Recent Advances in Seismic Hazard

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Pacific Rim Forum
Jan 23-24, 2017

Ergodic GM Model

$$\ln SA(M_i, Loc_i, Site_j) = \ln GMPE(M_i, R_{ij}, VS30_j) + \delta_{ij}$$

Global or regional average model for the median

σ

Assumed to apply to all sources relevant to my site

Aleatory

Non-Ergodic GM Model

$$\ln SA(M_i, Loc_i, Site_j) = \ln GMPE(M_i, R_{ij}, VS30_j) + \hat{A}mp_j + \hat{P}ath_{ij} + \hat{S}ource_i + \delta SP_{ij}$$

$\hat{A}mp_j$ → ϕ_{S2S}

$\hat{P}ath_{ij}$ → ϕ_{P2P}

$\hat{S}ource_i$ → τ_{L2L}

δSP_{ij} → σ_0

Epistemic

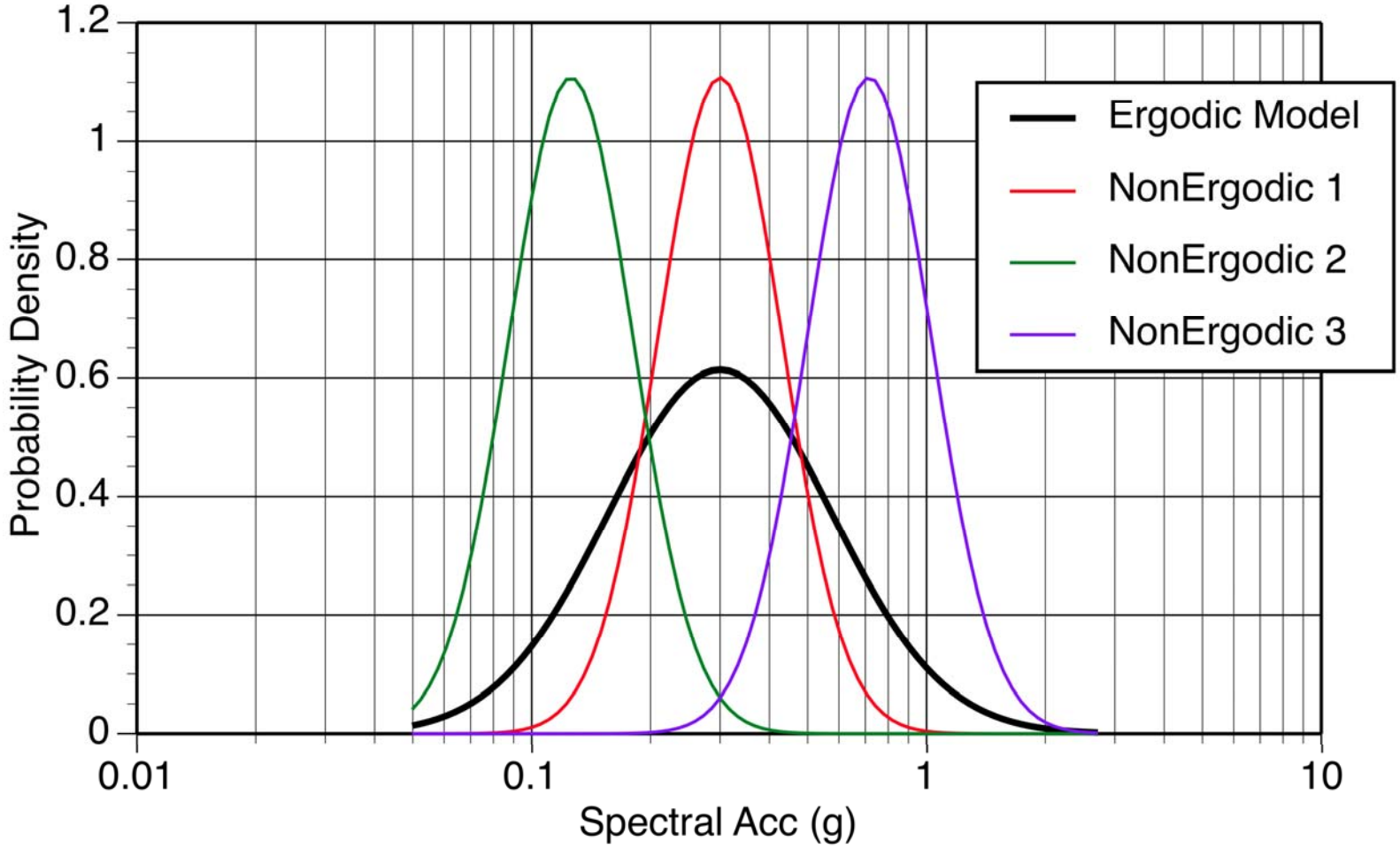
Aleatory

Component of GM Variability (from Taiwan data)

Spectral Period (sec)	σ	ϕ_{S2S}	ϕ_{P2P}	τ_{L2L}	σ_0
PGA	0.64	0.26	0.40	0.25	0.34
0.1	0.71	0.35	0.41	0.28	0.36
0.3	0.68	0.28	0.42	0.27	0.36
0.5	0.69	0.30	0.39	0.29	0.40
1.0	0.74	0.36	0.35	0.32	0.43
3.0	0.77	0.39	0.32	0.37	0.46

From: Lin et al (BSSA, 2011)

Ergodic vs Non-Ergodic ground motion pdfs



Additional Epistemic Uncertainty (missing from current hazard)

- Site, Path, Source – Specific Effects on GMPEs
  - New data sets with large number of earthquakes and recordings show how strong these effect are
    - Most of the standard deviation in traditional GMPEs is from systematic effects, not random
      - Ergodic standard deviation is about 0.65 LN units
      - Removing systematic site, path, and source: 0.36 LN units
  - We know there are site-, path-, and source-specific effects, but in most cases, the values are unknown
  - “Known Unknowns”
    - The uncertainty in the hazard is much larger than current estimates using traditional approaches

Move to Non-Ergodic Ground-Motion Models

- Global models – Fully Ergodic
  - Combine empirical data from broad tectonic regions
  - Numerical simulations for typical 1-D crustal models
- Regionalized Models – Partial non-ergodic
  - Include different distance and VS30 scaling in broad regions
    - NGA-W2 models
  - Numerical simulations using region-specific crustal models
- Single-station Sigma Models – Partially non-ergodic
  - Removes the systematic site effects from the aleatory standard deviation
  - Add site-specific site response effects
    - Analytical site response studies
    - Site factors from observed ground motions at the site

Move to Non-Ergodic Ground-Motion Models

- Finely regionalized models - Partially non-ergodic
  - Spatially varying GMPEs (coefficients depend on the site and eqk locations)
- Source-site specific models - Fully non-ergodic models
  - Numerical simulations using region-specific 3-D crustal models
  - Empirical path effects from region-specific observations

Non-Ergodic GM Model for DCPP

$$\ln SA(M_i, Loc_i, Site_j) = \ln GMPE(M_i, R_{ij}, VS30_j) + \hat{A}mp_j + \hat{P}ath_{ij} + \hat{S}ource_i + \delta SP_{ij}$$

σ_0

Aleatory

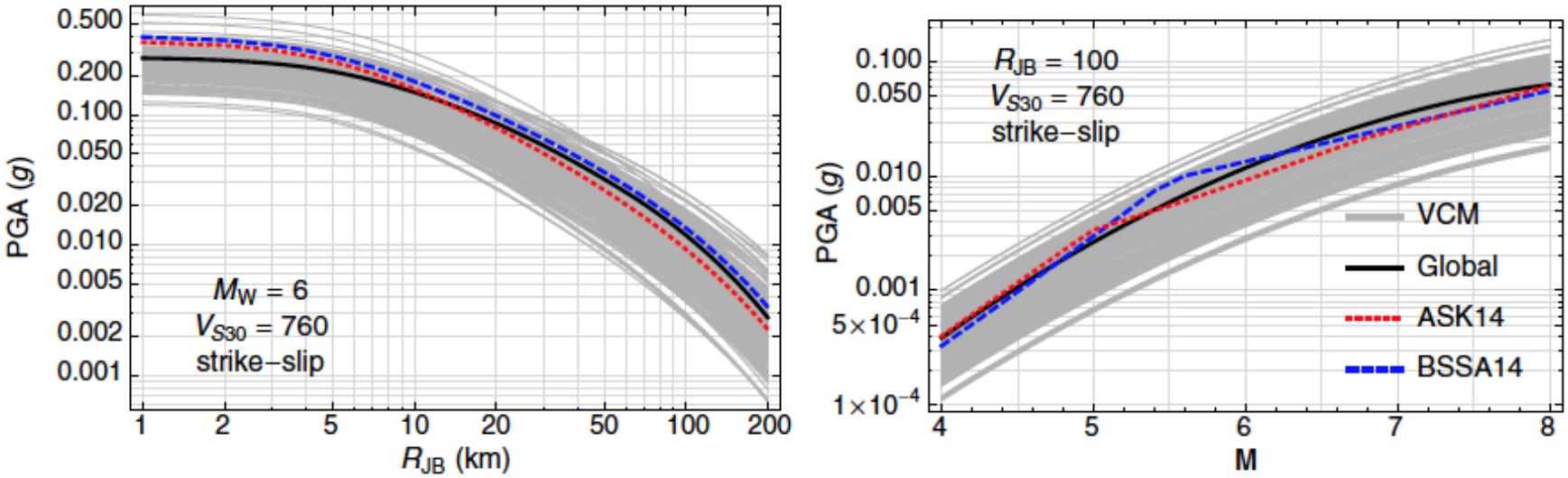
Estimating Site Terms

- Analytical modeling of site response
  - Should get both median and uncertainty.
  - Sample the uncertainty range of the inputs to the site response
  - If a shallow soil profile is used, then the site response may only capture the higher frequencies of the site response
- Empirical Data
  - Need recordings at the site of interest
    - Captures the full frequency band as the ground motion at the site is affected by the full profile.
  - Compute site residuals from an event-specific GMPE
  - Use of an average GMPE works if the data set is large

How to Constrain Path Terms?

- Observations
  - Mainly from small magnitude earthquakes
  - Not dense enough coverage
- Numerical simulations with 3-D crustal models
  - Provides dense coverage
  - Needs validation/calibration
  - Issue – frequency band with reliable 3-D models
    - 3-D simulations mainly used for low frequencies (< 2 Hz)
    - Use of stochastic models at high frequencies may not capture 3-D path effects

Example of Results from Continuous Coefficient Model



From Landwehr et al (2016)

Example of Results from Continuous Coefficient Model

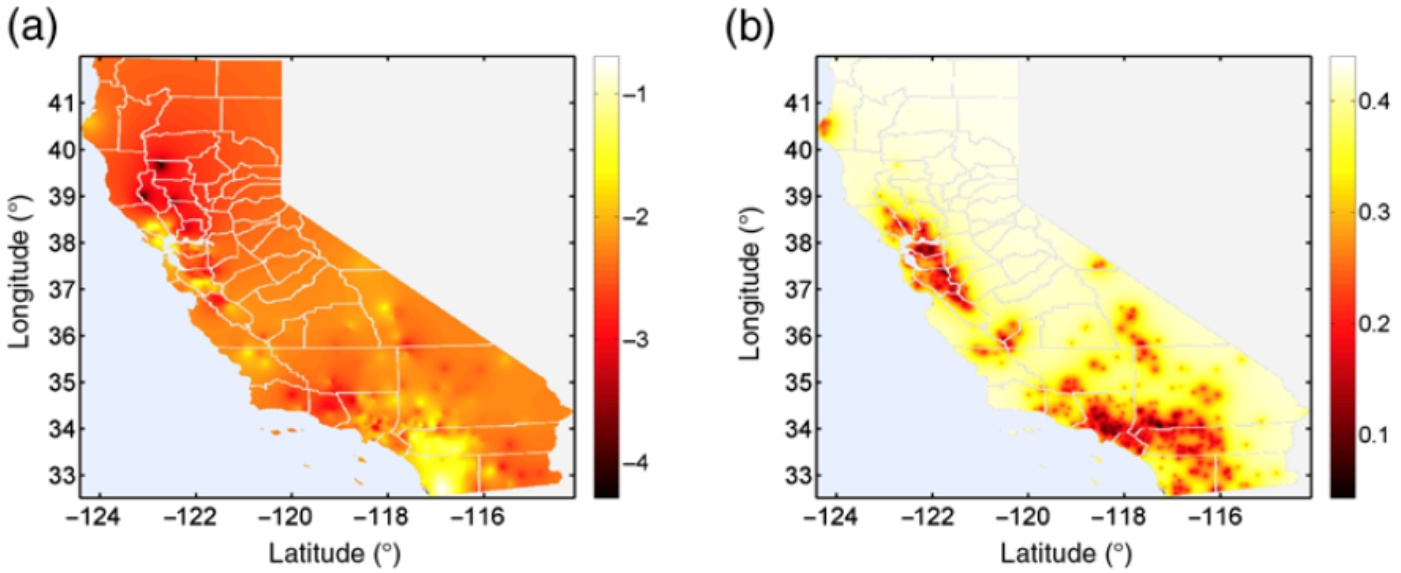
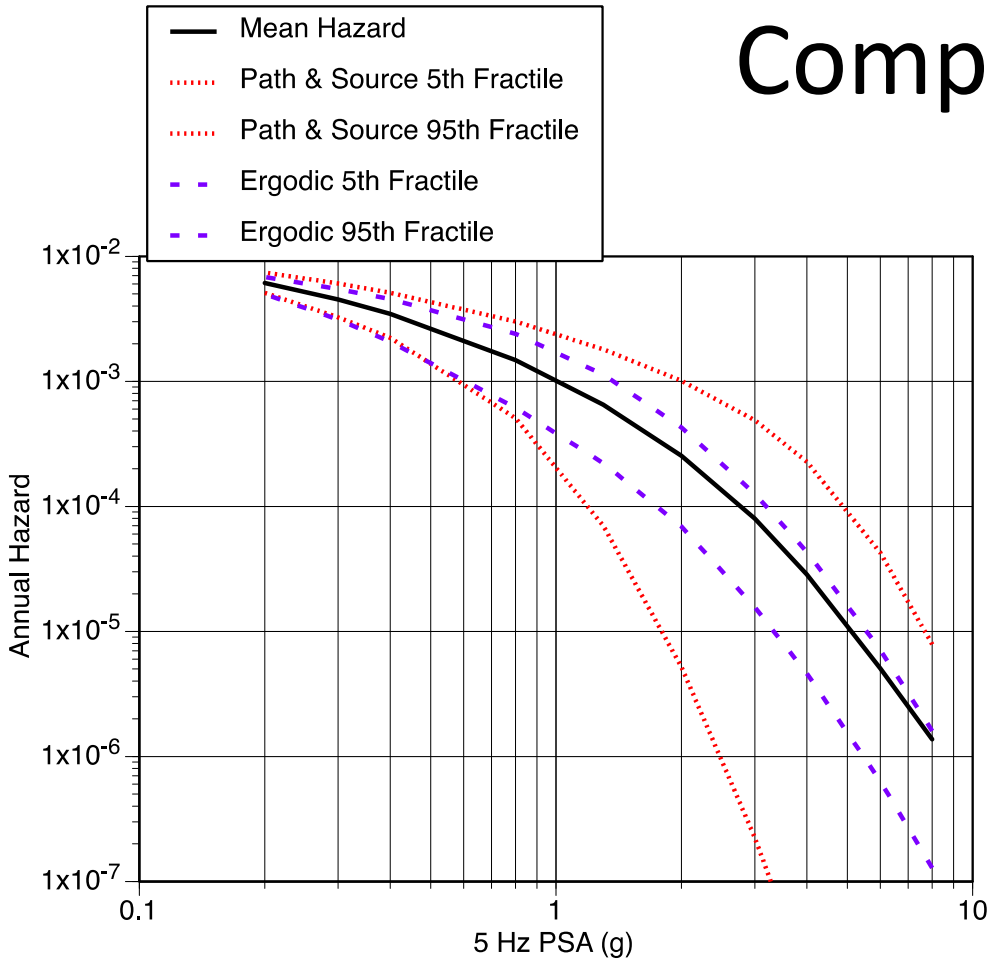


Figure 6. (a) Map of ln PGA predictions, coded by ground-motion value. (b) Epistemic predictive uncertainty ψ associated with ln PGA predictions. For simplicity, in both plots the same event–station coordinate is used for the coefficients. Predictor variables are set to $M = 6$, $R_{JB} = 10$ km, SoF $= 0$, and $V_{S30} = 760$ m/s, in which SoF indicates style-of-faulting. The color version of this figure is available only in the electronic edition.

Comparison of Epistemic Uncertainty:



Key Issues for Moving to Non-Ergodic Ground-Motion Models

- To justify the use of the reduced aleatory variability requires:
  - Estimates of site, path, and source terms
  - Estimates of the epistemic uncertainties in the site, path, and source terms

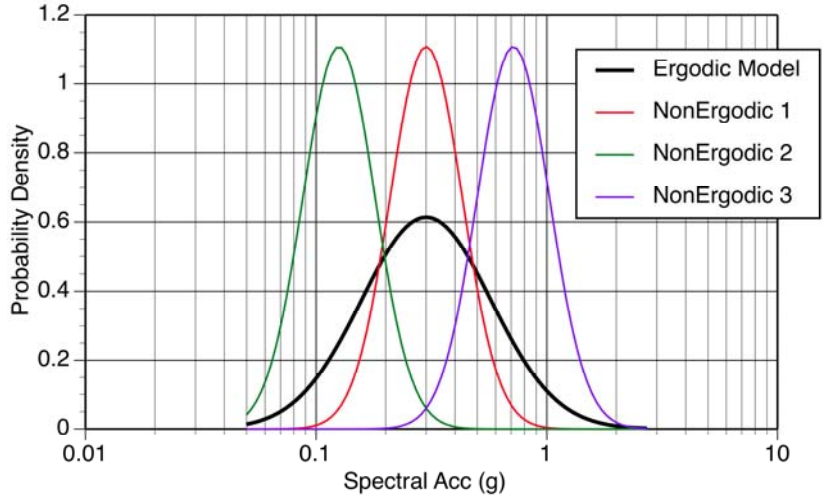
Inappropriate use of Non-Ergodic Ground-Motion Models

- Main misuse
  - Use reduced aleatory variability,
  - But assume average path and source effects

$$\hat{P}ath_{ij} = 0$$

$$\hat{S}ource_{i} = 0$$

  - And do not include the epistemic uncertainty in the estimated path, and source terms.



Summary (1/2)

- Need to Move to Non-ergodic GM Models
  - Empirical data have shown that systematic site, path, and source effects are the dominant parts of the ergodic aleatory variability
- Epistemic Uncertainty
  - Initially, move to non-ergodic GM models will lead to a large increase in the epistemic uncertainty in the hazard
  - Opportunity to make significant improvements in the hazard models

Summary

- Estimating Non-Ergodic Terms and their Epistemic Uncertainties
  - Site
    - Current practice addresses site response
  - Path
    - 3-D simulations at low frequencies
    - Empirical data to validate 3-D simulations and constrain path effects at high frequencies
      - Can use small magnitude data
  - Source
    - 3-D simulations can address geometry effects
    - More difficult to constrain source-specific dynamic source properties
      - Small magnitudes may not be informative for large magnitudes