# Summary of EPRI (2013) Update to EPRI (2004, 2006) Ground Motion Characterization

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NGA-East Workshop 2
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# Questions from TI Team

- Summarize the existing CENA GMPEs as they have been assessed by the EPRI (2004-2006) review project, including their technical basis.
- What is the distribution of magnitude, distance, site conditions, style of faulting, period range for which the EPRI review project GMPEs are well constrained?
- How was the extrapolation beyond these well-constrained ranges defined?
- What is the range of applicability of the GMPEs (distance, region, magnitude, depth, site, etc.)?
- What are the limitations of the GMPEs?
- What was the basis for the range of GMPEs defining the epistemic uncertainty used in the EPRI review project?

# EPRI (2004) SSHAC Level 3 Study (1 of 3)

- Built from consideration of available GMPEs
- Developed a weighting scheme involving two steps
  - Group models into clusters based on modeling approach – Single corner stochastic, double corner stochastic, hybrid, and finite fault simulation
  - Weigh models within clusters primarily on the fit with available data
  - Weigh clusters more on basis of "scientific principals"



# EPRI (2004) SSHAC Level 3 Study (2 of 3)

- For each cluster, fit the weighted median predictions of the member GMPEs with a single form (i.e. backbone model)
- Develop epistemic models for each cluster
  - Combined model to model variability with estimates of additional uncertainty to compute $\sigma_\mu$(M,R,F)
  - Represent uncertainty at 5$^{th}$ and 95$^{th}$ percentiles, $\pm 1.65\sigma_\mu$(M,R,F). Fit common form to obtain the 5$^{th}$ and 95$^{th}$ percentile GMPEs for each cluster

# EPRI (2004) SSHAC Level 3 Study (3 of 3)

- Aleatory model was built from the range of aleatory models for CEUS associated with the sample of GMPEs
- EPRI (2006) was a SSHAC Level 2 study use to evaluate the EPRI (2004) aleatory variability models
  - Concluded that no compelling reason for their to be a major difference from empirical aleatory variability observed for active tectonic regions
  - Developed aleatory model making minor adjustments to preliminary aleatory variability from NGA



# EPRI 2004/2006 Review Project (EPRI, 2013)

- Significant time had passed since the development of the GMPEs used by EPRI (2004)
  - Many models used by EPRI (2004) had been updated/ replaced by newer models and/or were no longer supported by their developers
  - More empirical CENA data were available
- Need to consider this newer information in developing responses to NRC requests in the short term (before completion of NGA East)

# EPRI 2004/2006 Review Project

- SSHAC Level 2 Project with workshops and a PPRP
  - TI Team (Gabriel Toro (lead), Martin Chapman, and Bob Youngs) with active participation by a large PPRP
- Project followed the evaluation framework of EPRI (2004, 2006)
  - Use available GMPEs
  - Group GMPEs into clusters, use empirical data to weight models within clusters, represent each cluster weighted median and epistemic uncertainty by fitted GMPE
  - Use finalized aleatory from NGA and initial values from NGA-West 2



# Questions from TI Team

- Summarize the existing CENA GMPEs as they have been assessed by the EPRI (2004-2006) review project, including their technical basis.

# Updating of EPRI (2004) Clusters

| Cluster | Model Type | Models |
|---|---|---|
| 1 | Single Corner Stochastic (0.275/0.351) | ~~Hwang and Huo (1997)~~<br>~~Silva et al (2002) - SC-CS~~<br>Silva et al (2002) - SC-CS-Sat<br>Silva et al (2002) - SC-VS<br>Toro et al (1997)<br>Frankel et al (1996) |
| 2 | Double Corner Stochastic (0.312/0.399) | ~~Atkinson and Boore (1995)~~<br>~~Silva et al (2002) DC~~<br>Silva et al (2002) DC - Sat |
| 3 | Hybrid (0.196/0.250) | ~~Abrahamon & Silva (2002)~~<br>~~Atkinson (2001) & Sadigh et al (1997)~~<br>~~Campbell (2003)~~ |
| 4 | Finite Source /Greens Function (0.217/0.000) | Somerville et al. (2001) |

←AB06' ?

←PZT11 ?

←A08' ?



# New GMPEs

- Atkinson (2008 with 2011 revisions: A08')
  - Referenced Empirical – fit adjustment factors to misfit of CEUS data by WUS GMPE (empirical adjustment rather than developing WUS→CENA scaling based on modeling)
- Atkinson-Boore (2006 with 2011 revisions: AB06')
  - Based on stochastic finite fault simulations rather than point source double corner simulations
  - Treated as a replacement of Atkinson and Boore (1995)

# New GMPEs

- Pezeshk et al. (2011)
  - Hybrid ground motion model build on NGA (West1)
  - Considered a replacement of Campbell (2003) and Tavakali and Pezeshk (2005) used better set of WUS GMPEs
- Silva et al. (2003)
  - Minor updates to Silva et al. (2002)
  - Based on point source (1 and 2 corner) stochastic simulations



# Re-Definition of Clusters 2 and 3

• EPRI-04 clusters 2 and 3 were based on approach (2-corner stochastic vs. hybrid), but some new models did not fit very well (i.e., AB06' spectrum does not have 2 specific corners; A08' perhaps is not a hybrid model in the traditional sense)

• **Practical Motivation**: very large within-cluster differences at ~50-100 km

- –due to different geometric spreading
- –difficult in in generating high and low GMPEs ($\pm$1.64 $\sigma_{epistemic}$) for clusters

# New GMPE Clusters

| Cluster | Model Type | Models |
|---|---|---|
| 1 | Single Corner Brune Source | Silva et al (2002) - SC-CS-Sat*<br>Silva et al (2002) - SC-VS*<br>Toro et al (1997)<br>Frankel et al (1996)<br>* Treated as one model for calculation of weights |
| 2 | Complex/Empirical Source<br>~$R^{-1}$ Geometrical spreading < 70 km | Silva et al (2002) DC – Sat<br>A08' |
| 3 | Complex/Empirical Source<br>~$R^{-1.3}$ Geometrical spreading < 70 km | AB06'<br>PZT11 |
| 4 | Finite Source /Green's Function | Somerville et al. (2001); slightly different models for rifted and non-rifted |



# How Well are GMPEs Constrained?

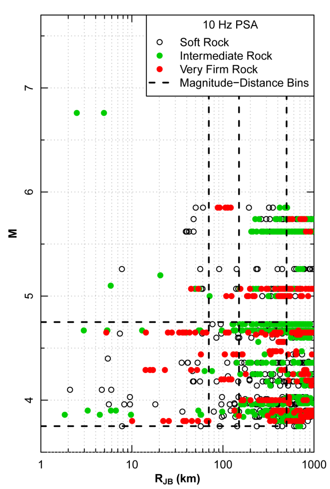
- Simulation based models are constrained by simulations and their calibration against empirical data – principally from active regions
- Hybrid models build on *well* constrained empirical models and assumption of correct modeling of WUS→CENA differences
- Referenced empirical based on *well* constrained empirical model and fit to empirical CENA data generally not in the range of primary interest

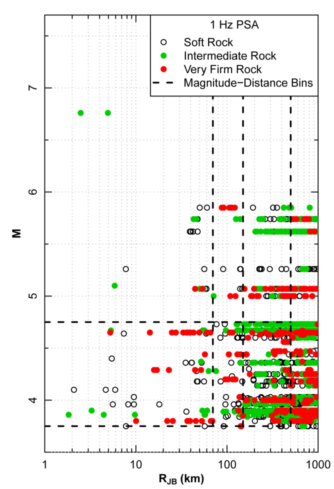
# Empirical Data Used for Weighting

- Used Initial NGA East database (August 2012)
- Classified sites based on geology and measured/inferred $V_{S30}$
  - Soft rock (younger rocks and/or $500 \leq V_{S30} < 1000$ m/s
  - Intermediate rock (older rocks and/or $1000 \leq V_{S30} < 1890$ m/s
  - $V_{S30} \geq 1980$ m/s
- $V_S$ measurements at a number of important recording sites



# Empirical Data Used for Intra-cluster Weighting

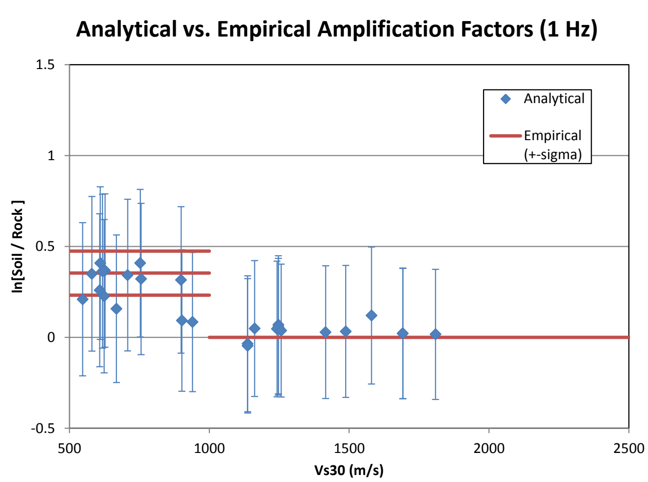


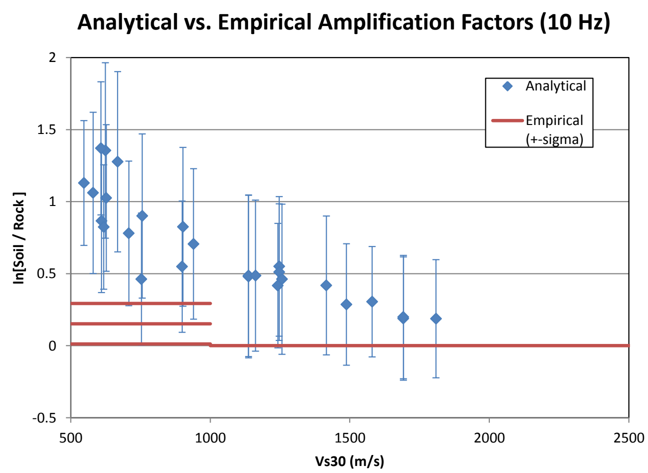



# Adjustment of Data to Reference Site Conditions

- Step not performed in EPRI (2004)
- Analytical adjustment for sites with velocity profiles
  - Quarter wavelength approach combined with delta kappa adjustment
  - Incorporated uncertainty in Vs and κ
- Empirical adjustment
  - Calculated adjustment terms for gross site classes
  - Could only distinguish statistically between soft rock and a combined intermediate-hard rock groupings










# Within Cluster Weights

Account for:

- Inter-event correlation
- Uncertainty in the soil correction (correlated)
- Weights that depend on magnitude and distance, to account for the engineering importance and diagnostic power of data in the various M-R ranges.
- Sensitivity to sample size

# Approach for Within-Cluster Weights

- Based on approach developed by Scherbaum and co-workers, but includes correlations and weights
- Use covariance matrix takes into account correlation (similar to random-effects formulation)

$$w_i = \frac{L(\boldsymbol{\varepsilon}_i)}{\sum_i L(\boldsymbol{\varepsilon}_i)} \qquad L(\boldsymbol{\varepsilon}_i) = \exp\left( -\frac{1}{2} \boldsymbol{\varepsilon}_i{}^T \boldsymbol{\Sigma}_{\boldsymbol{\varepsilon}}{}^{-1} \boldsymbol{\varepsilon}_i \right)$$

- More flexible and less ad-hoc than EPRI (2004) approach, but similar in spirit



# Building the Covariance Matrix

$$Cov\left[\varepsilon_{ijk}, \varepsilon_{ij'k'}\right] = \tau^2 \delta_{jj'} + \phi^2 \delta_{jj'} \delta_{kk'} + \sigma_{C,jk} \sigma_{C,j'k'} \delta_{kk'}$$

- First term: $\tau^2$ if both residuals are associated with the same earthquake and zero otherwise
- Second term: $\varphi^2$ between a residual and itself (same earthquake, same station)
- Third term: $\sigma_{C,jk}\sigma_{C,j'k'}$ if both residuals are associated with recordings at the same station and zero otherwise (site correction uncertainty).

Note: tau and phi taken from aleatory variability model described later

# Importance Factors (Weights) for Magnitude-Distance Bins

| | **M** 3.75 to 4.75* | **M** 4.75 and greater |
|---|---|---|
| Rjb 0 to 70 km | 1/ 4 (1/4) | **1 (1)** |
| Rjb 70 to 150 km | 1/12 (1/4) | 1/3 (1) |
| Rjb 150 to 500 km | 1/24 (1/4 ) | 1/6 (1) |

Importance Factor for High Frequencies

Importance Factor for Low Frequencies

* Using 0 weight for M 3.75 to 4.75 causes small changes in results



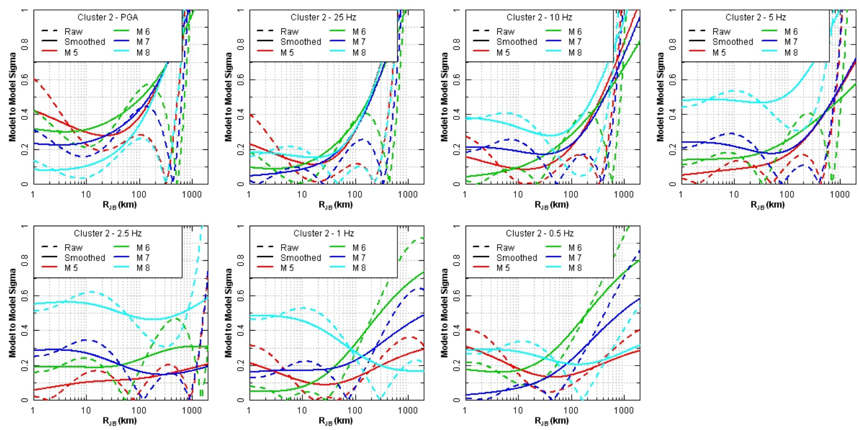
# Within Cluster Epistemic Uncertainty

- Use envelope of cluster model-to-model uncertainty and cluster independent data/ modeling uncertainty variances

$$\sigma(m,r,f)_{\text{cluster median}} = \max\left\{\sigma(m,r,f)_{\substack{\text{cluster}\\ \text{model-to-model}}}, \sigma(m,r,f)_{\substack{\text{cluster independent}\\ \text{data/modeling uncertainty}}}\right\}$$

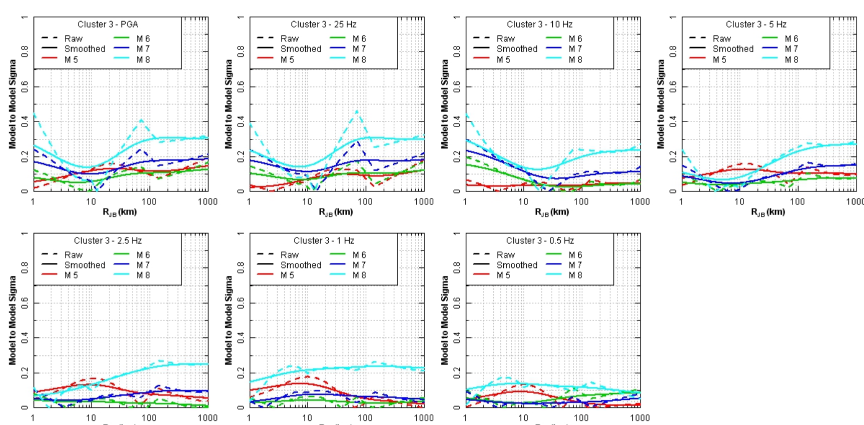
- These are considered to be different manifestations of the same underlying uncertainty

# Cluster 2 Model-to-Model






# Cluster 3 Model-to-Model



## Cluster Independent Within Cluster Epistemic Uncertainty

- NGA East strong motion database provides data-based constraint on median estimates for **M** ~ 5
- Incorporate uncertainty in magnitude scaling to provide estimate of epistemic uncertainty at larger magnitudes

$$\sigma_{\substack{\text{cluster independent}\\ \text{data/modeling}}} = \sqrt{\sigma^2_{\text{data}-\text{based at } \mathbf{M}\,5} + \sigma^2_{\ln[PSA(M)/PSA(M=5)]}}$$

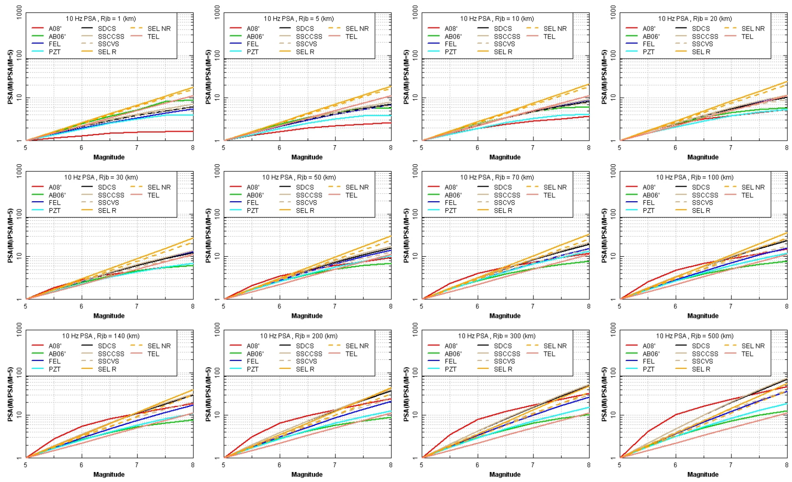


## Incorporation of Variability in Magnitude Scaling

- Compute PSA(M)/PSA(M=5) for all candidate models and $\sigma^{\text{total}}_{\ln\left[PSA(M)/PSA(M=5)\right]}$
- Compute PSA(M)/PSA(M=5) for cluster median models and $\sigma^{\text{cluster-to-cluster}}_{\ln\left[PSA(M)/PSA(M=5)\right]}$
- Within cluster uncertainty in magnitude scaling

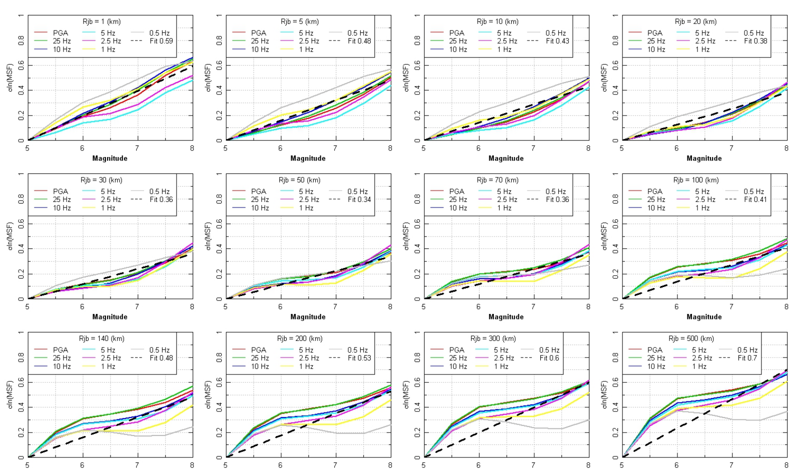
$$\sigma^{\text{within cluster}}_{\ln\left[PSA(M)/PSA(M=5)\right]} \approx \sqrt{\sigma^{2\ \text{total}}_{\ln\left[PSA(M)/PSA(M=5)\right]} - \sigma^{2\ \text{cluster-to-cluster}}_{\ln\left[PSA(M)/PSA(M=5)\right]}}$$

# Magnitude Scaling for 10 Hz

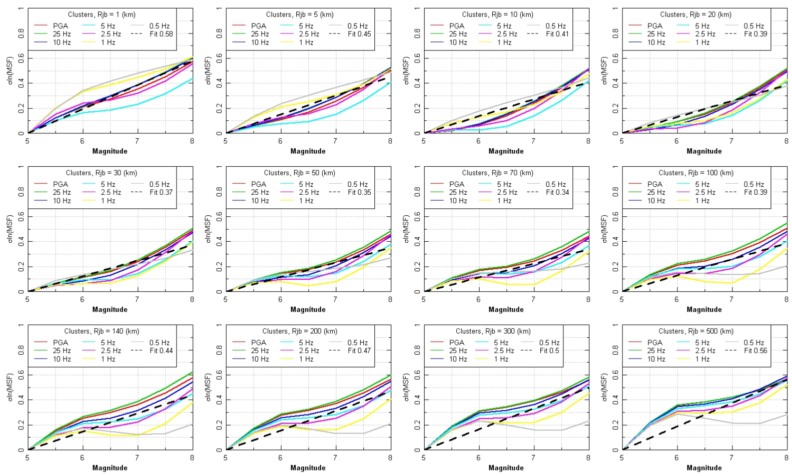





$$\sigma^{\text{total}}_{\ln\left[PSA(M)/PSA(M=5)\right]}$$

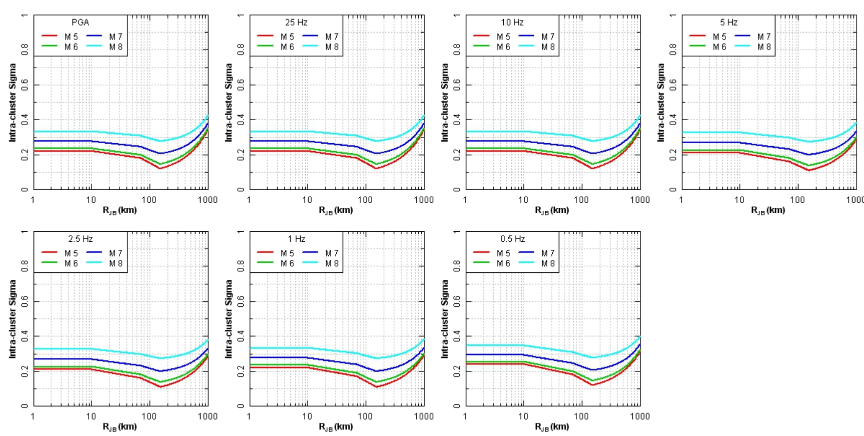


$$\sigma^{\text{cluster-to-cluster}}_{\ln\left[PSA(M)/PSA(M=5)\right]}$$



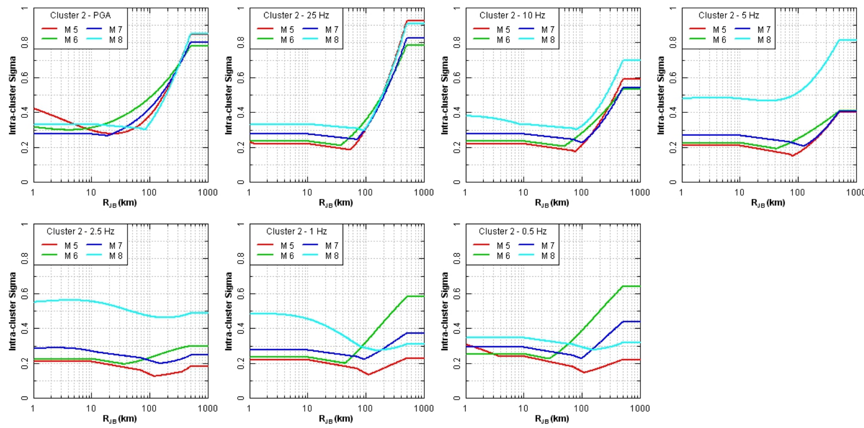



# Cluster-independent Intra-cluster Epistemic Uncertainty



# Cluster 2 Envelope Intra-cluster

(Capped at 500 km to prevent unrealistic values for 95$^{th}$%)



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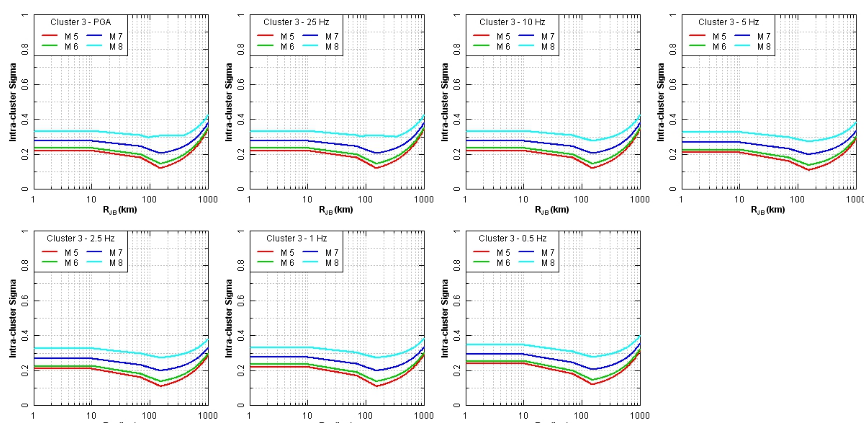
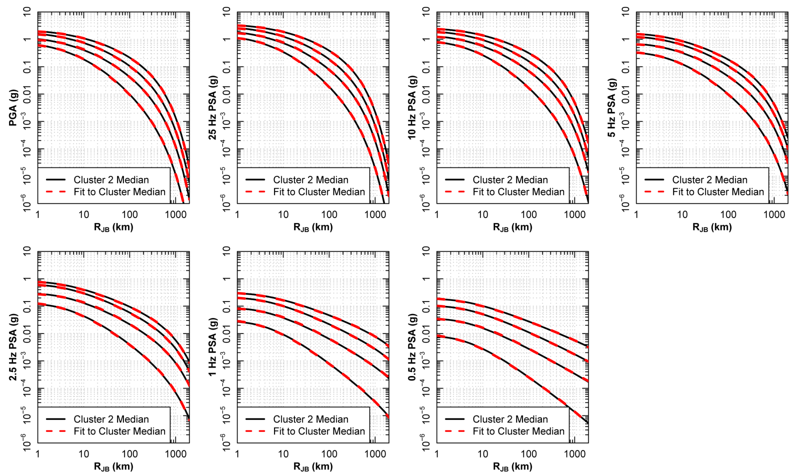
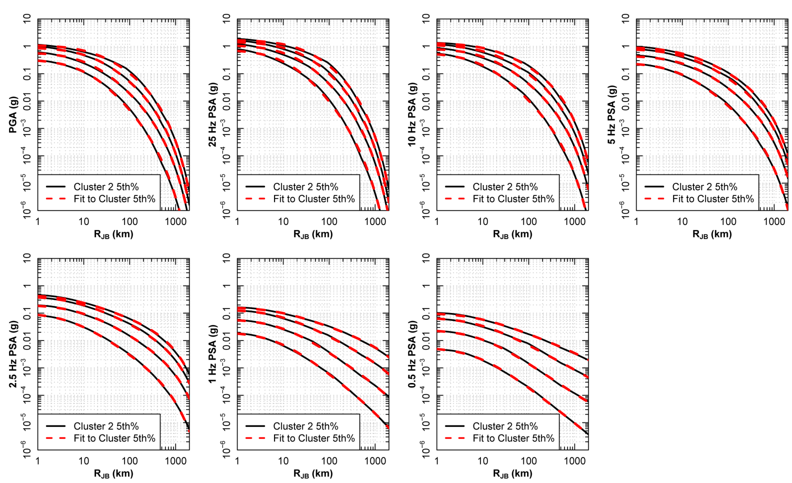


# Fitting of Medians

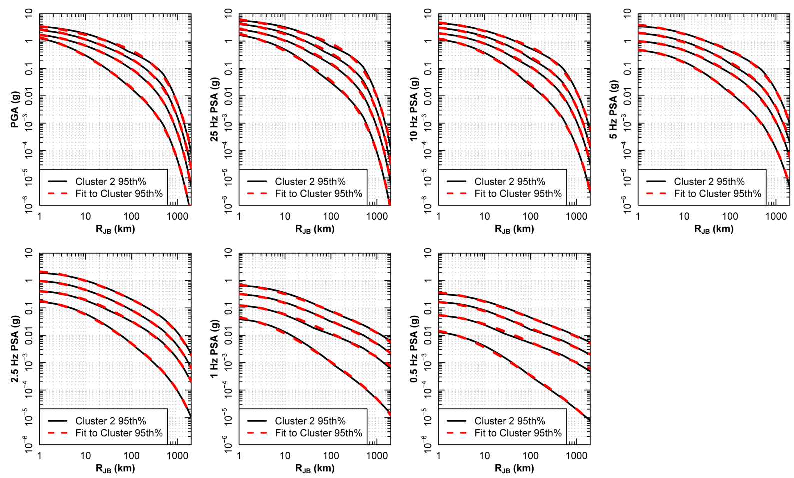





# Fitting 5th % Models



# Fitting of 95th % Models






# Questions from TI Team

- What are the limitations of the GMPEs?
  - Have we captured the model space using the available published GMPEs (expanded using a model to model sigma and selecting)?
  - Somewhat limited frequencies

- What was the basis for the range of GMPEs defining the epistemic uncertainty used in the EPRI review project?
  - Within cluster variation based on envelop of model-to-model variability and data constraints at **M** ~ 5 plus additional magnitude scaling

# Questions from TI Team

- What is the distribution of magnitude, distance, site conditions, style of faulting, period range for which the EPRI review project GMPEs are well constrained?
  - To the extent the underlying GMPEs are well constrained, primary data used are for distances up to 300 km M > 4 with emphasis on M > 5. Underlying GMPEs are for hard rock (Vs > 2 k/s to 2.7 km/s)
- How was the extrapolation beyond these well-constrained ranges defined?
  - Using fitted models
- What is the range of applicability of the GMPEs (distance, region, magnitude, depth, site, etc.)?
  - GMPEs are for **M** 4 to 8.2, 0 to 1000 km, hard rock, mixture of SS and Rev (no style of faulting), PGA and frequencies of 25, 10, 5, 2.5, 1, and 0.5 Hz.



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# References

EPRI , 2013, *EPRI (2004, 2006) Ground-Motion Model (GMM) Review Project, Elec. Power Research Institute,* Palo Alto, CA, Rept. 3002000717, June, 2 volumes.