single parameter IM

Vector Hazard

- Results from vector hazard are best presented in terms of a table of rates of occurrence, rather than as hazard curves.
  - Set bins of the values of each parameter
  - Sum the rates of scenarios that have ground motion values that fall within the bin
- Deaggregation is then conducted for each bin
  - Tables of deterministic scenarios and their rates
- Use of vector hazard is for risk calculations, not development of design ground motions
- Not practical for hazard maps

PSHA Calculation

- Standard form of hazard

$$v(Sa > z) = \sum_{i=1}^{nSource} N_i(M_{\min}) \int_M \int_R f_{mi}(M)\, f_{Ri}(r, M)\, P(Sa > z \mid m, R)\, dR\, dM$$

- Alternative form (explicit ground motion aleatory variability)

$$v(Sa > z) = \sum_{i=1}^{nSource} N_i(M_{\min}) \int_M \int_R \int_\varepsilon f_{mi}(M)\, f_{Ri}(r, M)\, f_\varepsilon(\varepsilon)\, P(Sa > z \mid m, R, \varepsilon)\, d\varepsilon\, dR\, dM$$