Approaches to Include Uncertainty in Site Response into Hazard Calculations, Including Host-to-Target (H2T) Approaches

SSHAC Workshop on Site Response
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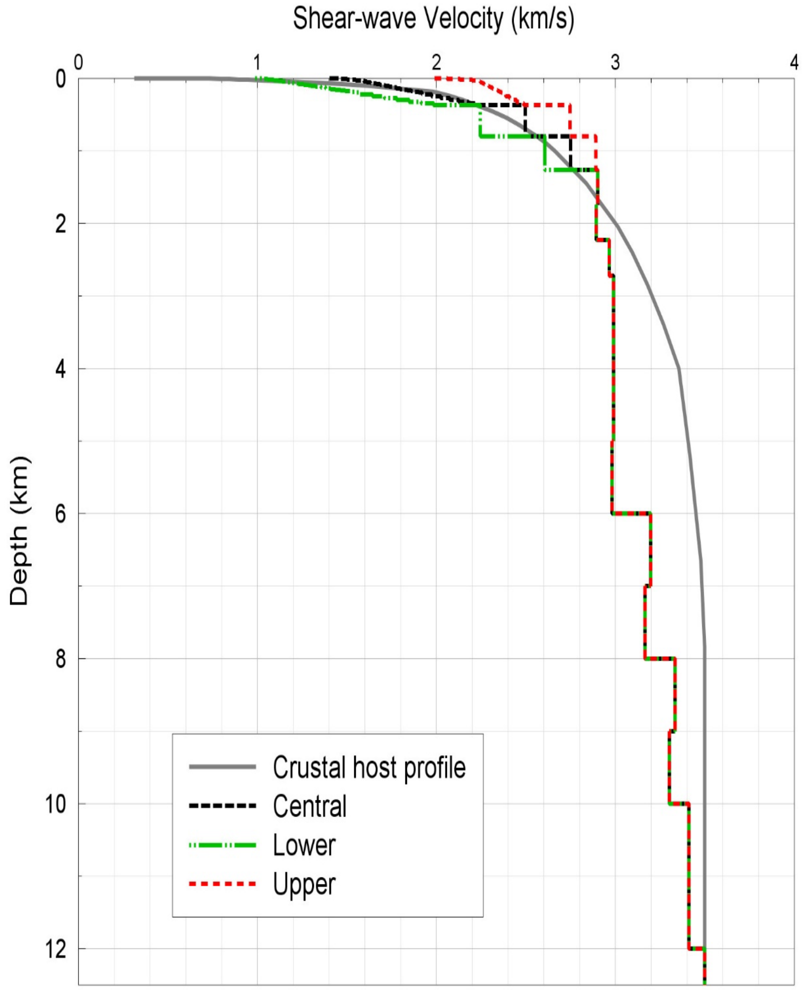
1. Discuss different approaches for accounting for epistemic uncertainty and aleatory variability in site response analyses, …

- Two types of site response analyses used to develop site-specific hazard
  - Reference rock motions is defined at some depth, representative rock motions are input at base of soil profile an amplification is computed relative to motion at depth – "Geotechnical" approach
  - Reference rock motions are defined for the surface on reference crustal profile. Site amplification calculations from source depths are made to the reference crustal profile and the site-specific profile to defined relative amplification functions – this are what are termed Host-to-Target (H2T) adjustments

H2T AF

- Reference site is a full crustal profile
- Target site is a full crustal profile
- AF is computed as ratio of surface motions computed from common source at depth



Components of Site Response

- Shear wave velocity profile – has both aleatory and epistemic
- Material density – usually only best estimates used
- Depth to reference rock horizon
- Shallow crustal damping, κ_0
- G/Gmax and damping relationships

Modeling

- Epistemic uncertainty typically modeled by defining weighted alternatives
  - e.g. base case profile with ± uncertainty factor, alternative sets of G/Gmax and damping relationship
- Aleatory variability typically modeled by randomization of the specific values in the epistemic alternatives
  - e.g. randomized layer velocities, layer thicknesses, individual G/Gmax and damping curves

Site amplification typically incorporated into site-specific hazard using "Approach 3"

$$P(Z_s > z|m, r, AF) = \int_0^\infty P\left(AF \geq \frac{z}{x}\middle|x\right) f(x|m, r)dx$$

$$P\left(AF \geq \frac{z}{x}\middle|x\right) = 1 - \Phi\left(\frac{\ln\left(\frac{z}{x}\right) - \mu_{ln(AF|\,x)}}{\sigma_{ln(AF|\,x)}}\right)$$

- Convolution of reference "rock" hazard (ground motion *x*) with probabilistic amplification for motion at control point, *z*, as a function of level of motion *x*
- *f*(*x*) is obtained by discretizing reference rock hazard curve at various levels of rock motion *x*

Two Ways to Apply Approach 3

- A. Combine the results of the epistemic alternative amplification cases into a composite estimate of $\mu_{\ln(AF)}$ and $\sigma_{\ln(AF)}$ that is convolved with the reference rock hazard
- B. Use Approach 3 to develop a soil hazard curve for each epistemic alternative. Apply the assigned epistemic weights to the alternative hazard curves to obtain a composite hazard curve

Differences?

- Conceptually the two should produce the same mean hazard provided the epistemic alternatives ~correspond to lognormally distributed alternatives
  - True for typical assignment of epistemic uncertainty in Vs, randomization of Vs, G/Gmax, and damping
  - What about cases where alternative Vs profiles are based on different interpretation on how to use the available information?

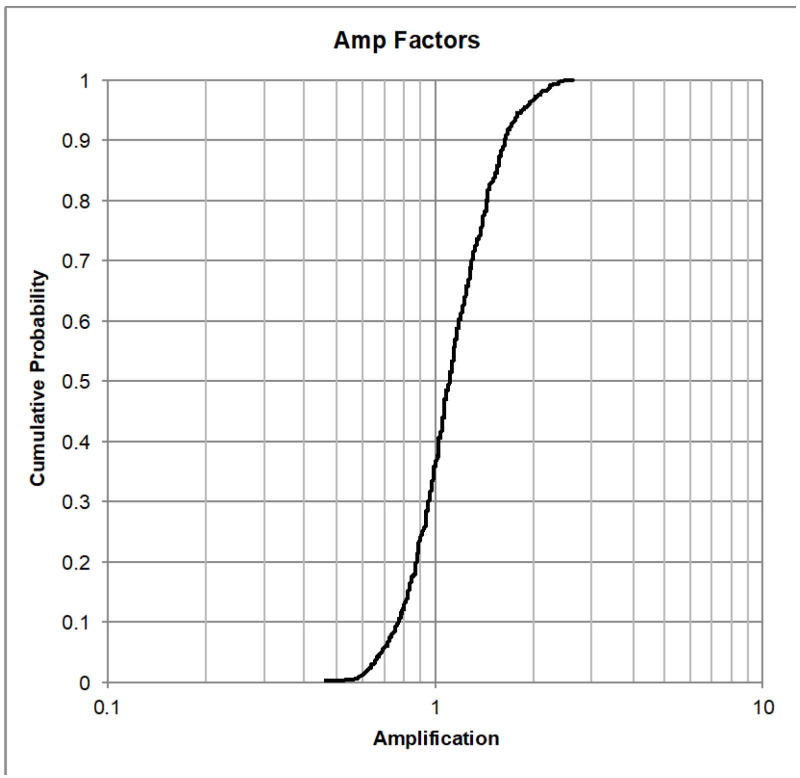
Preference for B

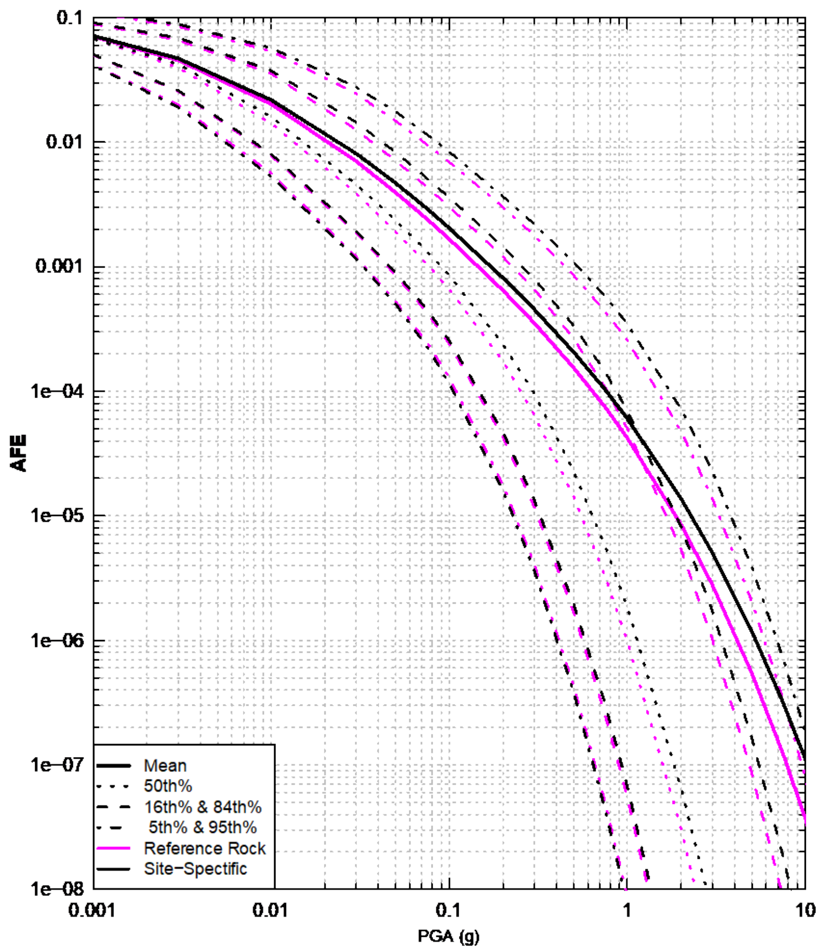
- Effect of non-normally distributed epistemic alternatives accounted for
- Effect of epistemic uncertainty in site amplification can be displayed and quantified

Sampling Test

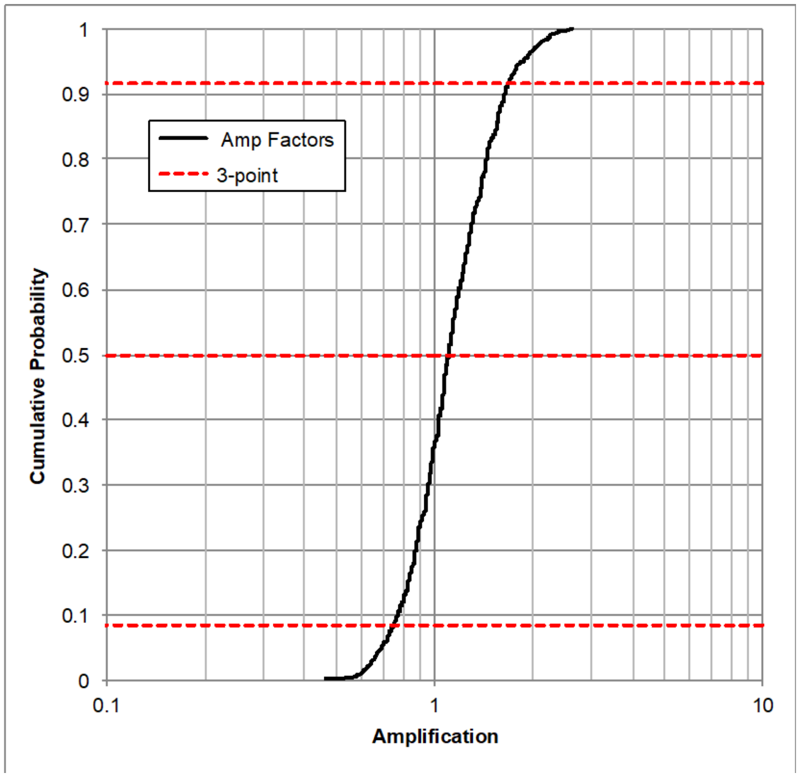
1. Create distribution of amp factors consisting of uniform from 1 to 1.3 (Vs term) convolved with lognormal with sigma of 0.3 (kappa term)
2. Generate amp factor distribution with 550 points (11 Vs x 50 kappa)
3. Convolve full distribution of amp factors with mean and fractile reference rock hazard to generate mean and fractile site-specific hazard
4. Repeat Step 3 using Miller and Rice (1983) discrete approximations to continuous distribution

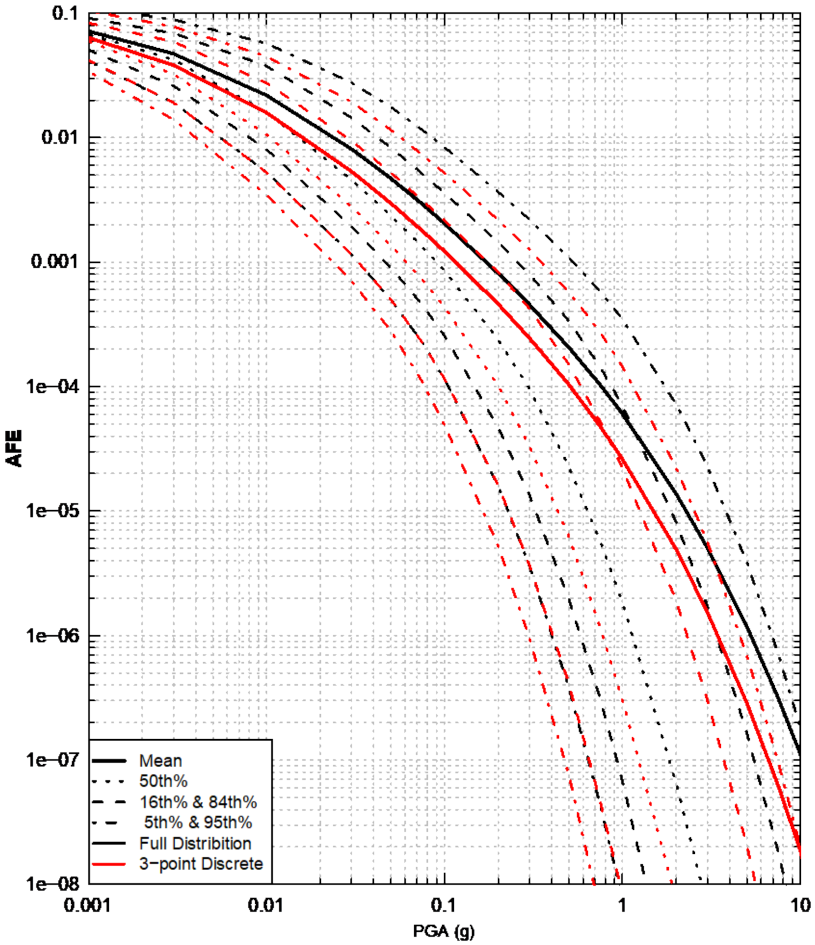
Reference Rock to Site-specific



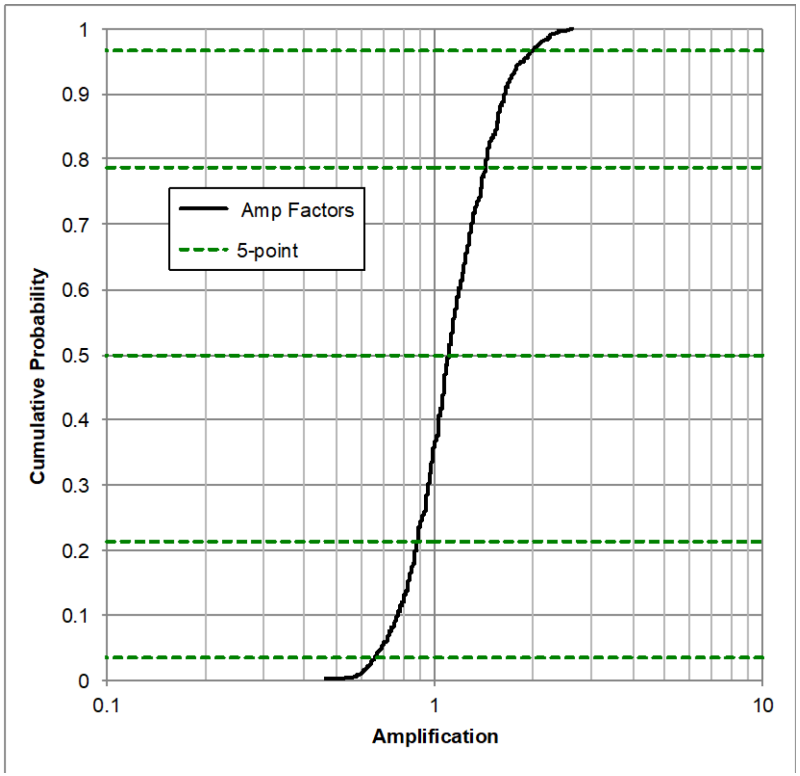


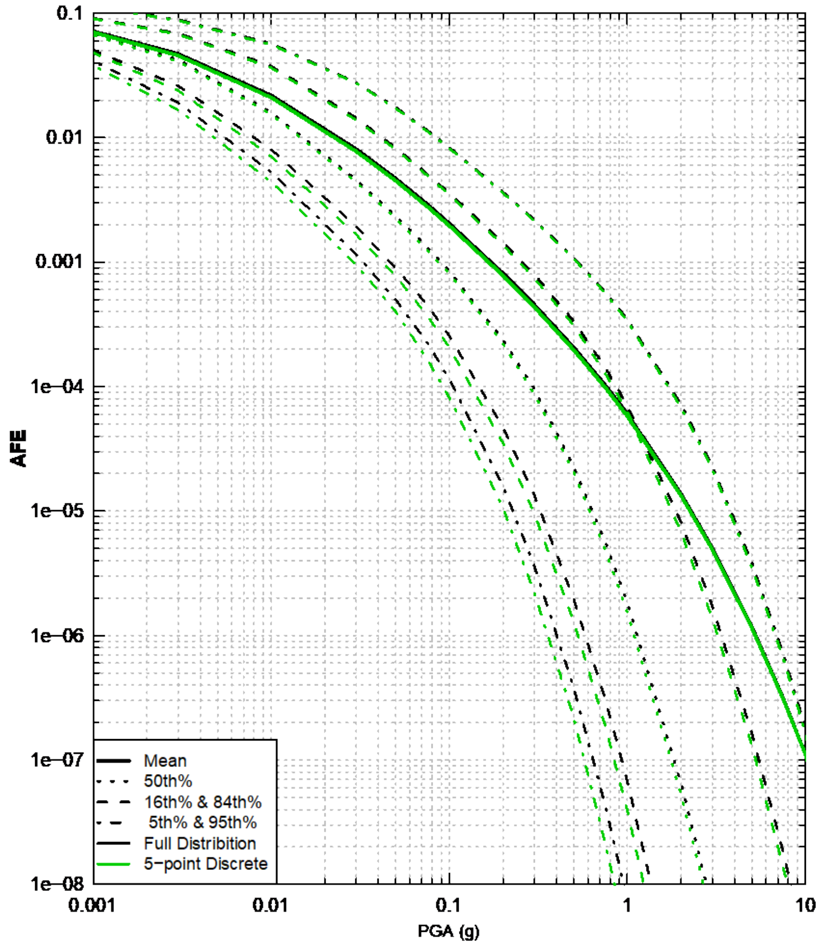
3-Point Approximation



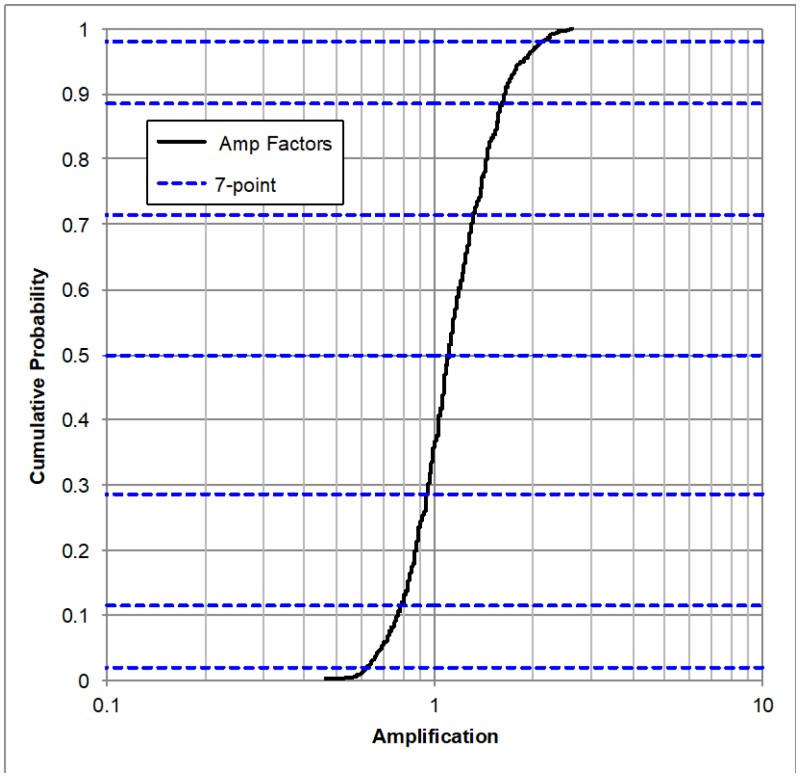


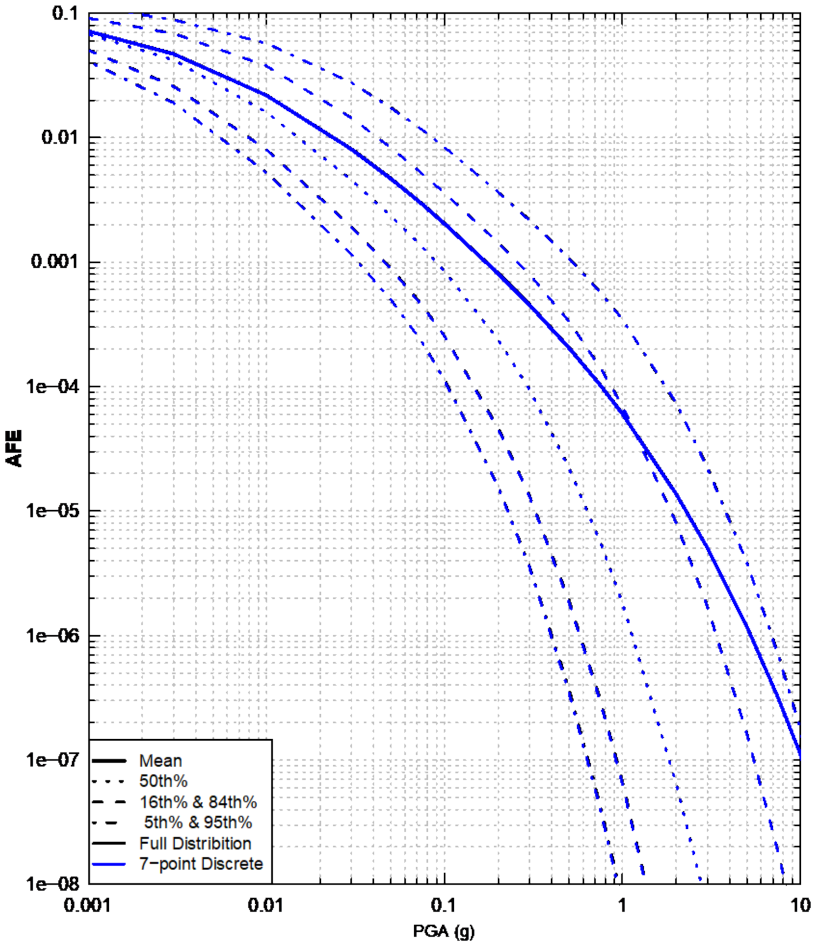
5-Point Approximation





7-Point Approximation





1. … including on which elements of aleatory variability in site response should be excluded from the uncertainty in site response to avoid double-counting of uncertainty. …

- "Modern" PSHAs are trending to the use of partially non-ergodic (single-station) sigma in which site-to-site variability in average amplification, ϕ_{S2S}, has been removed, with the requirement that epistemic uncertainty in the average amplification at your site needs to be included

Single-Station Sigma

$$\sigma_{SS} = \sqrt{\tau^2 + \phi_{SS}^2}$$

- Does ϕ_{SS} already include what is produced by the “aleatory” randomization of profiles and G/Gmax and damping relationships
  - Based on empirical recordings typically at moderately low ground motion levels – so probably not G/Gmax and damping at high strains
  - If reference site is like NGA-East, not observed on similar sites

A Proponent View

- ϕ_{SS} is assessed from recordings on sites that you would apply the randomization approaches to if you were attempting to model them, therefore includes $\sigma_{\ln(AF)}$ at “low” ground motion levels
- Account for the increase in $\sigma_{\ln(AF)}$ at large strains by using $\sigma_{\ln(AF)}^{NL} = \sqrt{\sigma_{\ln(AF)}^{2} - \sigma_{\ln(AF)-lowstrain}^{2}}$ in applying Approach 3

1. … It has been observed that an increase in epistemic uncertainty or aleatory variability can lead to a reduction in AF near resonances do to a smoothing effect. Please comment on if this is good or bad, and if bad how to minimize its impact.

- It would seem that the approaches suggested by Dr. Cox et al. for screening randomized profiles would help minimize undesirable effects of randomization
- In terms of epistemic, it indicates that there is more uncertainty near these frequencies than elsewhere. It argues for computing soil hazard results individually for all epistemic cases and examining their effect on the hazard, and perhaps ultimately on the risk if they occur at a critical frequency

2. Discuss benefits/limitations of different approaches for obtaining hazard fractiles that include epistemic uncertainty in site response …

- Alternative approaches
  - Post processing of hazard computed for a reference site
  - Incorporation of site amplification into hazard integral

Post processing probabilistic site amplification – NUREG/CR-6728 Approach 3

$$P(Z_s > z) = \int_0^{\infty} P\left(AF \geq \frac{z}{x} \middle| x\right) f(x) dx$$

$$P\left(AF \geq \frac{z}{x} \middle| x\right) = 1 - \Phi\left(\frac{\ln\left(\frac{z}{x}\right) - \mu_{n(AF|x)}}{\sigma_{ln(AF|x)}}\right)$$

- Post-process convolution of reference "rock" mean hazard curve (ground motion *x*) with probabilistic amplification for motion at control point, *z*, as a function of level of motion *x*
- *f*(*x*) is obtained by discretizing reference rock hazard curve at various levels of rock motion *x*

Post-processing (cont'd)

- Magnitude (and perhaps distance) effects on amplification can be incorporated
  - Deaggregate hazard to produce hazard curves for specific M (or perhaps M & R)
  - Convolve each with appropriate amplification function
  - Combine to produce composite mean hazard

Post-processing (cont'd)

- Assessment of fractiles of hazard
  - Represent distribution of reference rock hazard by set of alternative hazard curves
  - Convolve each with alternative site amplification functions to produce alternative site-specific hazard results from which fractiles can be constructed
- Development of distribution of reference rock hazard curves – two approaches
  - Cluster analysis of full logic tree characterization – most correct, but computational intensive
  - Use distribution of hazard at each level *x* to develop equally weighted "fractile" hazard curves (100+)

Difficulties with Use of Fractile Hazard

- Incorporation of magnitude (and distance) effects on amplification into fractiles requires either
  - Deaggregation of fractiles – a very computationally intensive process
  - Assessment of a representative magnitude (and distance) to use in applying the amplification functions

Incorporation of Amplification Function in Hazard Integral

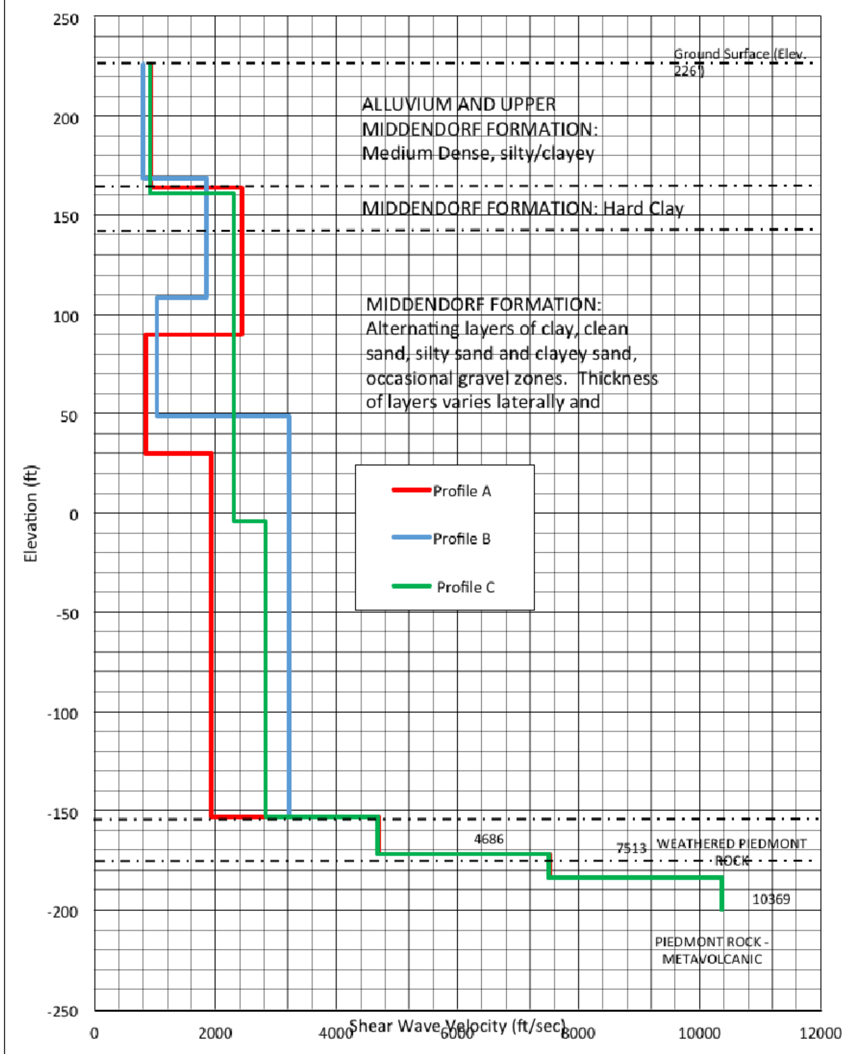
$$\nu(z) = \sum_n \alpha_n(m^0) \int_{m^0}^{m^u} f(m) \left[\int_0^{\infty} f(r|m) \cdot P(Z > z|m,r) \cdot dr \right] \cdot dm$$

$$P(Z_s > z|m,r,AF) = \int_0^{\infty} P\left(AF \geq \frac{z}{x}\middle|x\right) f(x|m,r)dx$$

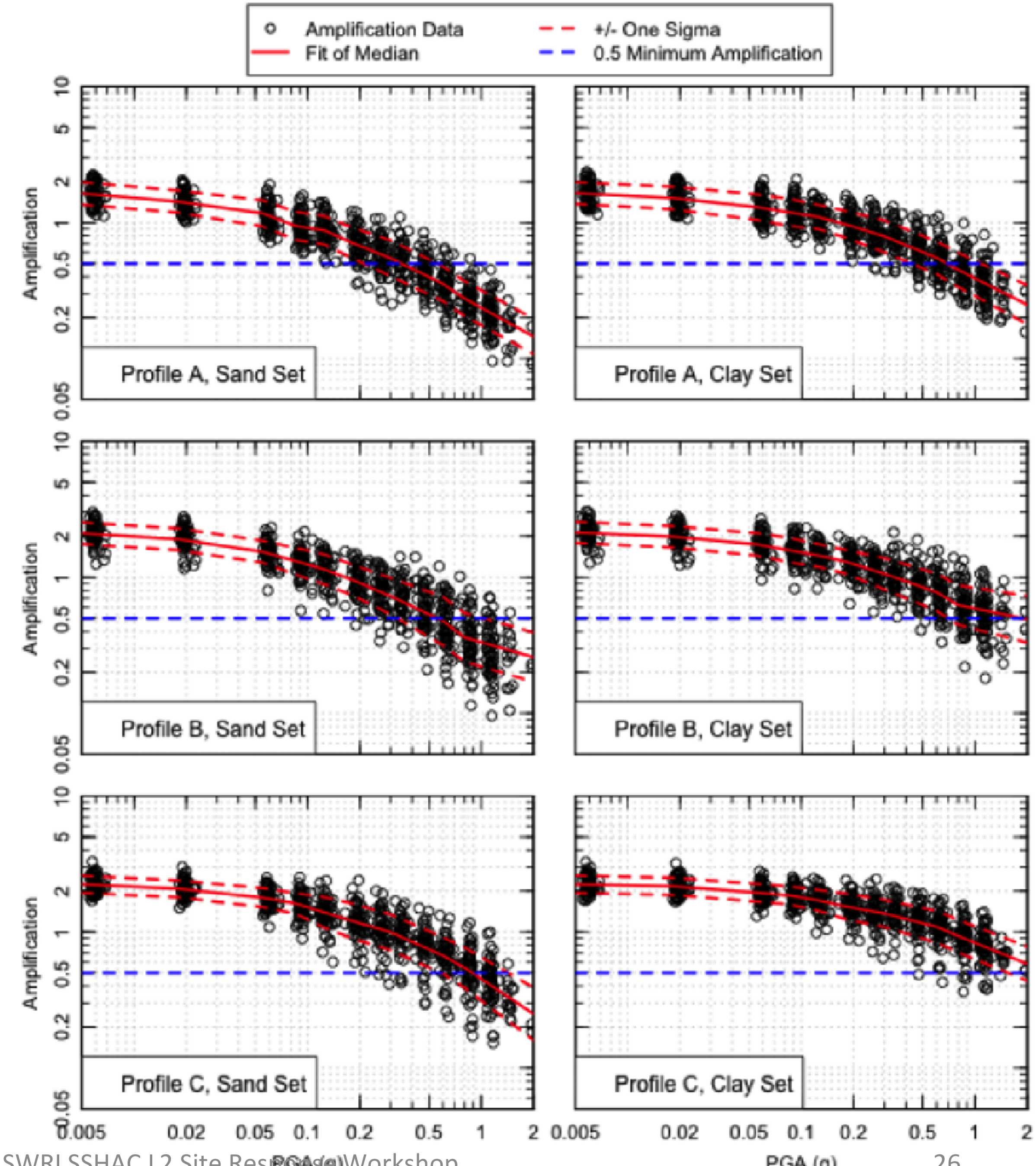
$$P\left(AF \geq \frac{z}{x}\middle|x\right) = 1 - \Phi\left(\frac{\ln\left(\frac{z}{x}\right) - \mu_{n(AF|x)}}{\sigma_{ln(AF|x)}}\right)$$

- Site amplification within hazard integral
- Hazard fractiles computed appropriately incorporating all epistemic uncertainties including those in *AF*
- More computationally intensive

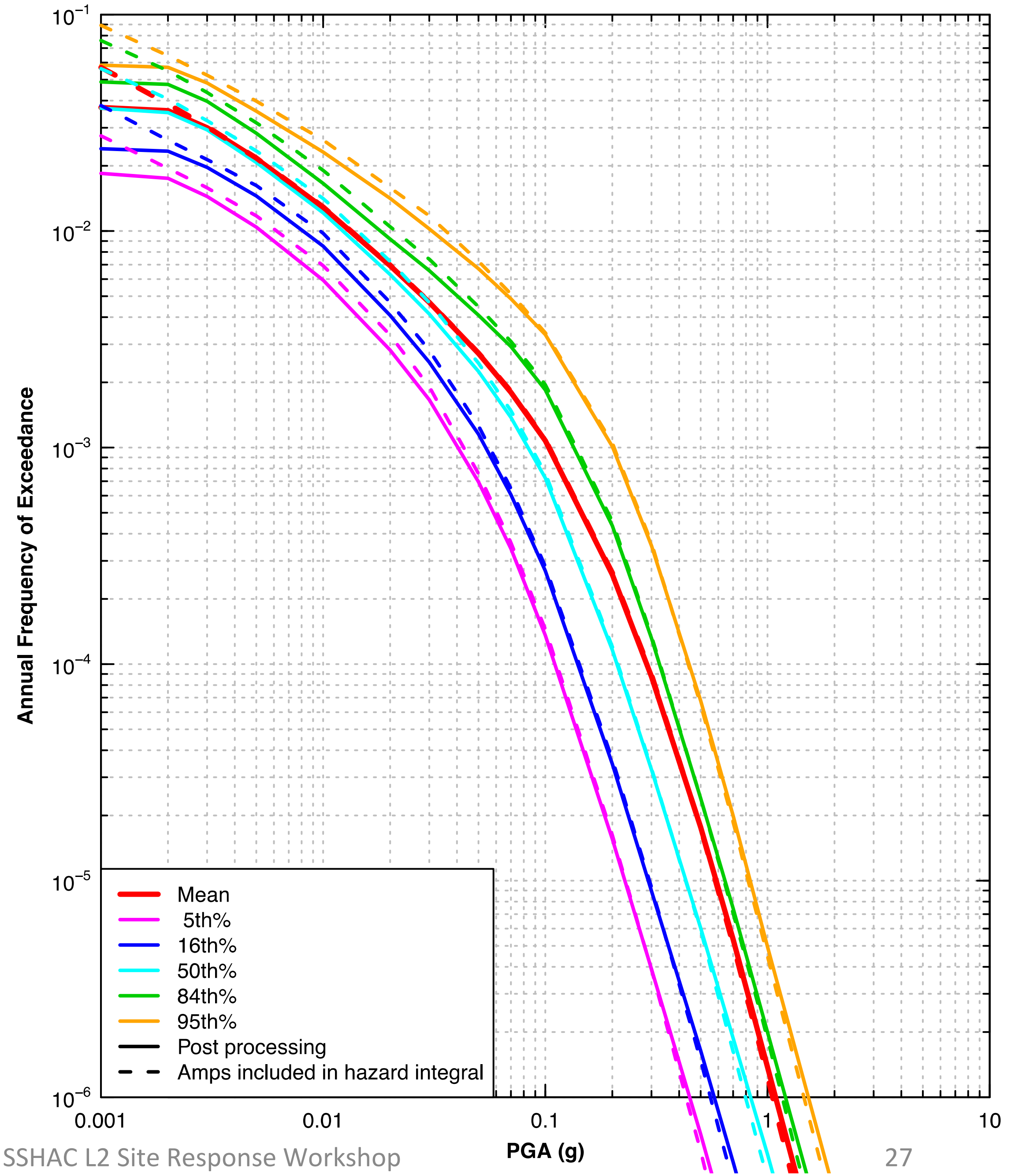
Comparison for a soil site with alternative Vs profiles



Non-linear amplification



Comparison of post processing and hazard integration



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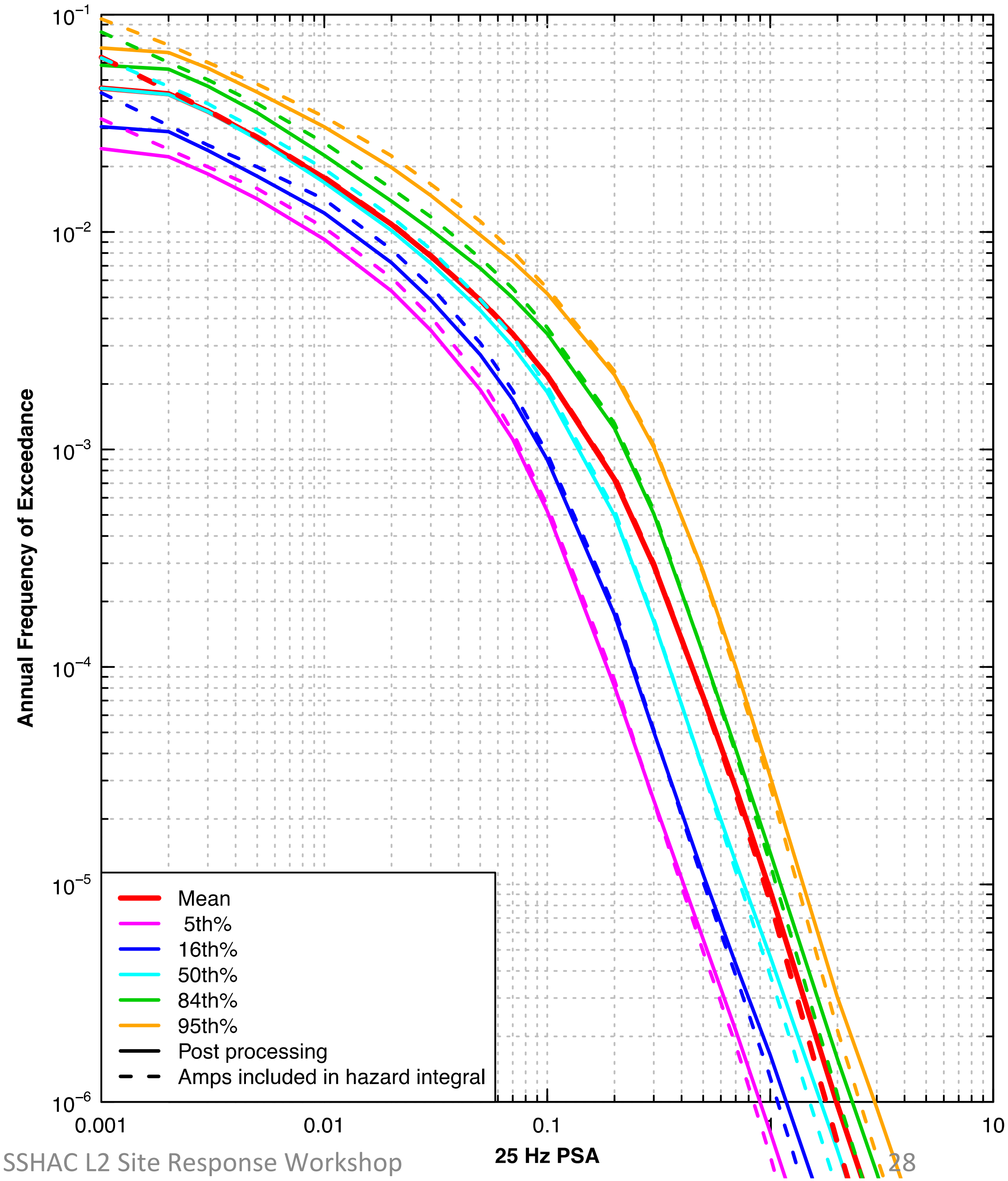

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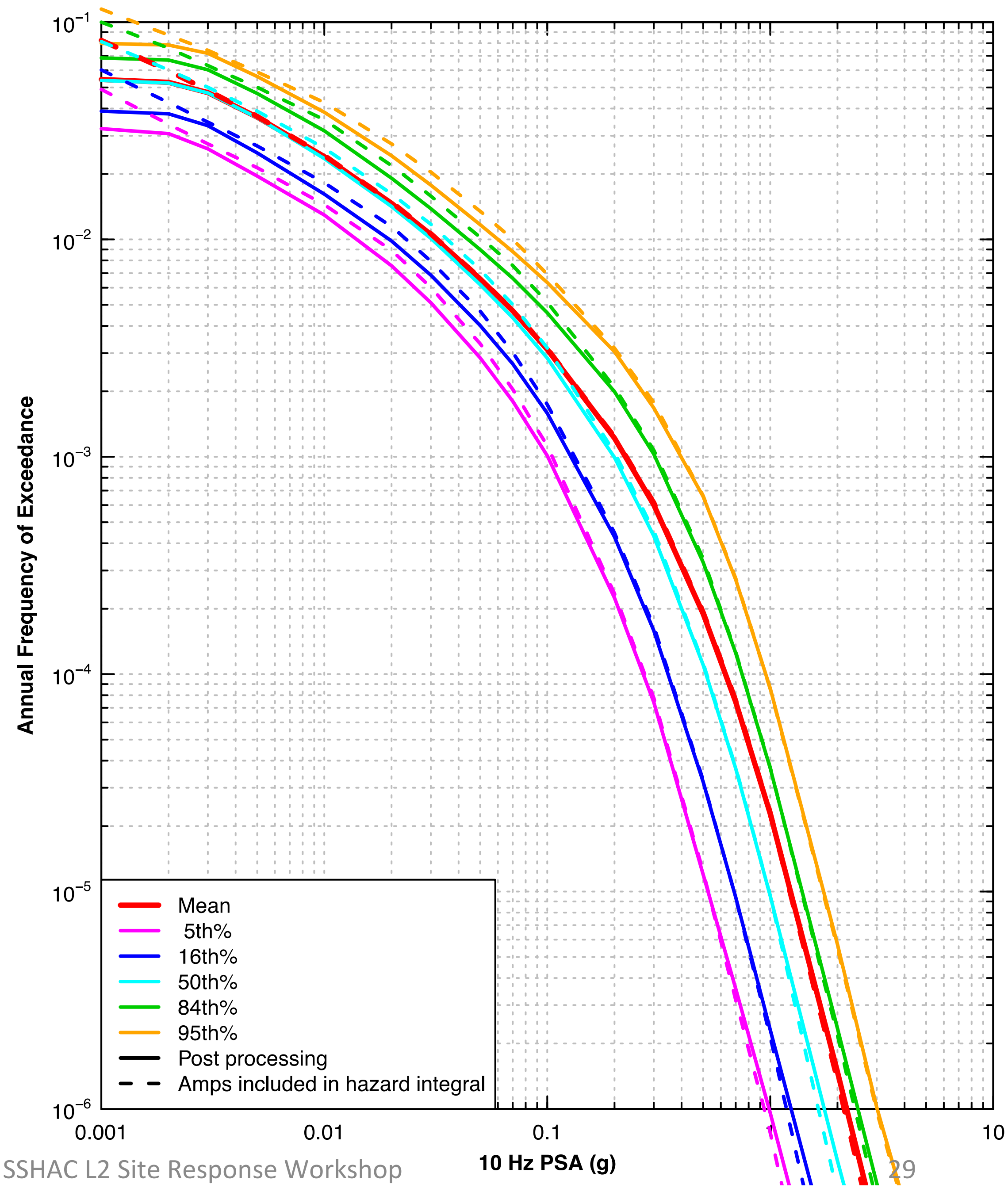

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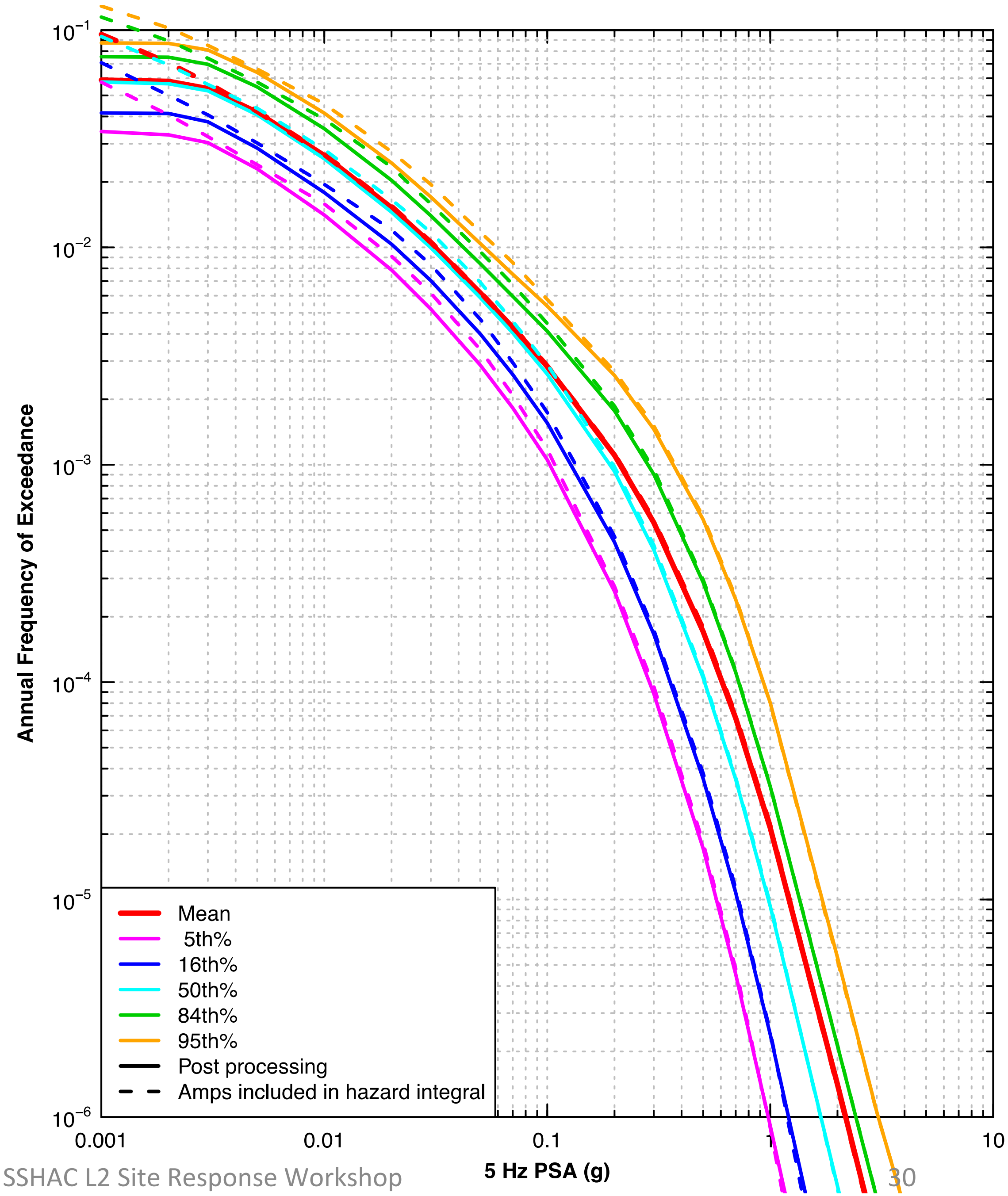

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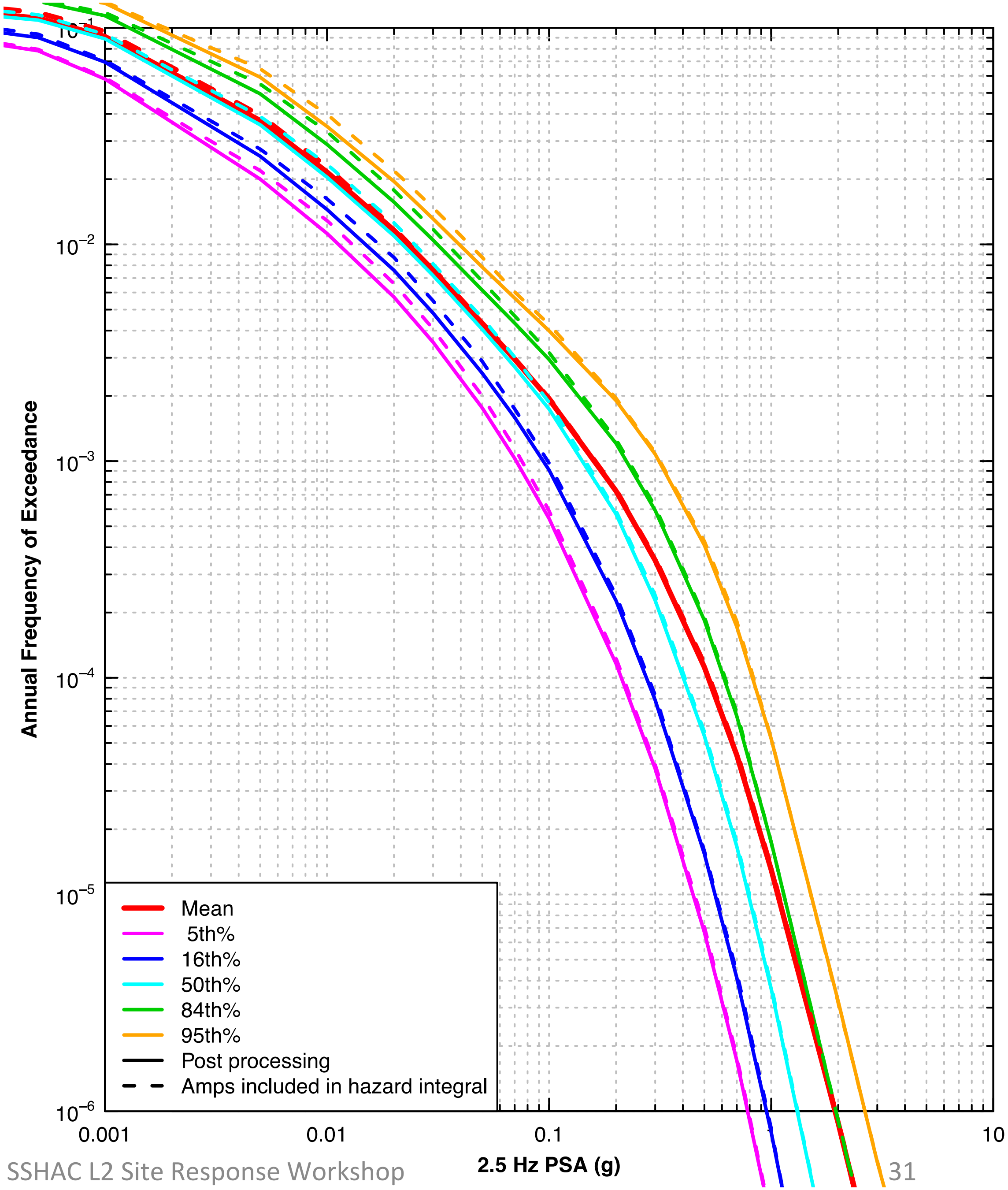

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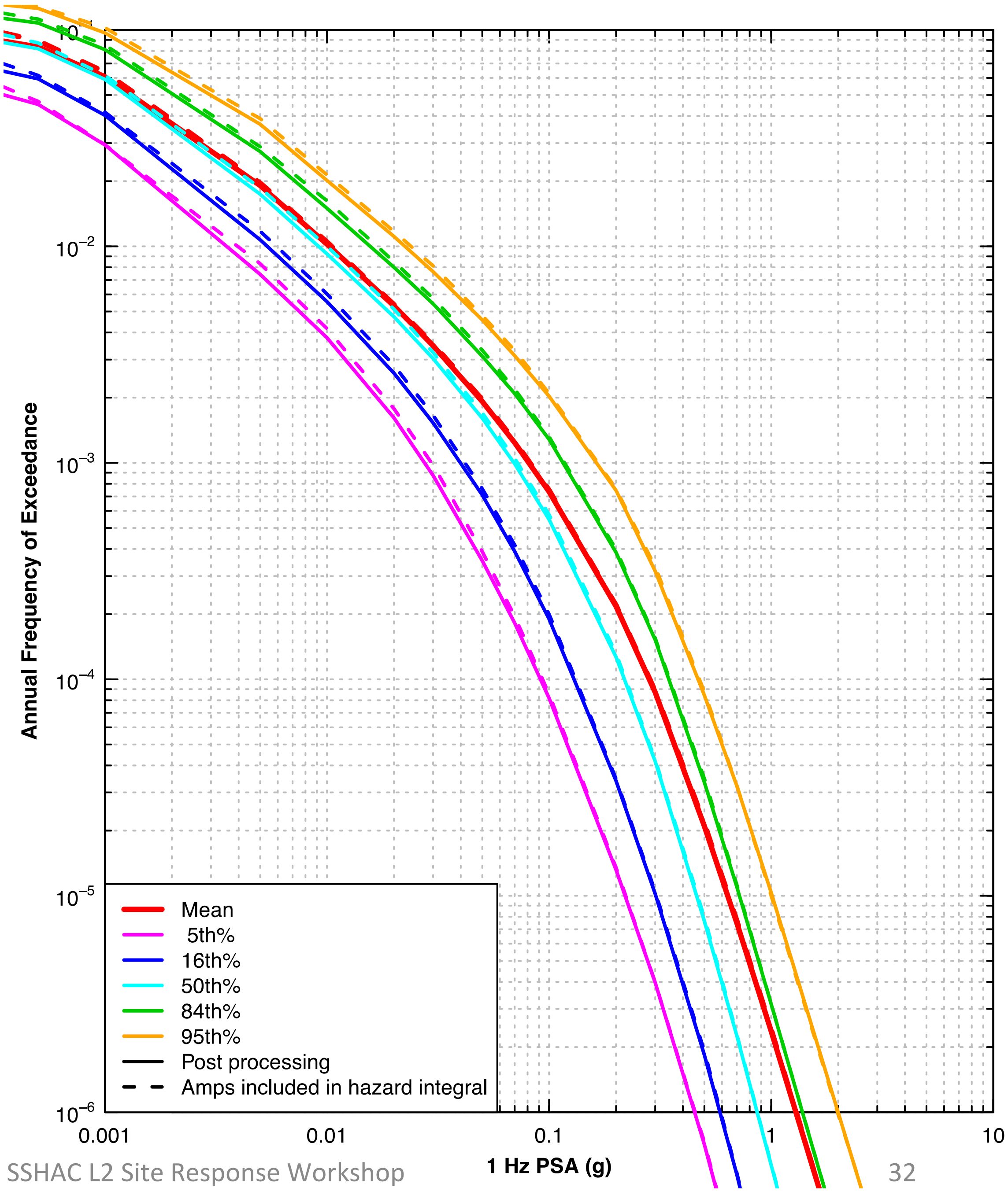

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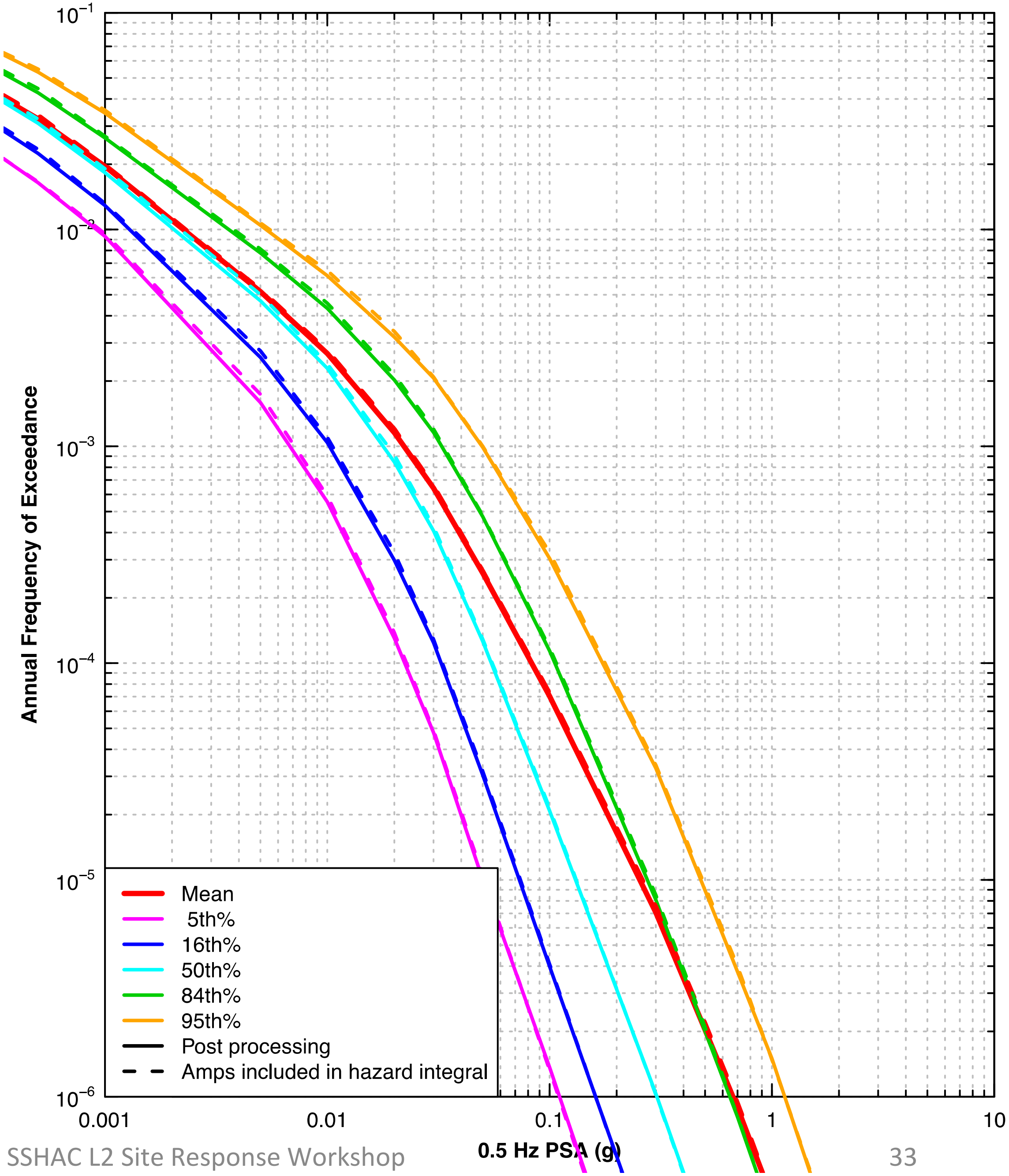

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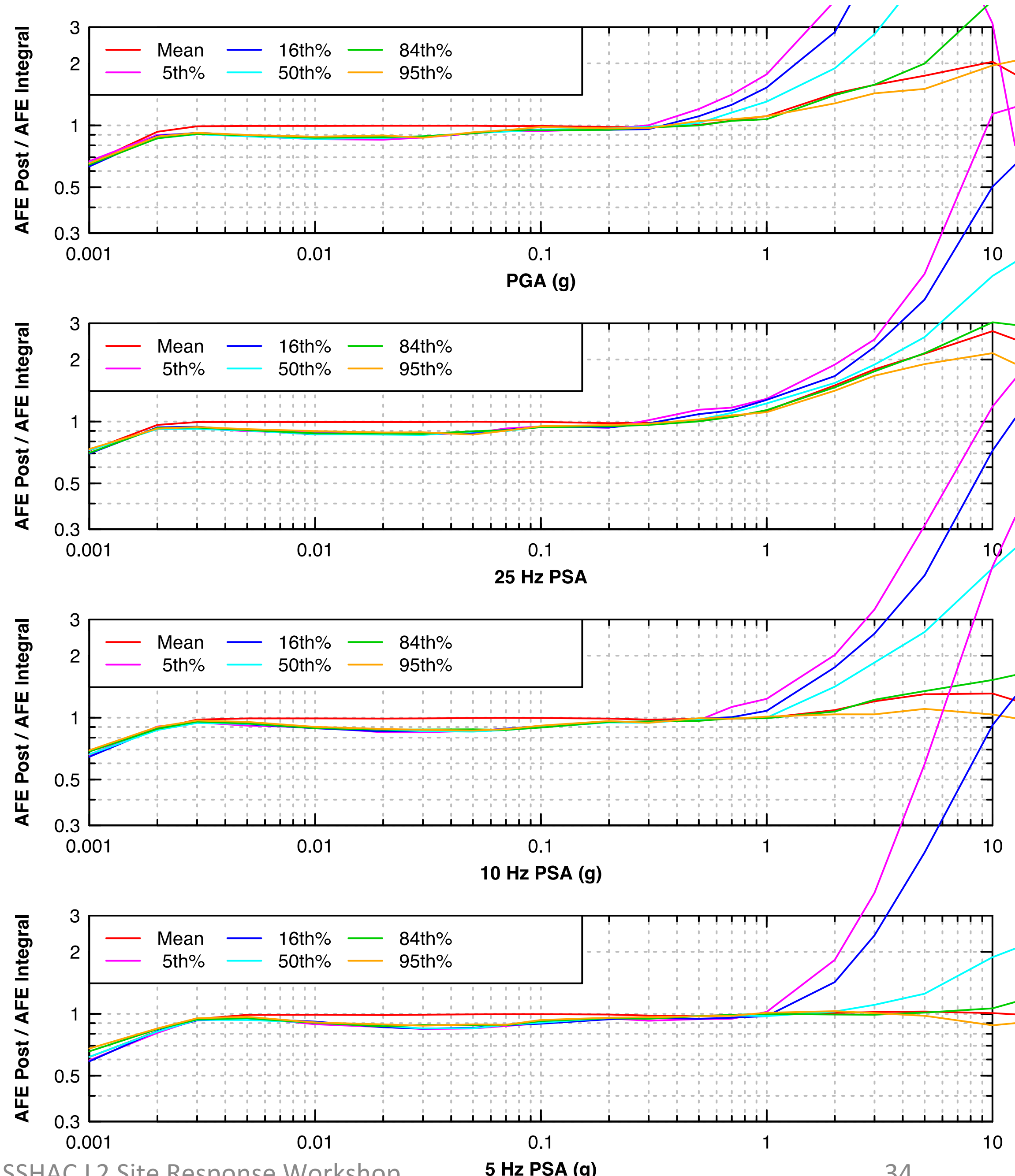

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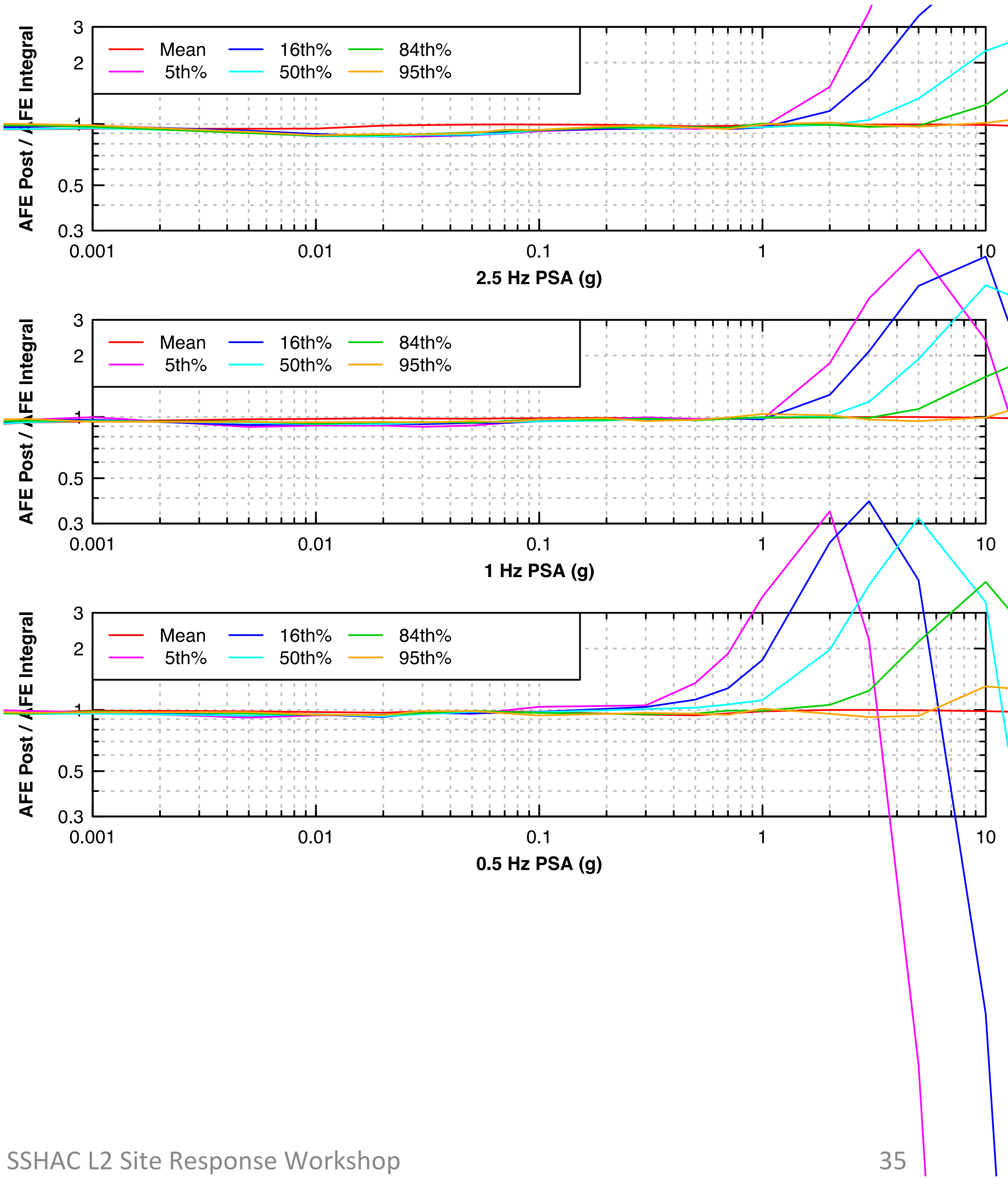


Observations

- Post-process Approach 3 is efficient, but perhaps best defined for obtaining mean soil hazard
  - Accuracy of fractiles may depend upon degree of nonlinear behavior and need to include magnitude dependence in AF ?
- Hazard integration provides more correct computation of fractiles at cost of more extensive computation time
  - This depends on complexity of reference rock GMPE

2. … Comment on how these approaches apply to cases where the reference rock hazard is at large depths or does not correspond to a local/regional profile

- Short response, I do not see that there would be any difference in this case

3. Discuss advantages and limitations of approaches for developing input motions for site response analyses …

- Alternative approaches
  - Stochastic representation of spectra for a set of target scenario earthquakes (typically median)
  - Time series conditioned to represent a set of target spectra

Stochastic Representation

- Specify scenario earthquakes in terms of M and R (R to get different amplitudes)
- Generate Fourier spectra for input motions accounting for specified amplification and shallow crustal damping in reference profile
- Can use alternative representations of the shape of the source spectrum
- With IRVT, could use other that “median” spectra

Time Series Representation

- Define a set of scenario earthquakes in terms of M, R, and target spectra
- Select sets of appropriate seed recordings
- Modify records to (loosely) match target spectra

Advantages and Limitations

- RVT is faster, but need to specify a bit more information (duration)
- Time series perhaps more flexible in terms of target spectra, takes longer to develop input and to run response
- Time series may be needed if nonlinear site response methods are to be used

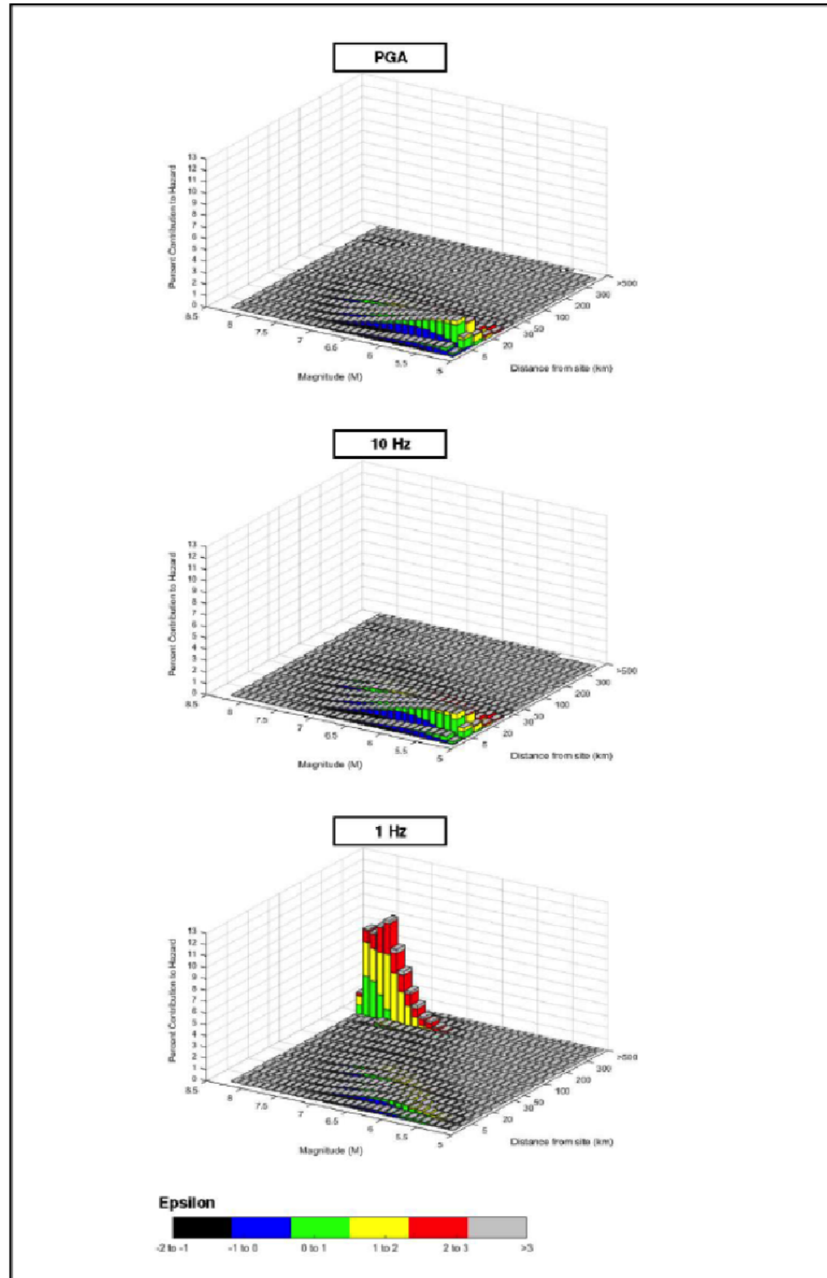
3. … Focus on approaches used to ensure input spectra cover range of expected hazard for site in terms of magnitude and distance contributions as well as reference kappa values. Discuss impact of input spectral shape on AF

- For sites where there is a potential for significant nonlinearity, frequency content of input motions has significant effect on AF.
- The concept of "Deaggregation Earthquakes" discussed in NUREG/CR-6728 can be used to define scenarios that represent the hazard contributions in different frequency bands

Input Motions (cont'd)

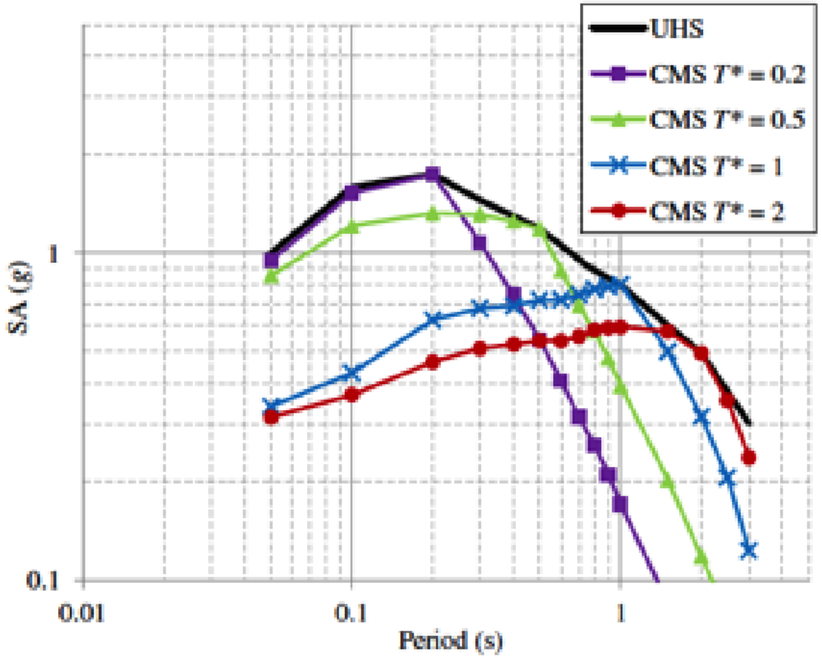
- Many (most) sites in the CEUS have a bimodal hazard deaggregtion, suggesting that the use of alternative scenario target spectra may have an impact on assessments where nonlinearity is significant
- Target scenario spectra can be developed using Conditional Mean Spectra or broadened CMS (Carlton and Abrahamson, 2014)

Deaggreagtion of hazard at AFE of 10^{-4} 450 km from New Madrid in the East Tennessee Seismic Zone

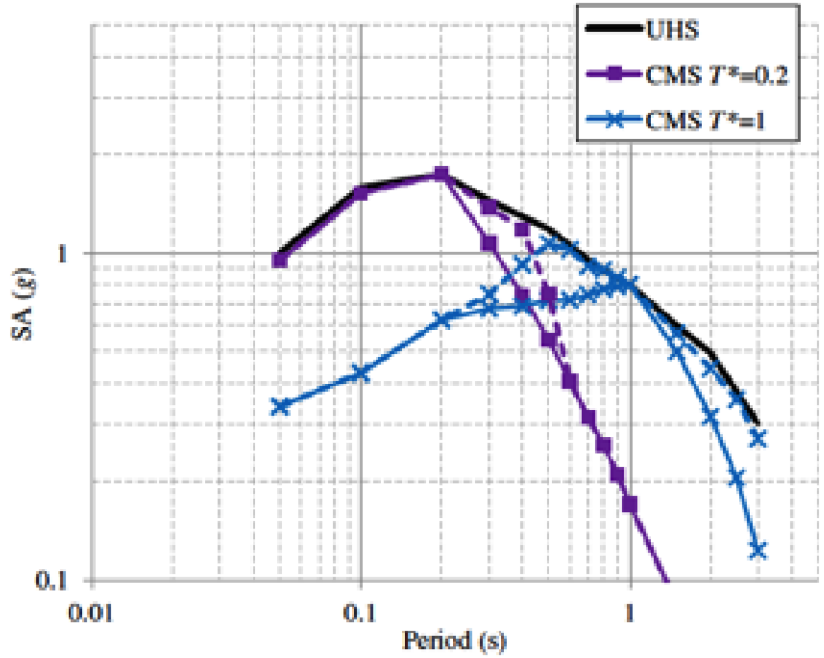


Carlton and Abrahamson (2014)

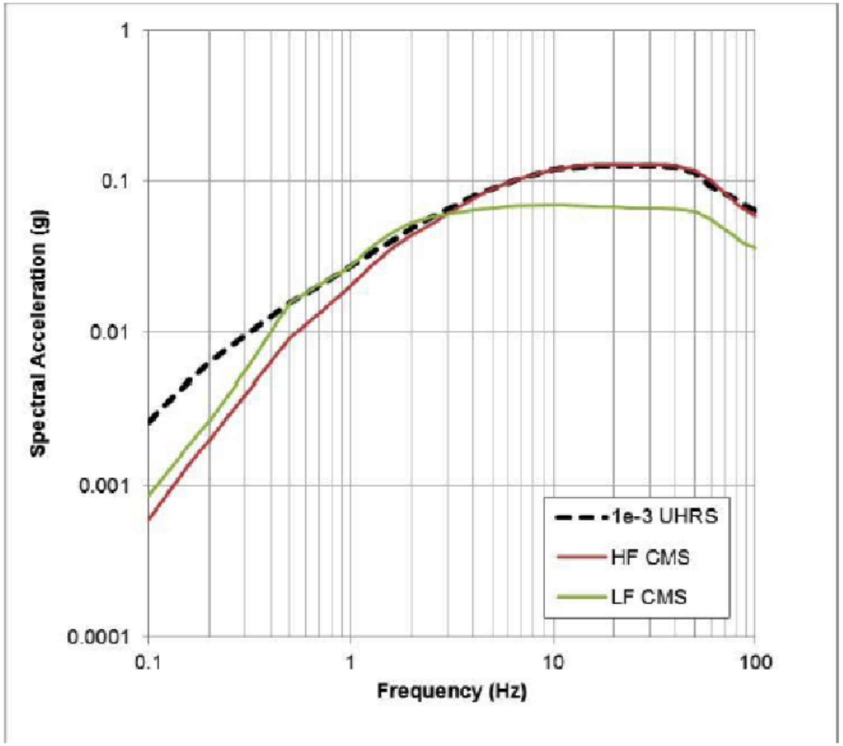
Multiple CMS for individual target periods

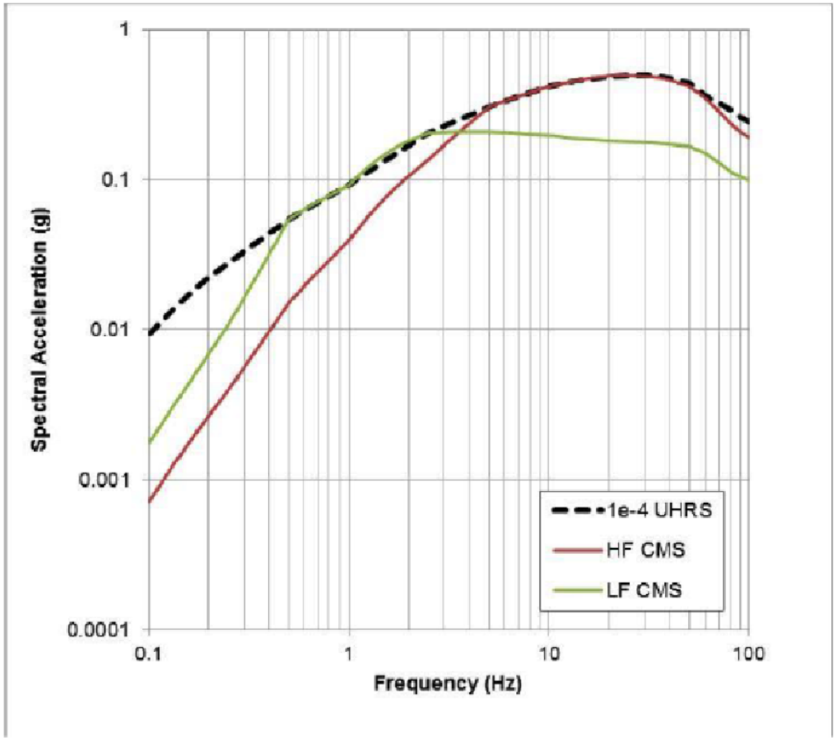


Broadened CMS for target period ranges



Extend Concept to Input Motions for Site Response





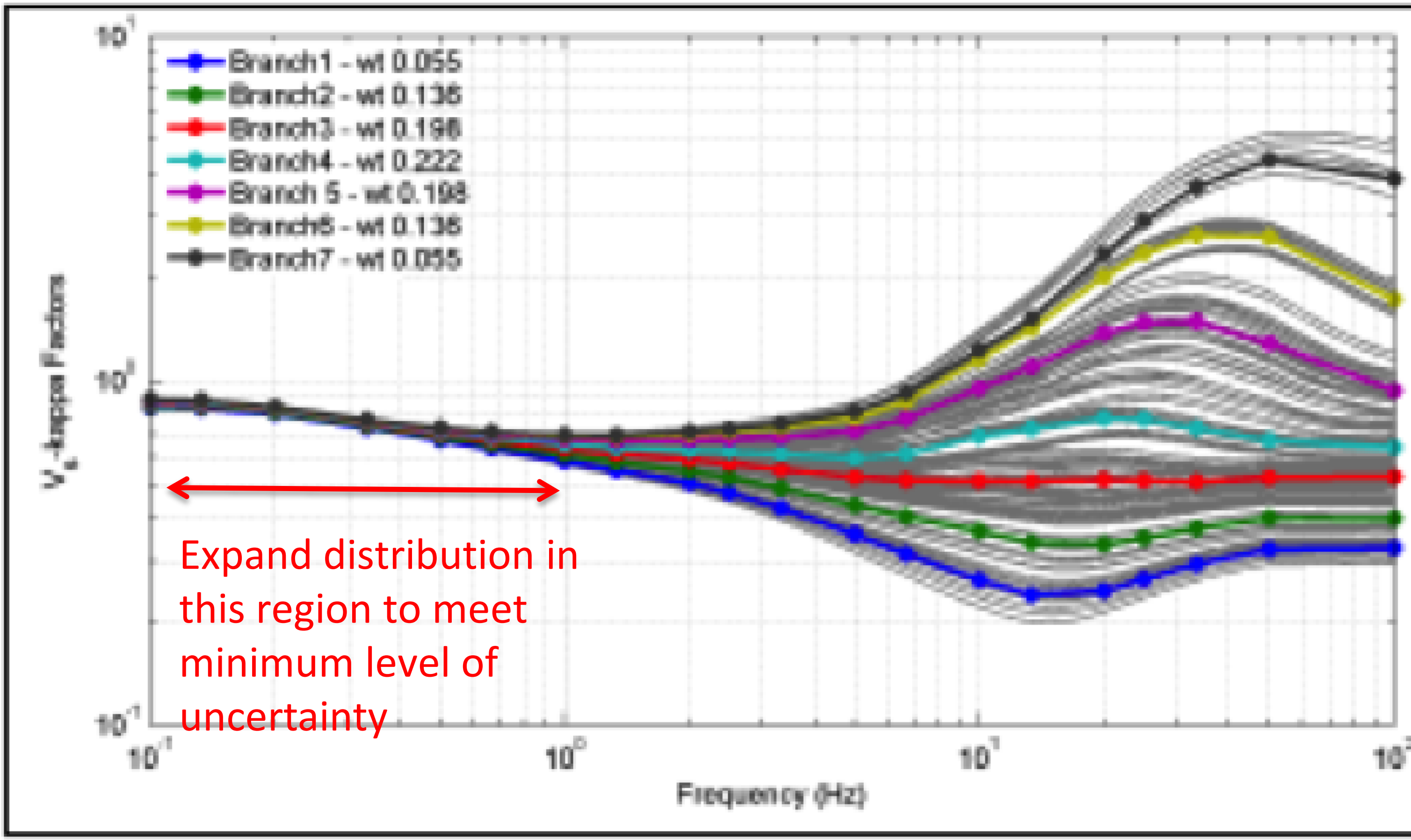
4. Discuss advantages and limitations of approaches used to incorporate site amplification factor distributions (median and sigma) into the hazard …

- Alternative approaches
  - Post processing of hazard computed for a “reference” site
  - Incorporation of site amplification into hazard integral
  - Development of alternative sets of site-specific GMPEs that incorporate site effects uncertainty perhaps by empirical data from other regions to site in question

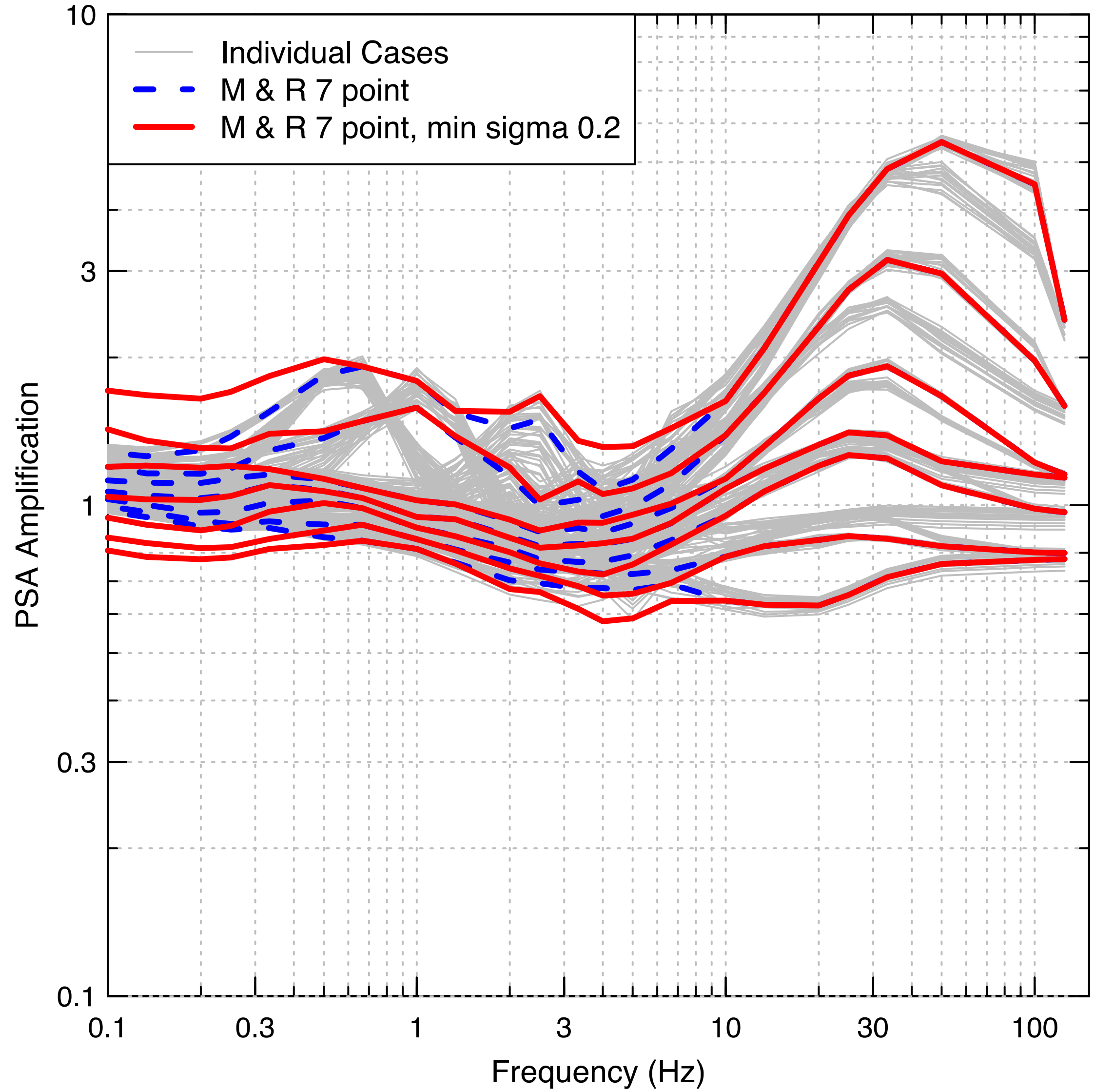
4. … Discuss approached for capturing distribution of site AF from each of the alternative site response logic tree branches …

- Develop alternatives capturing all the important uncertainties
- Develop a distribution of AF
- Represent this distribution in a convenient discrete manner for PSHA calculations
- Perhaps impose a minimum level of epistemic uncertainty to address modeling uncertainty in the process

Example Vs-kappa from Hanford PSHA (conceptually similar to AF)



- Example H2T amplification imposing minimum epistemic uncertainty in AF



4. … Discuss potential for double-counting aleatory variability (i.e. partitioning variability between "reference" GMM and site response …

- What does ϕ_{SS} already contain

4. …Discuss use of both Approach 3 and "Approach 4" for control point hazard

- 3 and "4" (AF in hazard integral) should produce same mean, and similar fractiles at least for moderately stiff sites