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Use of Numerical Simulations in Seismic Hazard Analyses

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Neo-Deterministic Method

- “Deterministic” Part
  - Source
    - Select single representative earthquake
- “Neo” Part
  - Ground Motions
    - Use Finite-fault numerical simulations in place of empirical models
    - Select a representative case
  - Avoids using empirical (e.g. statistical) models for the ground motion
    - “physics-based” hazard

Neo-Deterministic Method

- Main Issue
  - Large aleatory variability in the source parameters of future earthquakes
    - rupture area, hypocenter, slip-distribution, rupture velocity, rise-time, rake angle, …
  - Which of the simulations will be selected?
    - Typical case (median)
    - Above average case (84th percentile)
    - Case with strongest ground motion?
- Difficulty with deterministic approaches
  - Given a scenario, how to pick a ground motion that is “reasonable” for use in design
- Probabilistic approaches
  - Can be used to identify a “reasonable” deterministic case

Design Ground Motions

- For a given earthquake scenario (Mag, rupture location, rupture geometry, site location), there is a large variability in the ground motions
- Worst-Case (largest possible) ground motion due to physical limits
  - Extreme ground motion project addressed this issue
  - The worst-case ground motions are very large
    - Costly for use in design
    - Too rare to justify the high cost
- Worst-Case ground motion is not used in practice
  - Therefore, some residual risk remains
- Main Objective:
  - Select a design ground motion that leads to a residual risk that is acceptably small.
    - What is acceptably small?

Estimating Residual Risk

- Risk Approach
  - Calculate probability of consequence (loss of life or loss in dollars)
    - Select a design ground motion that leads to an acceptably low risk
- Simplified Approaches
  - Performance-based approach
    - Calculate probability of damage states of structure (e.g. Collapse)
      - Select performance probability
  - Probabilistic ground motion approach
    - Calculate probability of ground motion occurring at site
      - Select ground motion return period
  - Deterministic ground motion approach
    - Rare earthquake selected
      - Typically select median or 84th percentile ground motion
      - Other levels could be selected

Probabilistic and Deterministic

- DSHA is a simplified PSHA.
- DSHA is not always “conservative” or “unconservative” compared to PSHA.
  - Depending on the seismic setting and the return period used in PSHA:
    - DHSA > PHSA
    - DHSA ≈ PSHA
    - DSHA < PSHA

Deterministic Approach

- Worst-case ground motion is not selected
- 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”

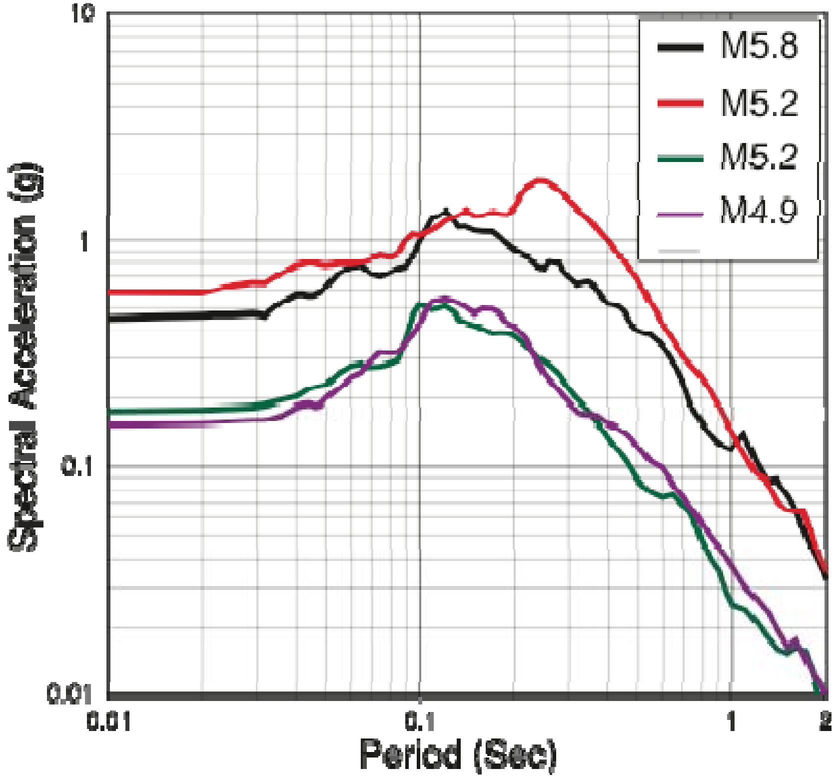
- The same number of standard deviation of ground motion may not be “reasonable” for all sources
  - Median may be reasonable for low activity sources, but higher value may be needed for high activity sources
- “Reasonable” implies a small enough residual risk, but non-zero residual risk
  - Simplified: small enough chance of the design ground motion being exceeded
    - Need to understand the performance of structure to beyond design basis ground motions
- Need to consider both the rate of the earthquake and the chance of the ground motion
  - PSHA

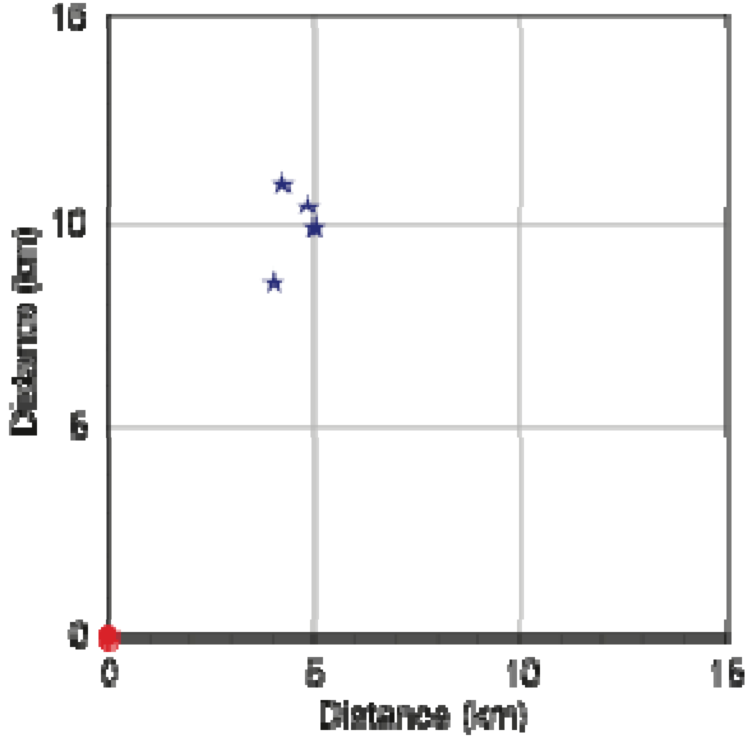
Why PSHA and not DSHA?

- Some DSHA considers the activity rate (e.g. slip-rate) of fault in selecting the ground motion level
  - E.g. slip-rate < 0.1 mm/yr use median
  - slip-rate > 1 mm/yr use 84^{th} percentile
  - Simplified PSHA with a single source
- PSHA considers all scenarios that contribute to the residual risk
  - Due to the large variability of the ground motion, a range of scenarios can contribute the residual risk
    - A very rare ground motion (2-3 sigma) from a smaller magnitude earthquake
    - An above average ground motion (1 sigma) from a large earthquake

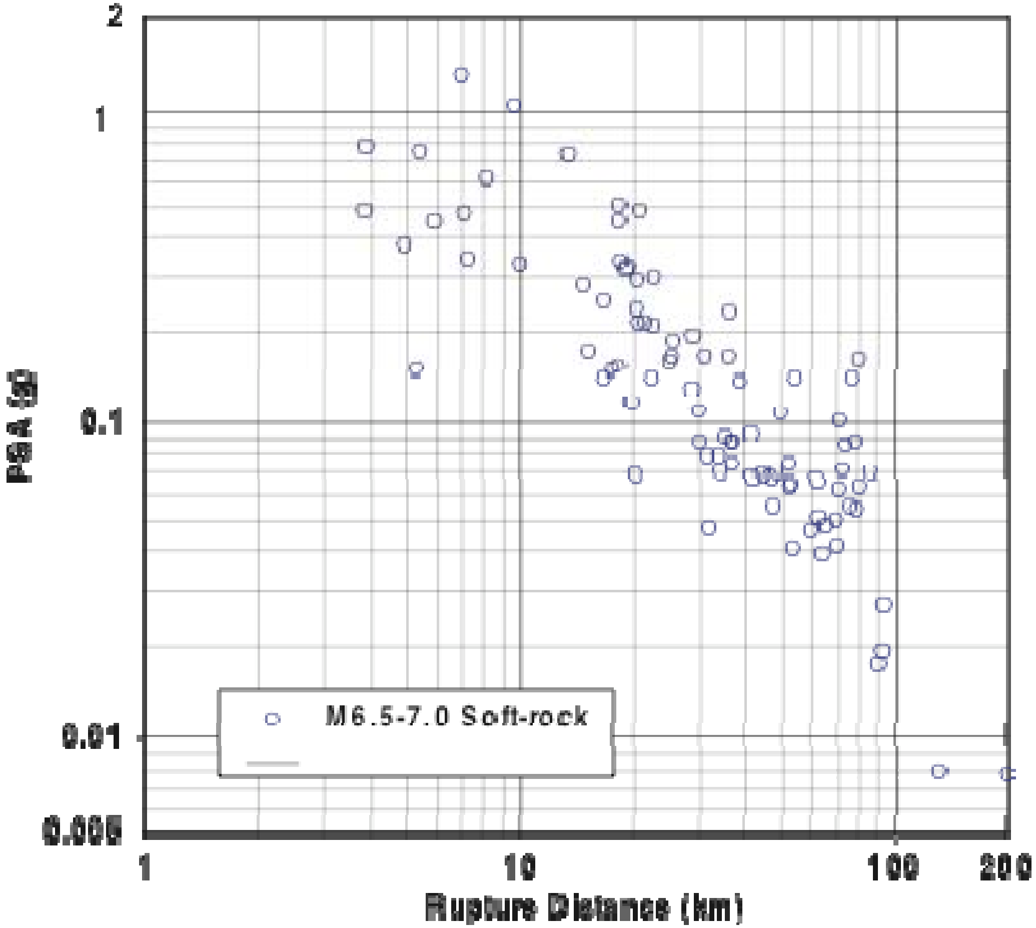
Variability of GM for Single Path/Site

1983 Coalinga Earthquake Aftershocks
Recorded at Station: Coalinga-14th & Elm
- Similar epicentral locations and focal depths





Example of GM Variability



Empirical Models

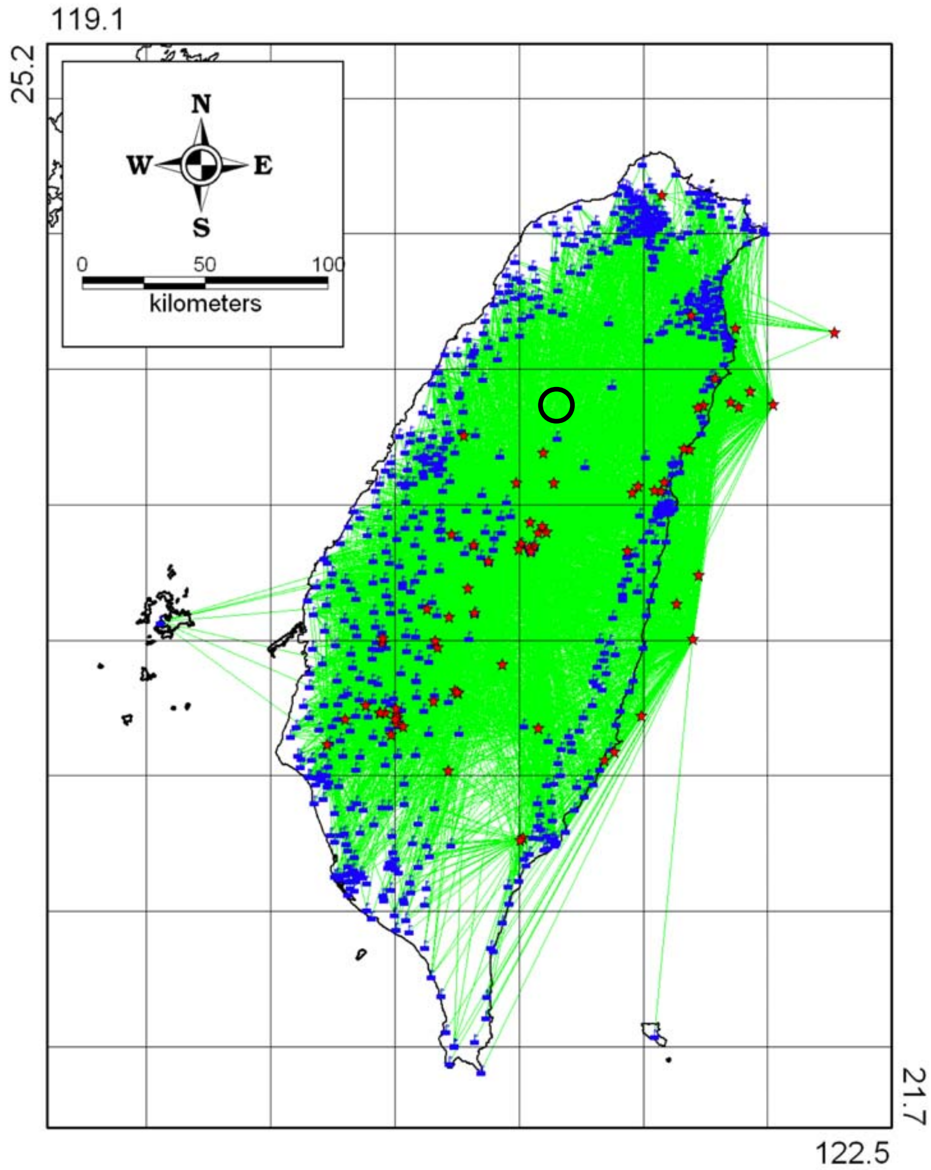
Mixing Epistemic and Aleatory

<u>Average Site Amplification</u>

For a single site, it is a constant. Therefore, epistemic uncertainty in its value,

Treated as aleatory in ground motion models that group sites together (by class or VS30).

With enough data, a site-specific constant can be estimated



Standard Deviations for LN PGA

	Region	Total	Single Station
Chen&Tsai (2002)	Taiwan	0.73	0.63
Atkinson (2006)	Southern CA	0.71	0.62
Lin et al (2009)	Taiwan	0.73	0.62
Rodriguez-Marek et al (2009)	Japan	0.82	0.63

Standard Deviations for LN SA(T=1)

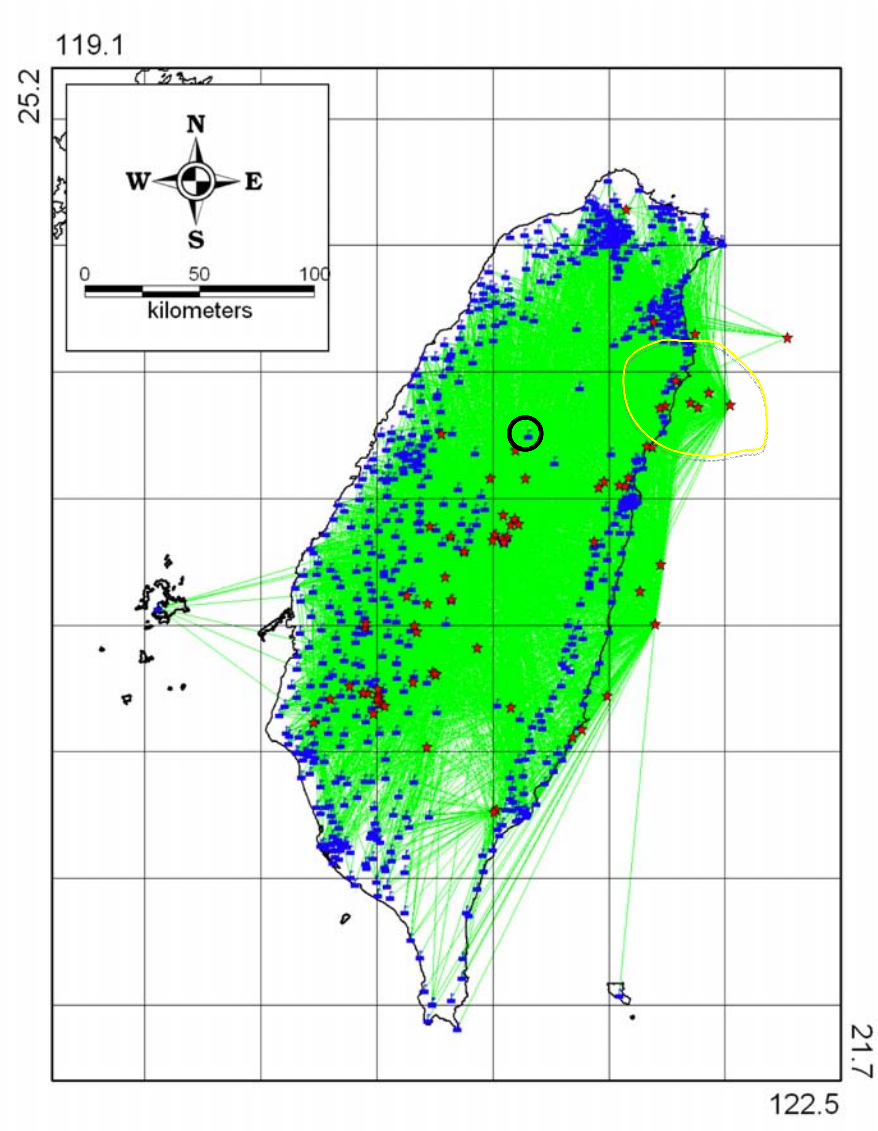
	Region	Total	Single Station
Atkinson (2006)	Southern CA	0.67	0.62
Lin et al (2009)	Taiwan	0.74	0.64
Rodriguez-Marek et al (2009)	Japan	0.80	0.62
Bindi et al (2009)	Italy	0.76	0.63

Single-Path Sigma

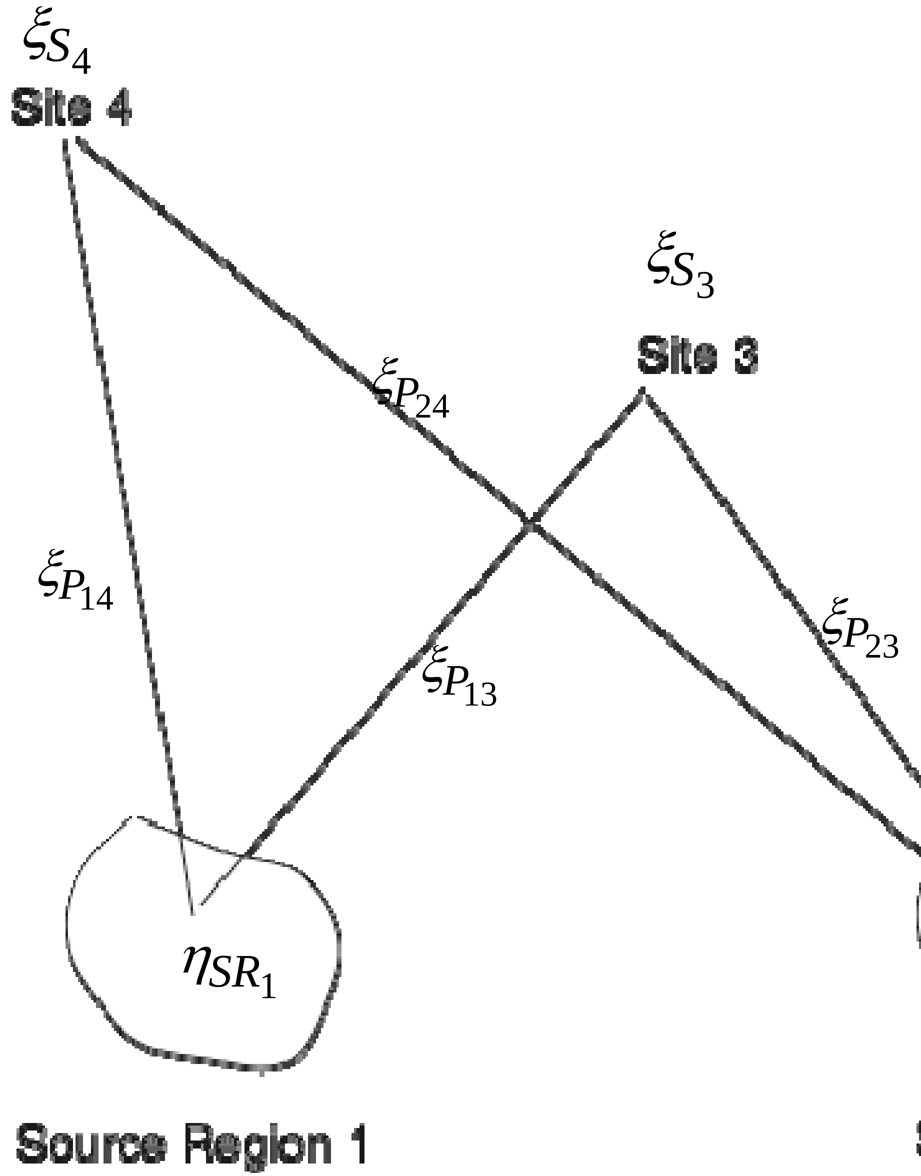
<u>Single Ray Path</u>

Repeatable wave propagation effects from a small source region to a single site.

Usually treated as aleatory, but should be epistemic



Single-Path, Single Site

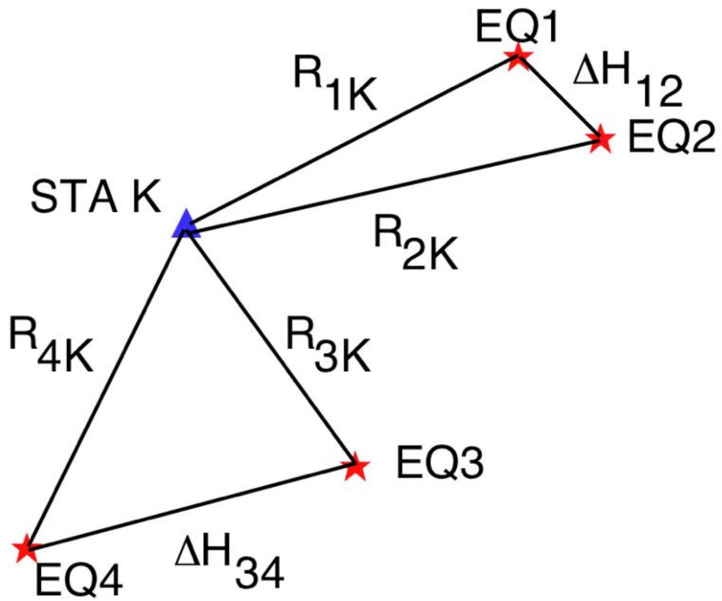


$\xi_{P\,lk}$ is the average difference from the regional GM model

η_{SR_l} is the average difference of source (e.g. stress-drop) from the regional GM model

Path Similarity (Closeness) Index

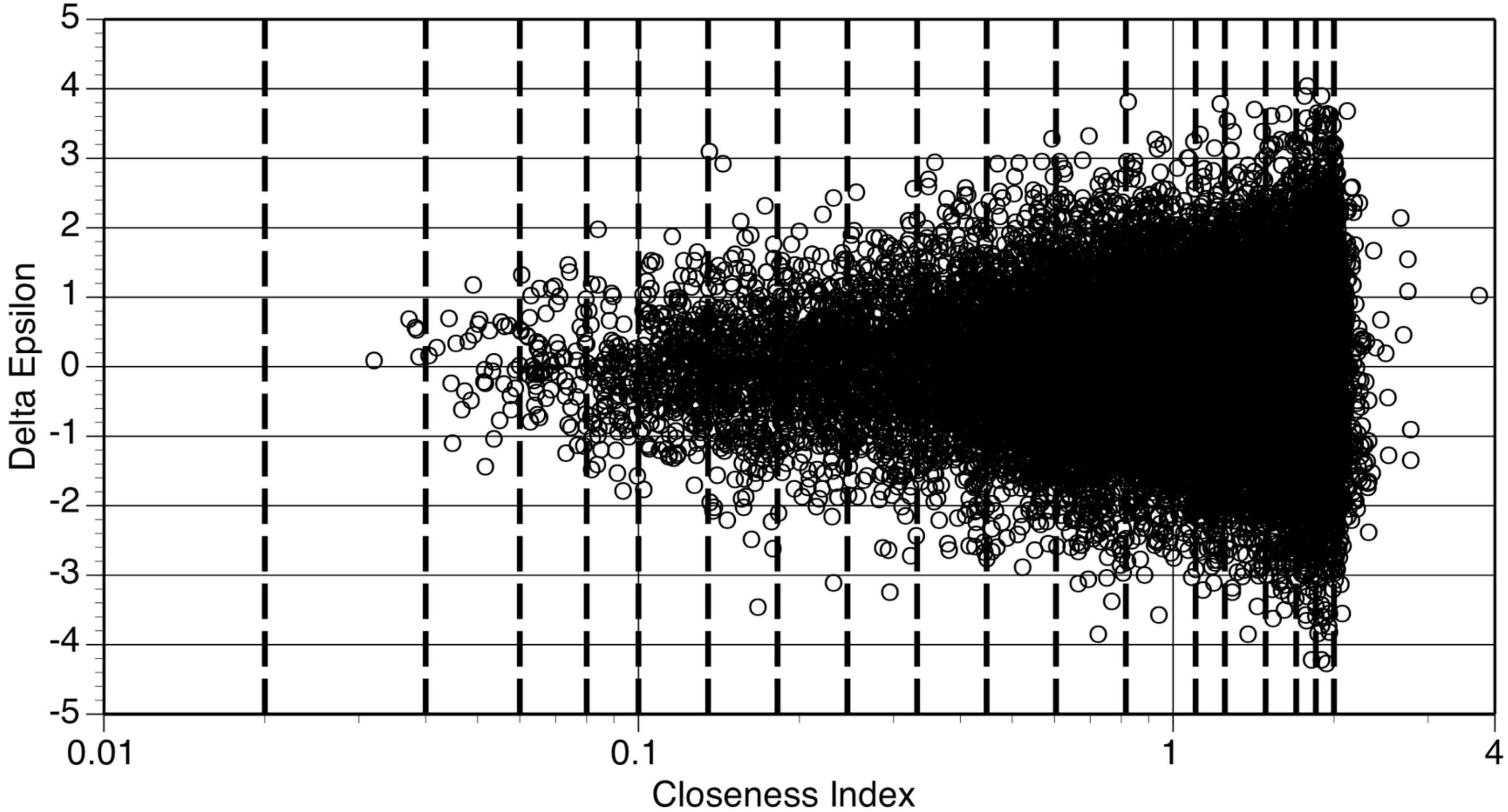
From Lin et al (2010)



$$CI = \frac{\Delta H_{12}}{(R_{1k} + R_{2k})/2}$$

Path Similarity

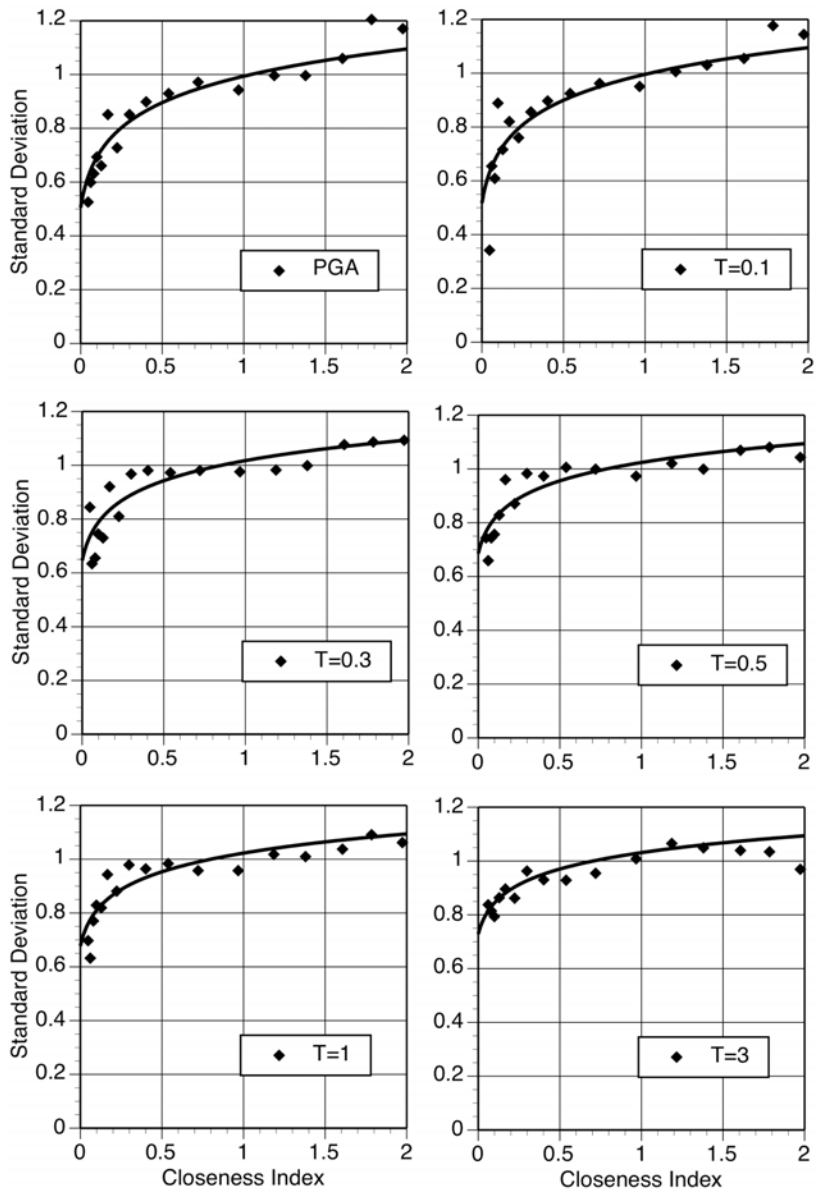
From Lin et al (2010)



Path Similarity

From Lin et al (2010)

Standard Deviation of Epsilon
(Normalized residual)



Total vs Single Path Sigma

Ergodic:

$$\sigma = \sqrt{\tau_0^2 + \tau_{SR}^2 + \phi_0^2 + \phi_S^2 + \phi_P^2}$$

Non-Ergodic Single Site, Single Path:

$$\sigma_{SP} = \sqrt{\tau_0^2 + \phi_0^2}$$

Standard Deviations for LN PGA

	Region	Total	Single Site	Single Path and site
Chen&Tsai (2002)	Taiwan	0.73	0.63	
Atkinson (2006)	Southern CA	0.71	0.62	0.41
Morikawa et al (2008)	Japan	0.78		0.36
Lin et al (2009)	Taiwan	0.73	0.62	0.37

Standard Deviations for LN SA(T=1)

	Region	Total	Single Site	Single Path and site
Atkinson (2006)	Southern CA	0.75	0.62	0.50
Morikawa et al (2008)	Japan	0.80		0.38
Lin et al (2009)	Taiwan	0.74	0.64	0.44

Global Empirical Models

- Large over-estimation of aleatory variability due to ergodic assumption
  - For M3-M6 earthquakes:
    - Global Sigma ~ 0.7
    - Site Site Sigma ~ 0.6
    - Single Path Sigma ~ 0.4
- To use reduced sigma, need estimates of the site and path effects
  - Penalty: Need to include the epistemic uncertainty in these terms

Estimating Site and Path Terms

- Empirical constraints
  - Does weak motion tell you something about the site and path terms for strong motion?
    - Yes, some correlation
    - Epistemic uncertainty depends on number of observations
- Simulation constraints
  - Can use site response studies to constrain the (average) site terms
    - Epistemic uncertainty depends on how well the soil properties are known
  - Can use finite-fault simulations to provide constraints on the path effects
    - Epistemic uncertainty depends on how well the 3-D crustal structure is known
  - Requires validation of the simulation procedure

Validating FF Simulation Methods

- For engineering applications:
  - Need to show the accuracy of the model through comparisons with ground motions from past earthquakes
  - Quantitative, not just “good fit”
- Measuring the fit
  - Does the model systematically over-predict or under-predict the observed ground motions for a large number of cases?
    - Identify the source parameters that were event-specific for the validation
    - Estimate the model bias
  - What is the variability between the model predictions and the observations
    - Modeling variability (σ_{mod})

Variability from Forward Modeling

- Sample distributions of source parameters for future earthquakes
  - Include all source parameters that were event-specific in the validation
    - Slip-distribution, hypocenter location, rupture velocity, …
  - Exclude source parameter that are based on fixed rules in the model
    - E.g. rise-time based only on magnitude
    - The variability due to the fixed-rule parameters is captured in the modeling variability
  - The required source parameters for distributions will depend on the simulation method used
    - Not the same for all approaches
  - Compute the “parametric” variability of the ground motion

Sigma from Numerical Simulations

	Aleatory	Empirical	FFS Simulation
Modeling	σ_{mod} Validation: Variability between model predictions and observations	Misfit from data	Decreases as more source parameters and better path included
Parametric	σ_{par} Forward modeling: Variability of simulations using different combinations of input parameters	0 (no parameters)	Increases as more source parameters are included

Sigma from Numerical Simulations

	Aleatory	Epistemic
Modeling	σ_{mod} <u>Validation:</u> Variability between model predictions and observations	Is the model unbiased with optimized inputs? (σ_{μ}) How well do we know that 3-D structure? How well is σ_{mod} estimated? (σ_{σ})
Parametric	σ_{par} <u>Forward modeling:</u> Variability of simulations using different combinations of input parameters	Constraint on median inputs? (σ_{μ}) Constraint on variability of inputs? (σ_{σ})

Numerical Simulations

- Inputs
  - 3-D region-specific crustal model
  - Site-specific site velocity
- Avoids ergodic assumption
  - Potential for reduced aleatory variability

Use of Numerical Simulations in PSHA

- Replace empirical ground motions models with numerical simulations
  - Hutchings et al (2007)
  - SCEC CyberSHAKE
- Advantages
  - Remove ergodic assumption
    - Use the region-specific crustal structure and source specific geometries
    - Reduced aleatory variability
  - Physically based
    - Avoids unphysical combinations that may results from extrapolating statistical models

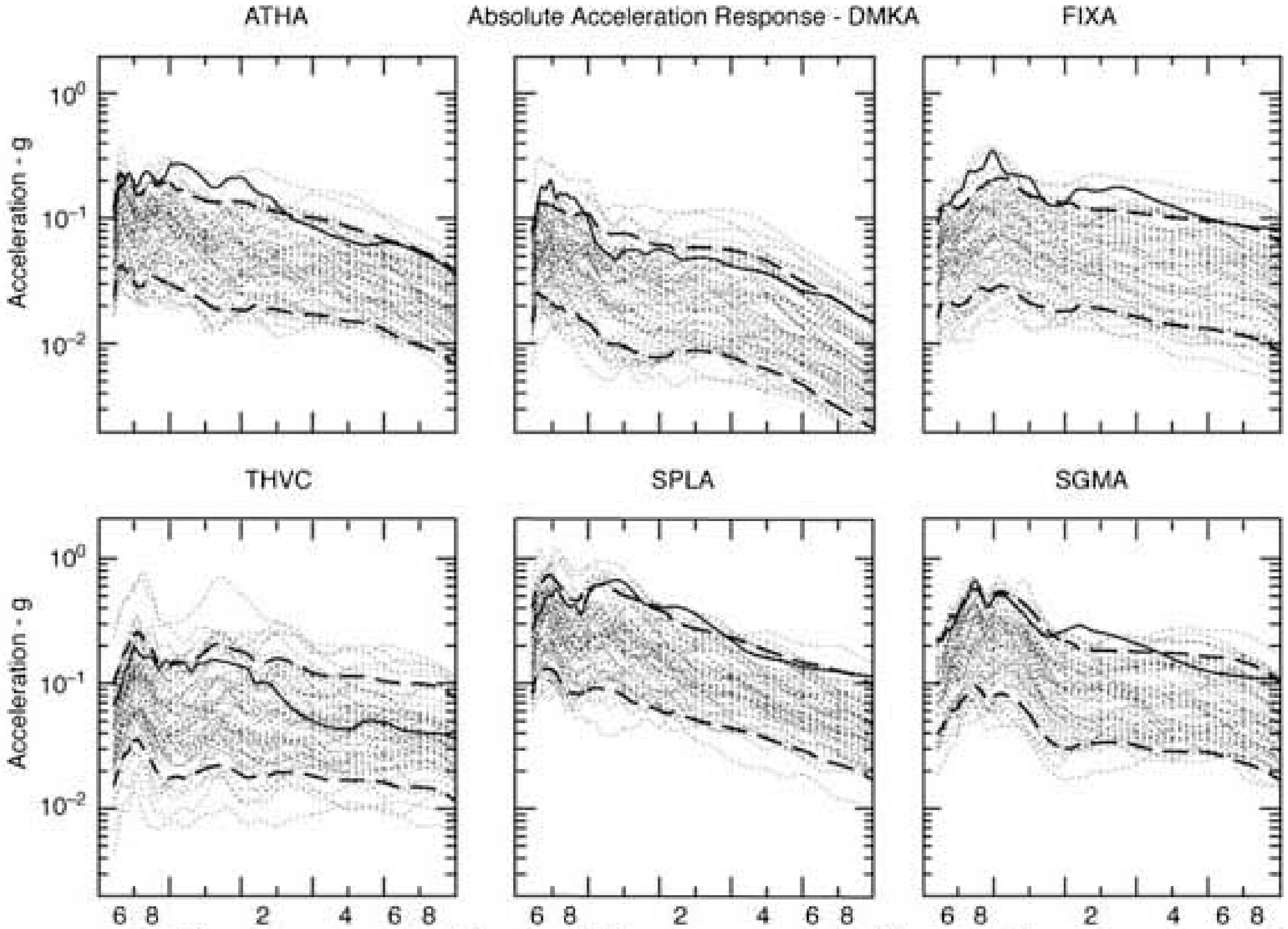
Use of Numerical Simulations in PSHA

- Advantages (cont)
  - More complete sampling of earthquakes
    - Empirical models are based on just a small set of earthquakes that were recorded by strong motion networks
    - Numerical simulations can sample a complete distribution of earthquakes
      - Earthquakes that have not yet been recorded by strong motion networks can be included
      - May increase the variability

Hutching et al (2007)

- Example site with hazard dominated by a single source
  - M6 earthquake
- Empirical GF Method
- Multiple realizations (500) of the M6 earthquake with variability in source parameters
  - Rupture geometry (area and aspect ratio)
  - Strike, Dip, Rake
  - Slip distribution (asperity size and number)
  - Hypocenter
  - Rupture roughness
  - Rupture velocity
  - Healing velocity

Example: Variability from Numerical Simulations



57 M6 eqks at a single location

(Hutching et al 2007)

Dashed Lines Show ± 1 sigma Including modeling uncertainty

Comparison of Standard Deviations

Method	Standard Deviations For M6, T=0.1 to 1 sec (natural log units)
Empirical (NGA models) Includes Ergodic Assumption	0.6 - 0.75
Hutching et al (2007)	0.6 - 0.9 (σ_{par}) 0.8 - 1.0 $\sqrt{\sigma_{par}^2 + \sigma_{\mathrm{mod}}^2}$

Why Increased Sigma from FFS?

- Empirical data under-estimates sigma
  - Sparse sampling of earthquakes in empirical set does not represent all future earthquakes
- FFS over-estimates sigma
  - Too much variability in the source parameters
    - Too large of marginal distributions
    - Not accounting for correlations of the source parameters that reduce variability

SCEC CyberSHAKE

- “Physics-Based PSHA”
- FFS with 3-D crustal structure for all ruptures in the PSHA
  - Sampling source parameter distributions
    - Only for the larger magnitudes
  - Only includes the parametric variability
    - Modeling variability is ignored
    - Modeling variability is statistical and does not fit with the concept of “physics-based” approach
    - Critical short-coming for engineering applications

Inputs for Kinematic FFS

- Distributions of Inputs for Kinematic models
  - Generally based on marginal distributions for individual source parameters developed from source inversions
- Improving constraints on source parameter distributions
  - Focus on joint distributions
    - Avoid combinations of source parameters that are not physically realizable
  - Use dynamic rupture models to develop suites of source models for future earthquakes
  - Parameterize into kinematic model inputs
  - Run suites of kinematic simulations

Inputs for Kinematic FFS

- Two Approaches for Inputs for Kinematic models based on dynamic rupture models
  - 1. Use the sources from dynamic rupture runs directly
    - More direct, but requires dynamic rupture calculations for each case
  - 2. Parameterize the sources into statistical models of the source parameters including correlations
    - J. Schmedes PhD Thesis, UC Santa Barbara, 2009
    - Results for Sub-shear rupture:
      - Slip is correlated with rise-time
      - Rupture velocity is correlated with slip-velocity
      - Rise-time and slip velocity are correlated with distance from the hypocenter
      - Slip independent of local rupture velocity
    - Developed a kinematic source parameter generator
      - Avoids having to run the dynamic rupture model for each realization
      - Short-coming: model excluded super-shear ruptures

Use of Dynamic Rupture Models

- Addresses issue of correlation of kinematic source parameters
- Adds new problem:
  - Need to specify the distributions for inputs to the dynamic rupture models
  - Topic of SCEC workshop May 21, 2010
    - Funded by PG&E & DOE

Issues for High Frequencies

- Dynamic rupture models currently for low frequencies
  - Do the resulting models still apply to high frequency ground motions?
- Need validation for high frequencies
  - Inverted slip models have been smoothed and cannot resolve the high wavenumbers of the slip distribution
  - Empirical ground motion data used for checking the source parameter distributions for high frequencies

Issues for High Frequencies

- Calibrate using empirical ground motion data
  - Causse et al (2010) use the empirical PGA sigma as a constraint on the roughness of the slip distribution
    - Inverted for the distribution of k_c that would reproduce the observed standard deviation of PGA.
      - k^{-2} model with lognormal distribution on k_c
        - » Standard deviation of 0.12 $\log_{10}$ units
  - Gets us back to the empirical standard deviations
    - Which sigma for calibration?
      - Total, single station, single path?
      - Causse et al (2010) used single-station sigma

Summary

- I support the move to a greater use of finite-fault numerical simulations, but in a PSHA framework (physics-based PSHA)
  - Key issue is specifying the joint distributions of the source parameters for future earthquakes
    - Dynamic rupture models can be used to constrain joint pdf of kinematic source parameters, but still need to specify the distributions of inputs to the dynamic rupture models
      - For low frequencies
  - High frequencies ($f>1$ Hz) still need significant improvement before being ready for engineering applications
    - Modeling of high frequencies have not received much attention in last 10 years.
    - Most engineering applications today use simple models, such as the point source stochastic model, for high frequencies
    - Empirical constraints on source parameter distributions

Summary

- I support the use of deterministic scenarios for design and/or regional risk evaluation and planning
  - But, PSHA should be used to guide the selection of the scenario earthquakes and the ground motion level,
  - A deterministic approach (neodeterministic or traditional) that ignores the rate of earthquakes is a step backward
    - Will lead to a wide range of residual risk
      - Sometimes too large
      - Sometimes just right
      - Sometimes too small

Summary

- I do not support the move from PSHA to the Neo-Deterministic approach
  - Objective of selecting design ground motions is acceptable residual risk
  - Need to consider how frequent the earthquake is when selecting how rare of a ground motion given the earthquake (e.g. median, 84th, 95th, …)
  - Residual risk comes from many different earthquake scenarios. PHSA accounts for all of the earthquakes that contribute to the residual risk.