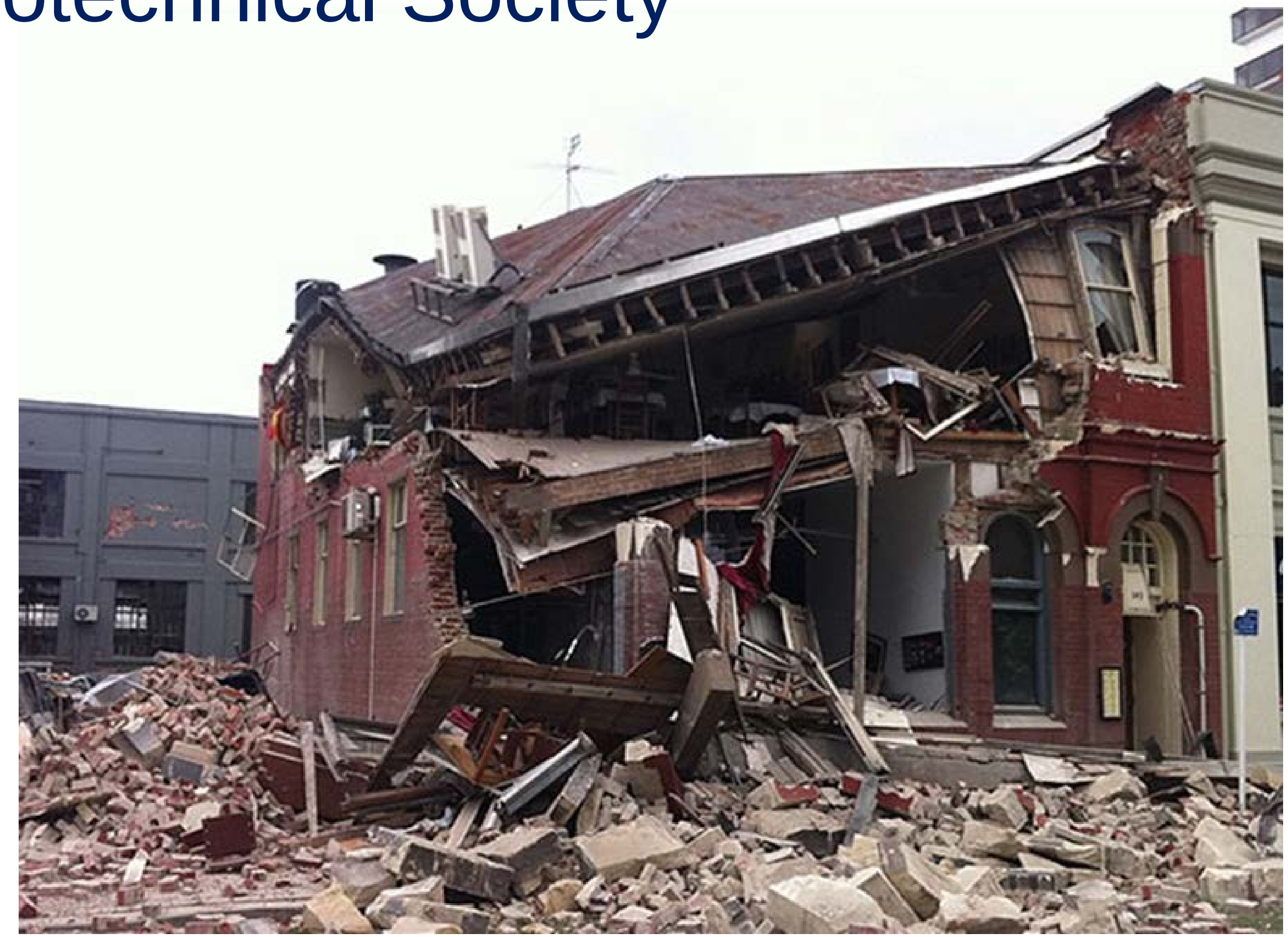
Vancouver Geotechnical Society

NBC 2020-Compatible Seismic Site Response Analysis Approach

Chris Weech, M.A.Sc., P.Eng.

November 16, 2022



Christchurch, NZ (Feb. 22, 2011)

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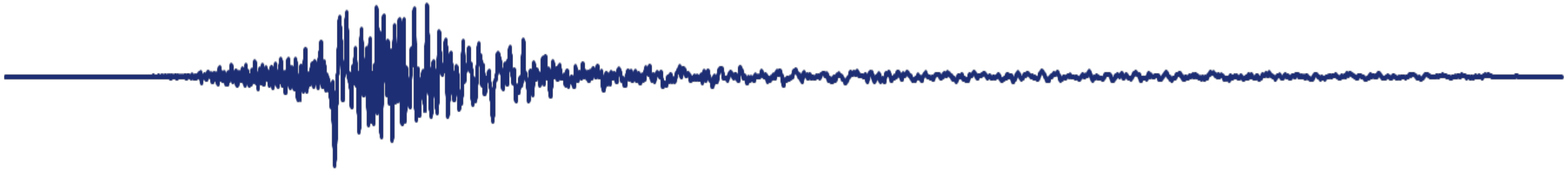

Presentation Outline

- Aggregated hazard from seismic hazard calculator vs event scenario hazard as examined from deaggregation data
- Differences in site amplification treatment in the 6th Generation Seismic Hazard Model of Canada (SHMC-6) adopted by NBC 2020 compared to NBC 2015:
    - NBC 2015 – Non-linear amplification according to aggregated probabilistic PGA_{ref}
    - SHMC-6 – Non-linear amplification according to event scenario median ground motion intensity
- Probabilistic distribution of event scenario hazard values from NBC 2020 deaggregation data
- Current practice for Seismic Site Response Analyses (SSRA) based on NBC 2015 aggregated hazard values
- Study demonstrating implementation of SSRA results within SHMC-6 compared to simplified methods of calculating NBC 2020-compatible Uniform Hazard Response Spectra (UHRS) using SSRA results

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Probabilistic Seismic Hazard Values

https://www.earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/calc-en.php

Site: 48.4191 N, 123.3703 W   User File Reference: Legislative Assembly of BC, Victoria, BC

Requested by: ,

1 / 2,475 years

National Building Code ground motions: 2% probability of exceedance in 50 years (0.000404 per annum)

Uniform Hazard Response Spectrum (UHRS)

Sa(0.05)	Sa(0.1)	**Sa(0.2)**	Sa(0.3)	**Sa(0.5)**	**Sa(1.0)**	**Sa(2.0)**	**Sa(5.0)**	**Sa(10.0)**	**PGA (g)**	**PGV (m/s)**
0.709	1.082	**1.300**	1.301	**1.154**	**0.674**	**0.397**	**0.124**	**0.043**	**0.579**	**0.830**

Notes. Spectral (Sa(T), where T is the period in seconds) and peak ground acceleration (PGA) values are given in units of g (9.81 m/s^2). Peak ground velocity is given in m/s. Values are for "firm ground" (NBCC 2015 Site Class C, average shear wave velocity 450 m/s). NBCC2015 and CSAS6-14 values are specified in **bold** font. Three additional periods are provided - their use is discussed in the NBCC2015 Commentary. Only 2 significant figures are to be used. ***These values have been interpolated from a 10-km-spaced grid of points. Depending on the gradient of the nearby points, values at this location calculated directly from the hazard program may vary. More than 95 percent of interpolated values are within 2 percent of the directly calculated values.***

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Aggregated Probabilistic Seismic Hazard

- Probabilistic Hazard Values referenced to Probability of Exceedance in 50 yrs (PoE_{50}) or Annual Exceedance Rate (AER):

$$1 - PoE_{50} = (1-AER)^{50}$$

- "Return Period" = 1/AER – not to be confused with the Average Recurrence Period of the EQ event
- Probabilistic Hazard Value at a specified AER obtained from a "Hazard Curve"

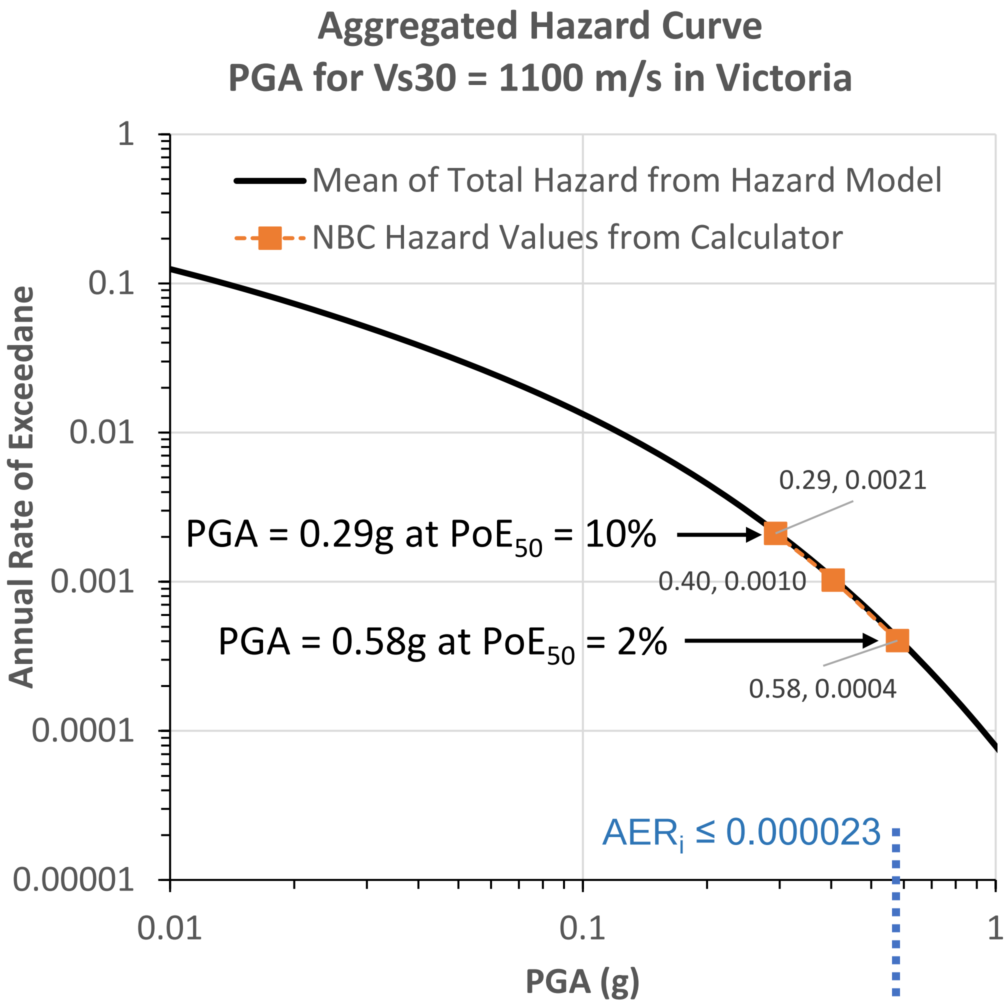
  eg. PGA(AER = 0.000404) = 0.58g

- Total Hazard: $AER_{TH}(X) = \Sigma\ AER_i(X,M_i,R_i)$, where

  X = probabilistic hazard value (eg. PGA)

  M_i = earthquake magnitude of event scenario i

  R_i = source-site distance of event scenario i



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Deaggregated Hazard

- Deaggregation data indicates % contributions of individual event scenarios to total hazard value (*X*) at specified AER_{TH}:

  Event scenario contribution, $c_i = AER_i/AER_{TH}$

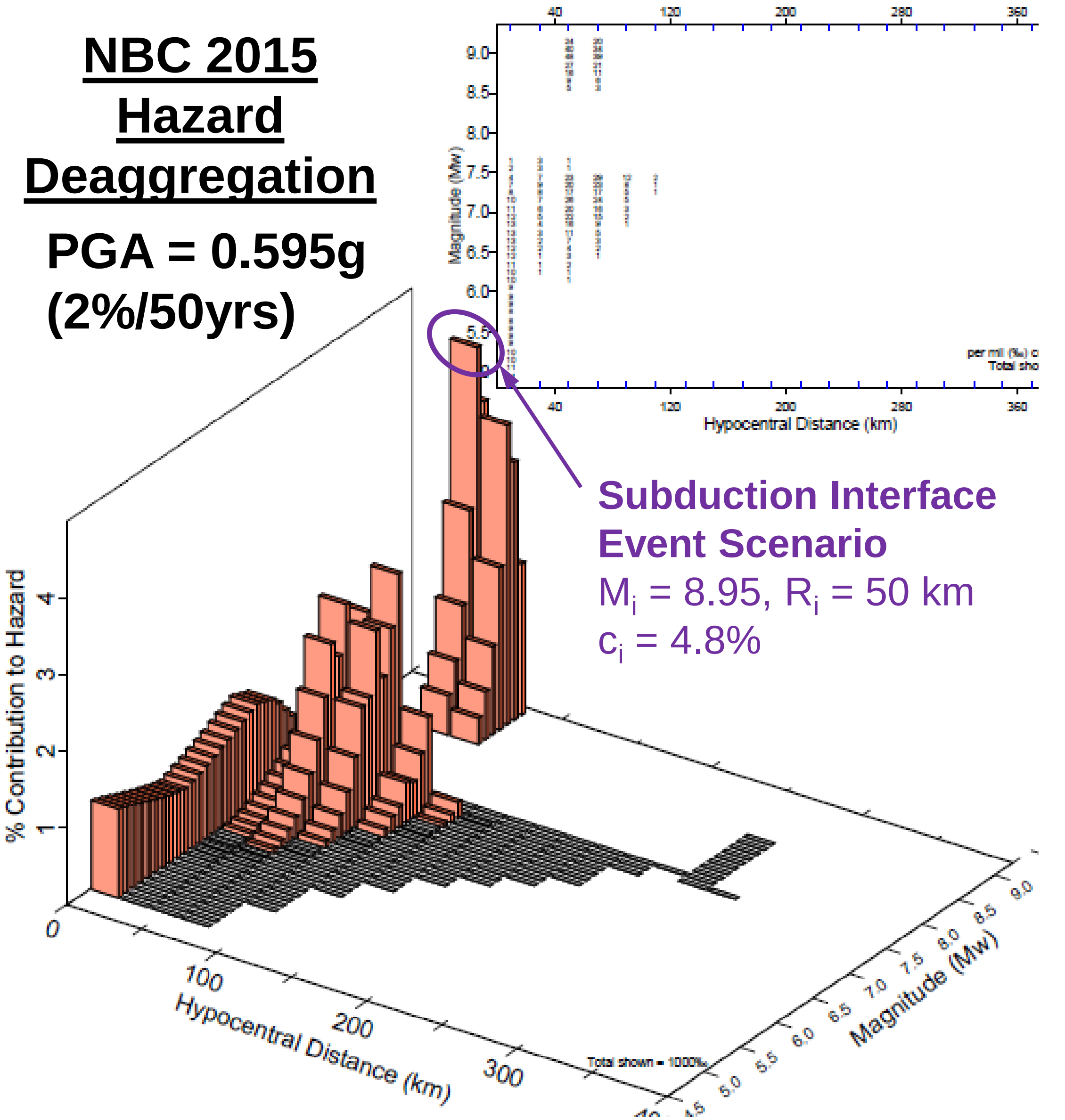
- Deaggregation data provides c_i for each M_i, R_i "bin"
- NBC 2015 does not reveal predicted PGA_i

➢ Example:

  - PGA = 0.595g, AER_{TH} = 0.0404% p.a. (NBC 2015)
  - Modal M_i = 8.95, R_i = 50 km, c_i = 4.8%
  - $AER_i = c_i \cdot AER_T$ = 0.0019% (PoE_{50} = 0.097%)
  - $1/AER_i$ = 52,000 years

<u>NBC 2015 Hazard Deaggregation</u>

PGA = 0.595g (2%/50yrs)



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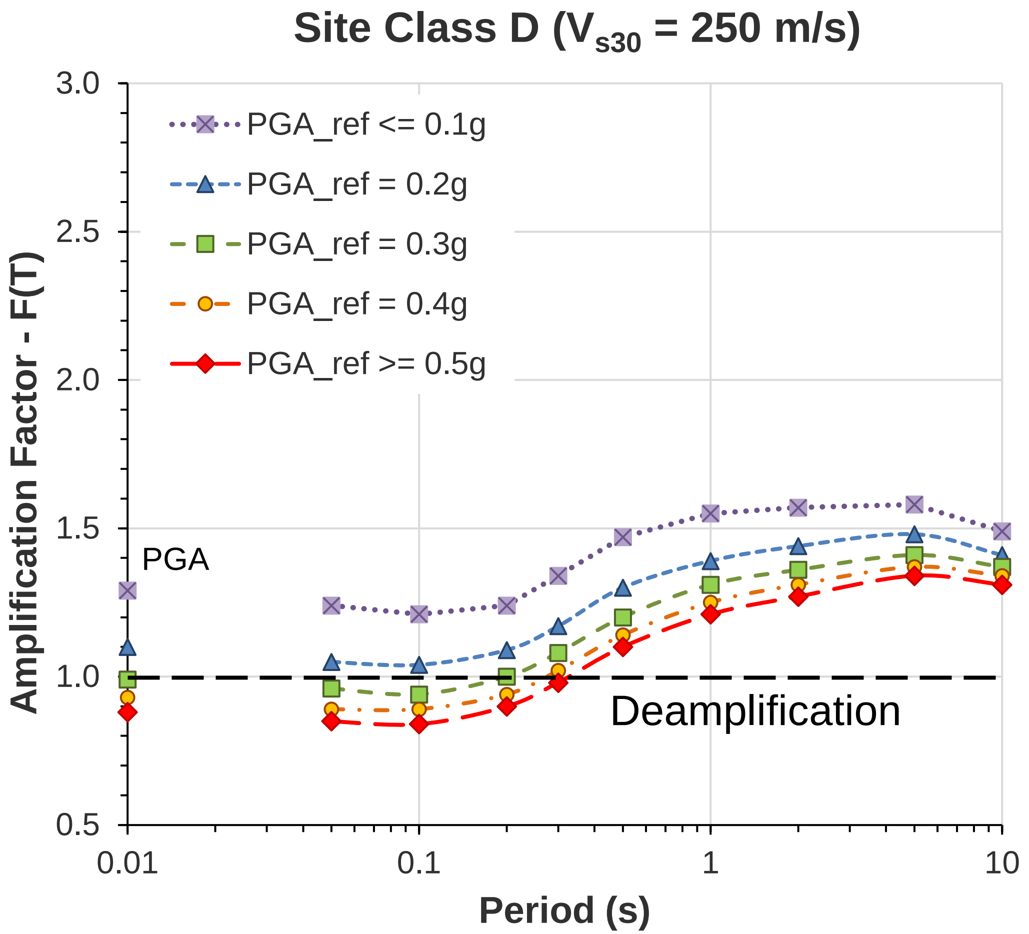
Amplification in NBC 2015

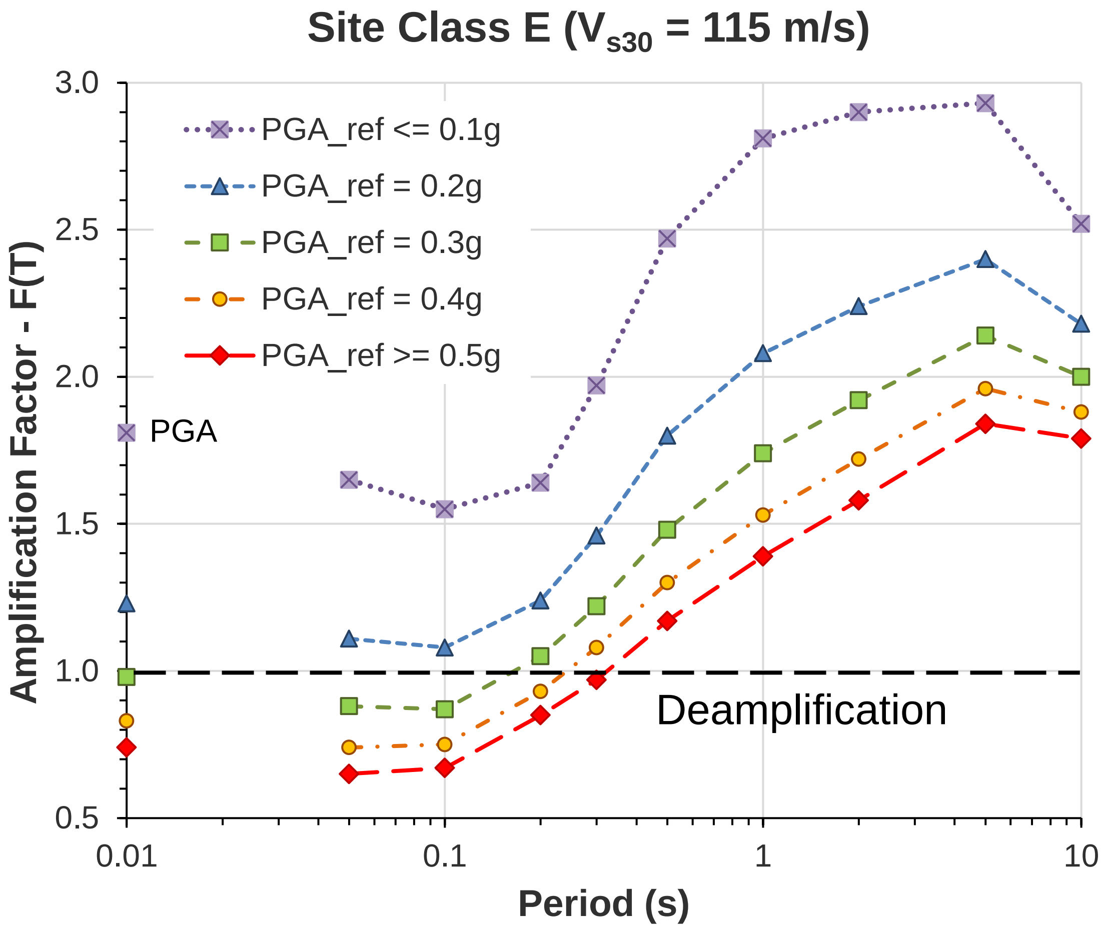
- Probabilistic hazard values ($S_a(T)$, PGA, PGV) for Site Class C reference ground condition generated by 5th Generation Seismic Hazard Model of Canada (SHMC-5)
- Site amplification from Site Coefficient tables provided in the code: $F(T, \text{Site Class}, PGA_{ref})$:
  - PGA_{ref} is the ground motion "intensity measure" to account for non-linear amplification effects
  - $PGA_{ref} = PGA_C$, or $0.8 PGA_C$ (if $PGA_C/S_a(T) > 0.5$)
  - PGA_C is the probabilistic PGA (for Site Class C) at the design hazard level
- Site Class-specific amplified hazard values: $S(T,SC) = S_a(T) \cdot F(T,SC,PGA_{ref})$

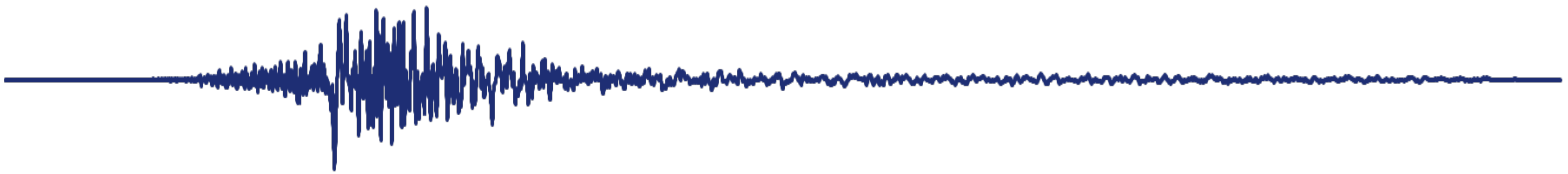
Table 4.1.8.4.-B
Values of F(0.2) as a Function of Site Class and PGA_{ref}
Forming Part of Sentences 4.1.8.4.(4) and (5)

Site Class	Values of F(0.2)				
	$PGA_{ref} \leq 0.1$	$PGA_{ref} = 0.2$	$PGA_{ref} = 0.3$	$PGA_{ref} = 0.4$	$PGA_{ref} \geq 0.5$
A	0.69	0.69	0.69	0.69	0.69
B	0.77	0.77	0.77	0.77	0.77
C	1.00	1.00	1.00	1.00	1.00
D	1.24	1.09	1.00	0.94	0.90
E	1.64	1.24	1.05	0.93	0.85
F	(1)	(1)	(1)	(1)	(1)

NBC 2015 Site Coefficients – $F(T, PGA_{ref})$







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Amplification in NBC 2020

- Amplification of rock ground motion values associated with individual event scenarios are calculated internally within SHMC-6 using multiple Ground Motion Models (GMMs) specific to each tectonic regime
- For each empirical GMM:
  - a site term based on V_{s30} is used to calculate linear (elastic) amplification
  - a site term based on the median prediction of (typ.) PGA_{rock} for individual event scenarios is used to calculate non-linear effects
- The amplified hazard values are probabilistically aggregated to generate Uniform Hazard Response Spectra (UHRS), PGA, PGV as a function of V_{s30}

Tectonic Regime	GMM	Weight
Subduction Inslab	Aea15	0.25
	Zea06	0.25
	AB03	0.25
	Gea05	0.25
Subduction Interface	Aea15	0.25
	Zea06	0.25
	GA14	0.25
	AM09	0.25
Active Crust	ASK14	0.25
	BSSA14	0.25
	CB14	0.25
	CY14	0.25

Ref: Kolaj et al. (2019). "Ground-motion models for the 6th Generation Seismic Hazard Model of Canada"

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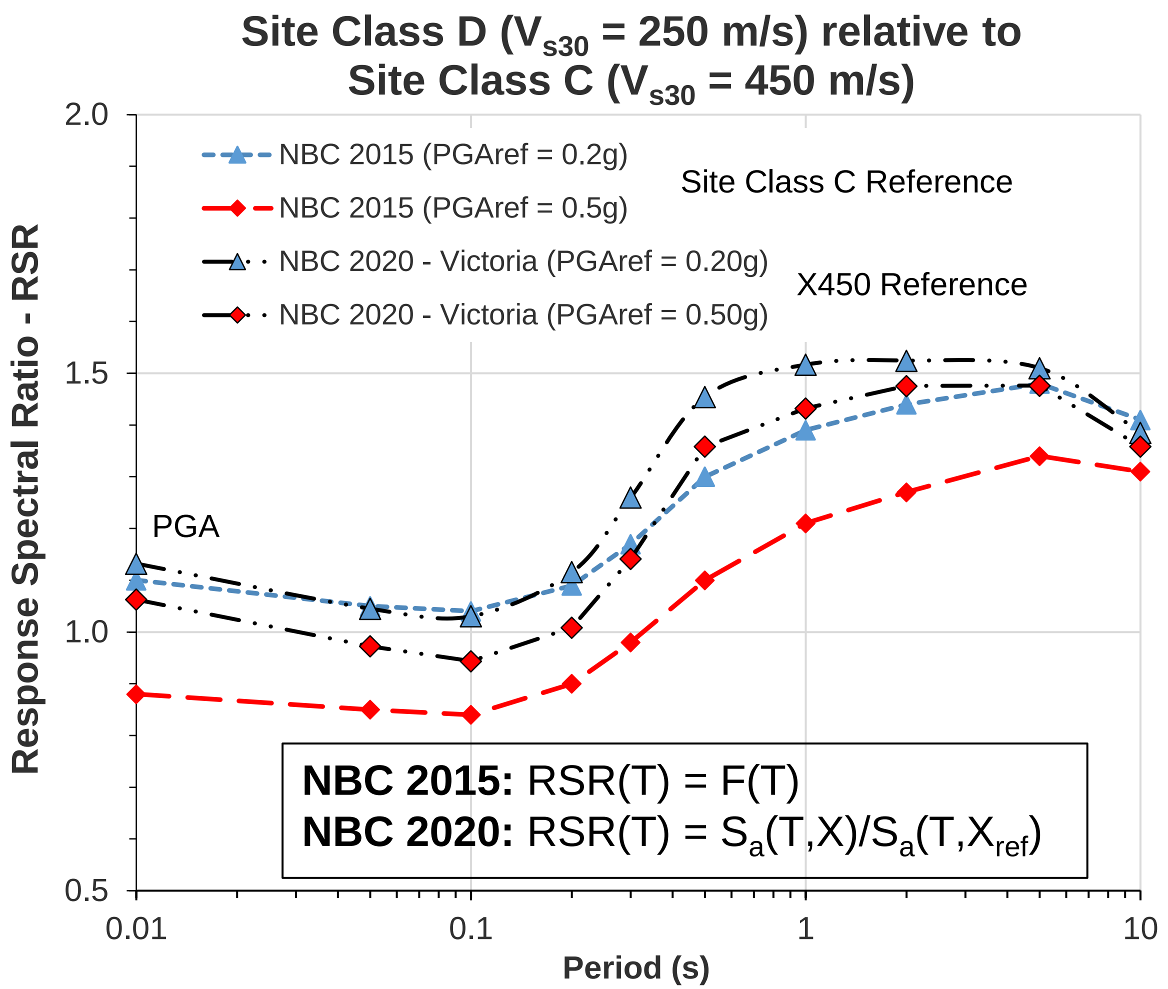
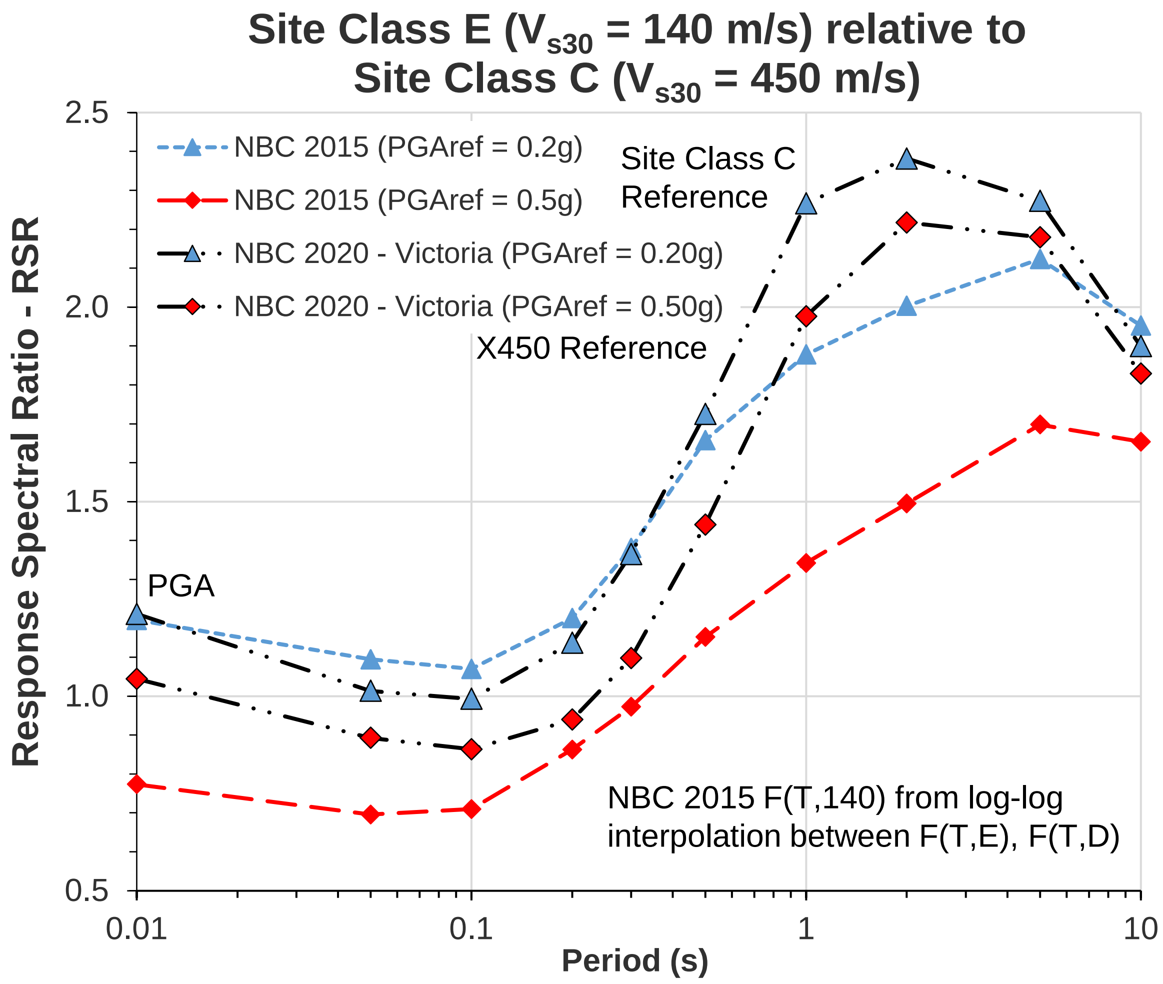
NBC 2020 vs NBC 2015 Amplification





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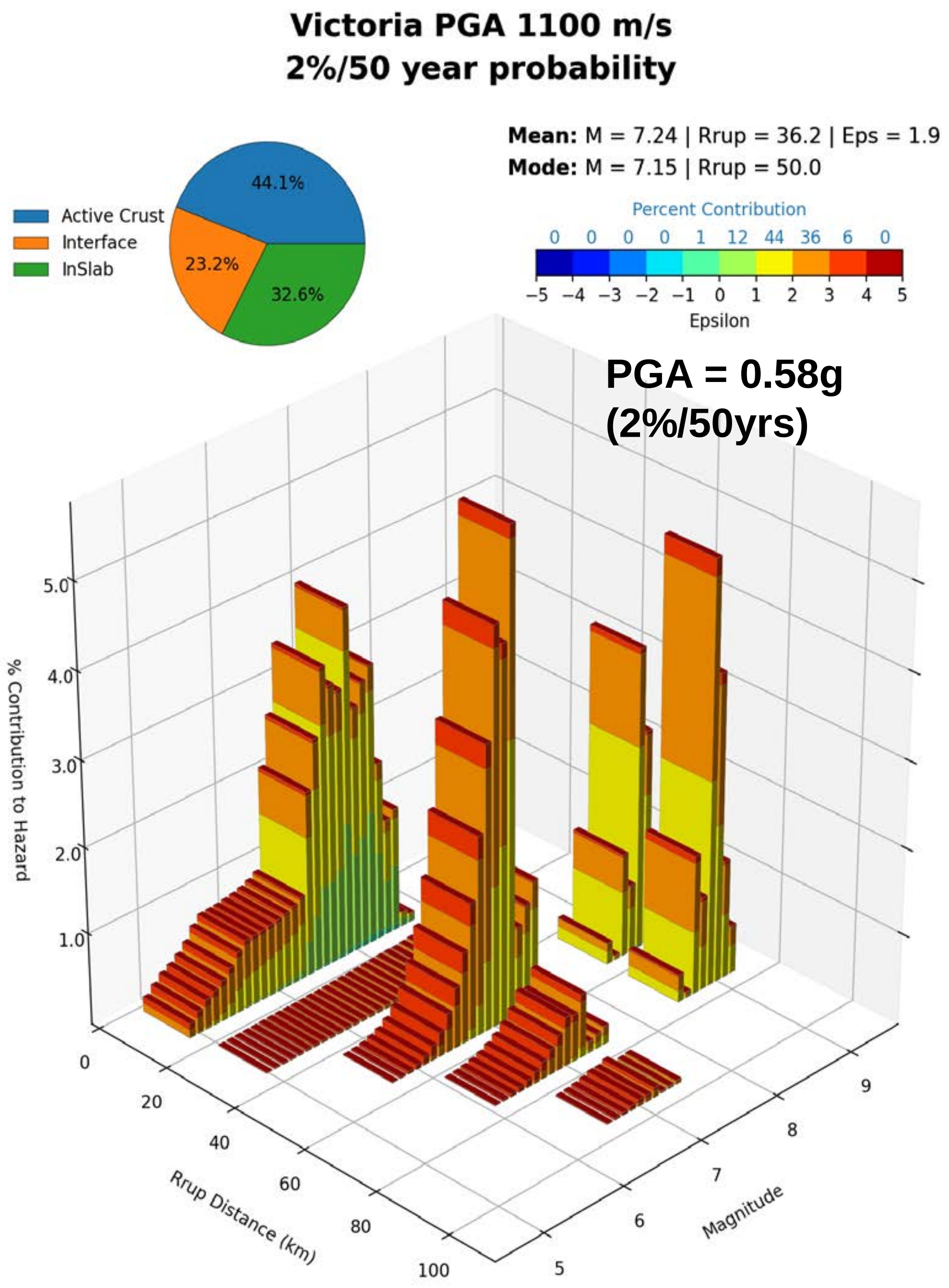
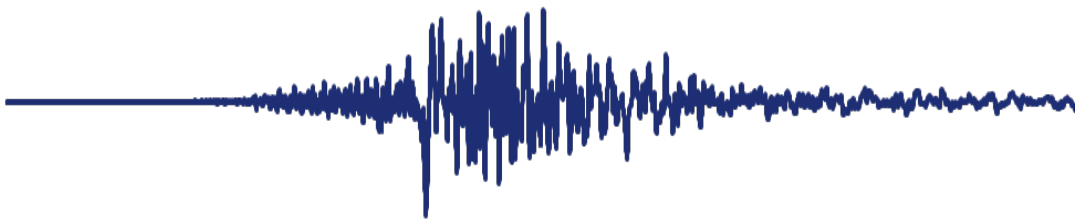
SHMC-6 Deaggregation

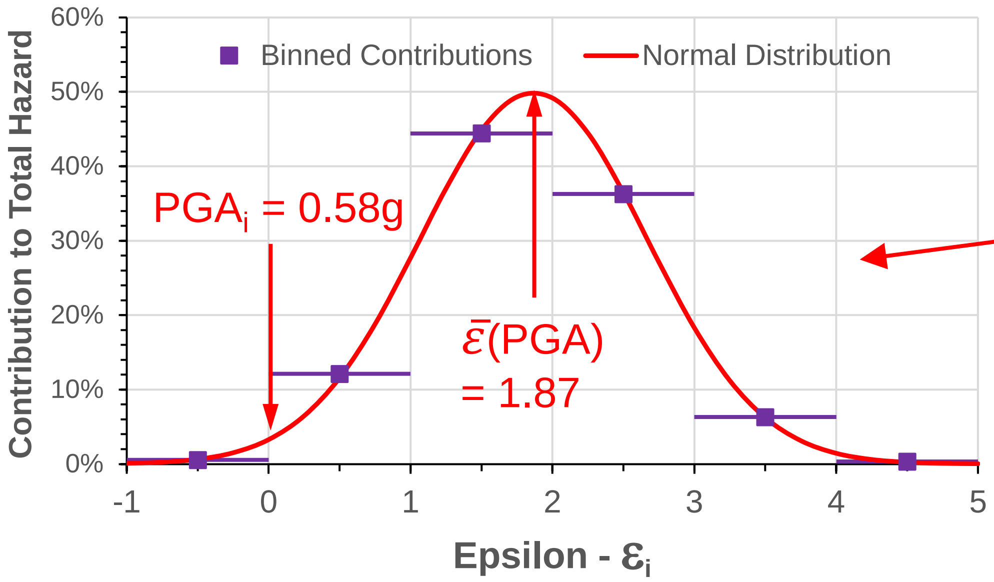
- Deaggregation data from OpenQuake provides c_i for each M_i, R_i bin which are now proportioned according to "epsilon"
- Epsilon (ε) is a measure of the number of standard deviations (in log units), σ, between the natural log of the probabilistic total hazard value at the design hazard level, $\ln(X)$, and the mean (μ_i) of $\ln(x_i)$ for event scenario i having M_i, R_i

  i.e. $\mathbf{\ln(X) = \mu_i + \varepsilon_i \cdot \sigma}$
- $\mu_i = \ln(\text{med\_}x_i)$, where med_$x_i$ is the <u>median</u> of the log-normal distribution of x_i – i.e. med_$x = e^{\mu}$
- σ is a measure of the aleatoric uncertainty in GMM's prediction of μ_i which is attributed to event-to-event and site-to-site variability

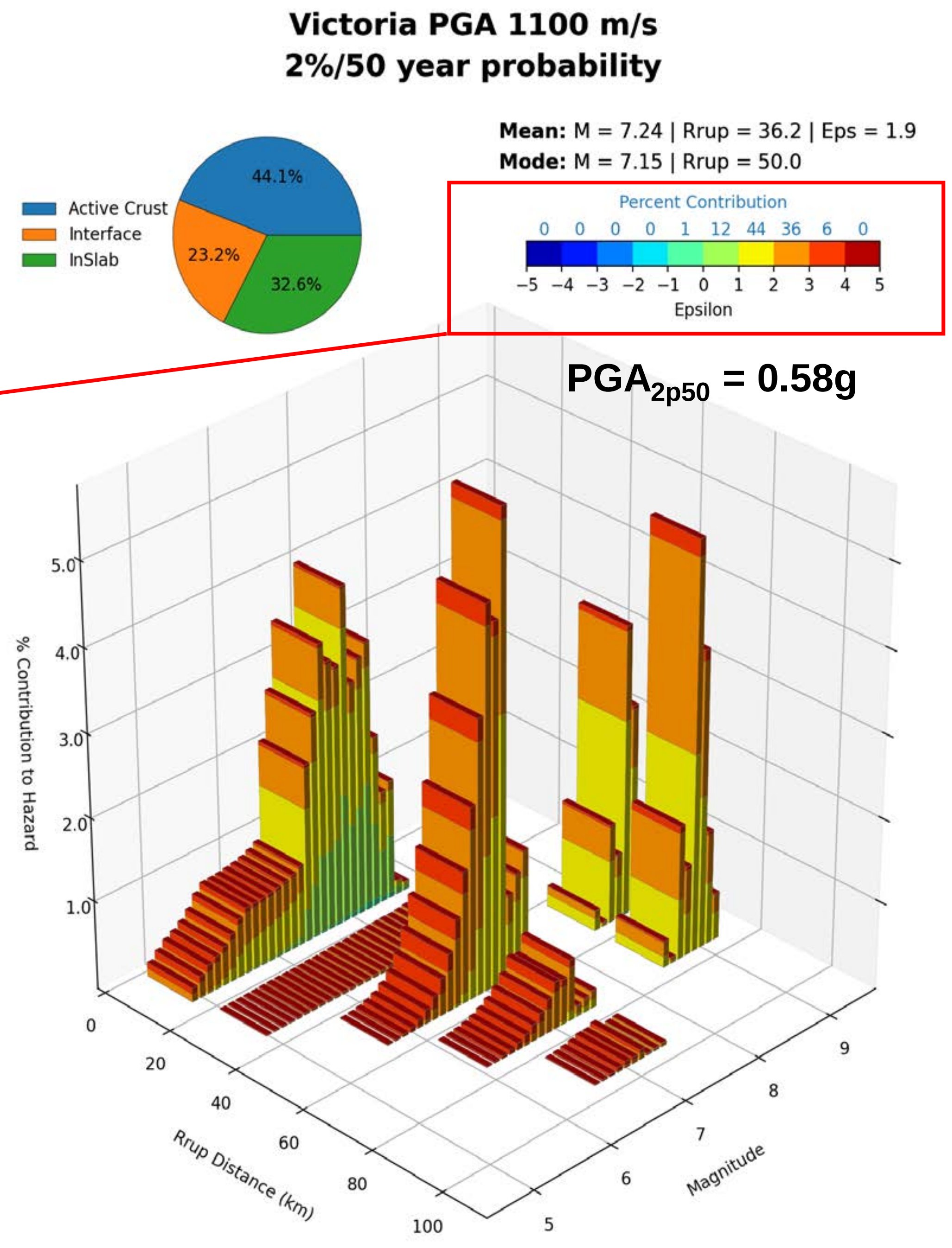




ε_i & $\bar{\varepsilon}$ from Deaggregation



Tectonic Regime	Contribution	$\bar{\varepsilon}$(PGA)
Crustal	44%	1.51
In-Slab	33%	2.29
Interface	23%	1.96



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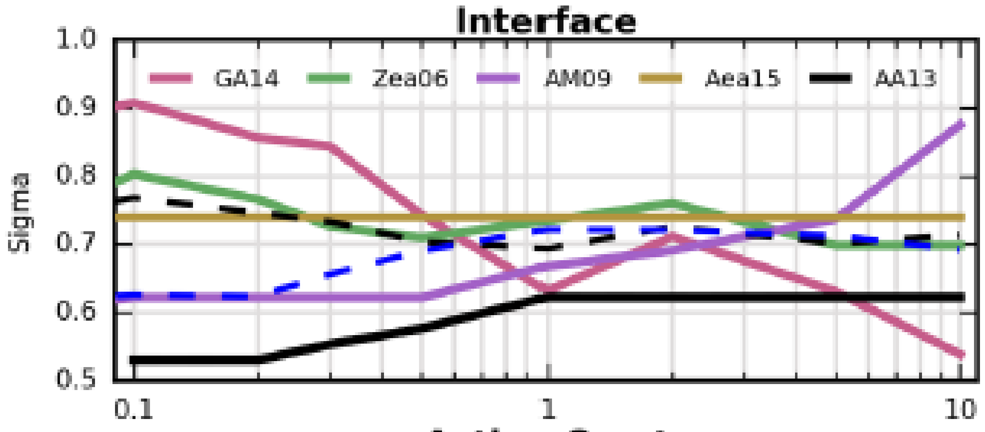
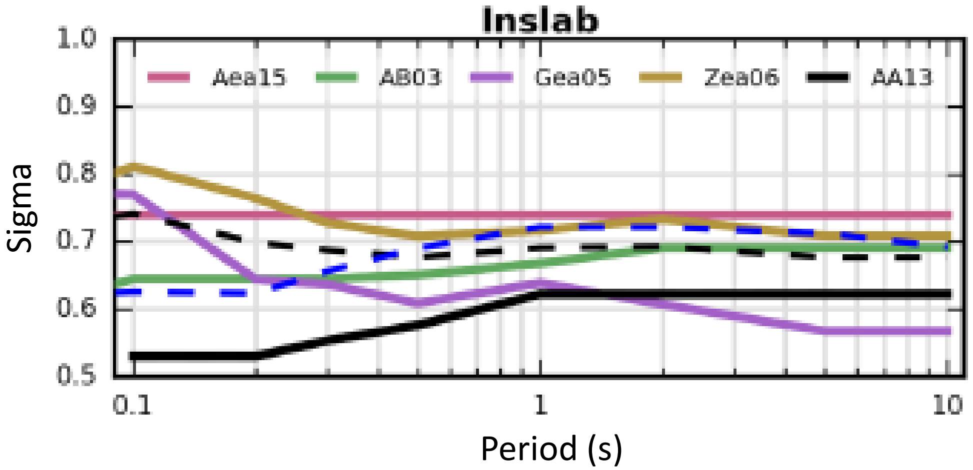
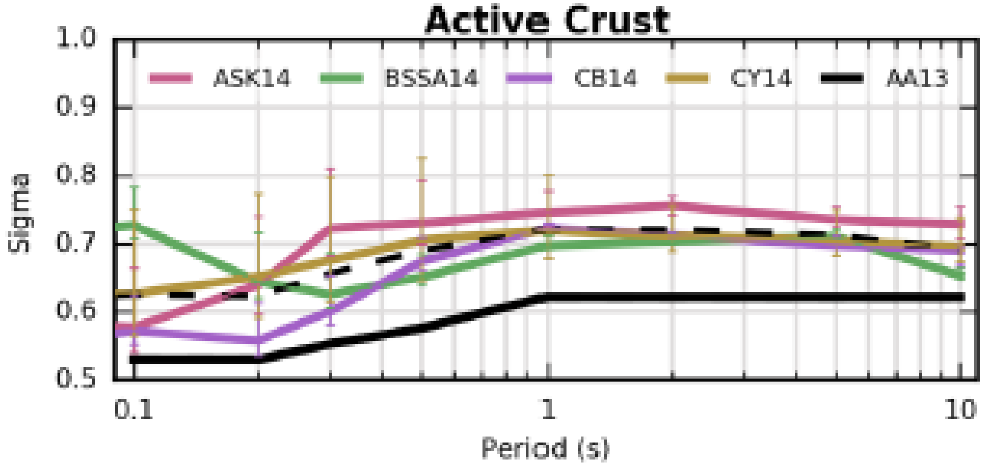
SHMC-6 GMM Sigma Values - σ(*x*)

Tectonic Regime	$\overline{\sigma}$(PGA)
Crustal	0.590
In-Slab	0.676
Interface	0.692

Source: Earthquake Engineering Research Facility, UBC







Source: Kolaj et al. (2019). "Ground-motion models for the 6th Generation Seismic Hazard Model of Canada"

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Median X from $\bar{\varepsilon}(x)$ and $\bar{\sigma}(x)$

$$\ln(\text{med\_PGA}) = \mu = \ln(\text{PGA}_{2p50}) - \bar{\varepsilon}(\text{PGA}) \cdot \bar{\sigma}(\text{PGA})$$

From deaggregation of PGA = 0.580g at 2%/50-years (V_{s30} = 1100 m/s):

Tectonic Regime	Contribution	$\bar{\varepsilon}$(PGA)	$\bar{\sigma}$(PGA)	Median PGA (g)
Crustal	44%	1.51	0.590	0.240
In-Slab	33%	2.29	0.676	0.125
Interface	23%	1.96	0.692	0.150
Total Hazard	100%	1.87	0.642	0.175

μ_{total} = ln(0.175) = -1.74

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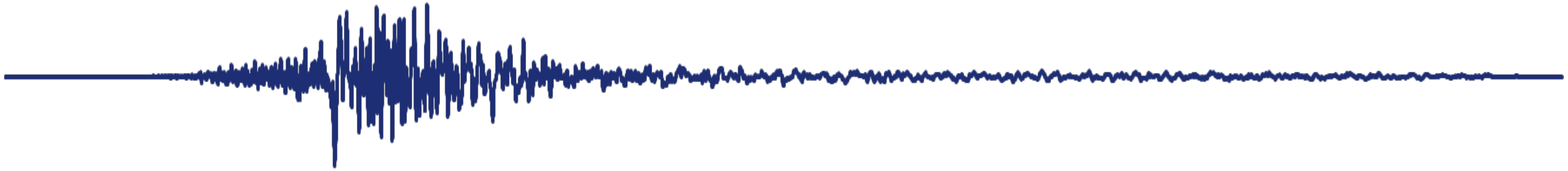
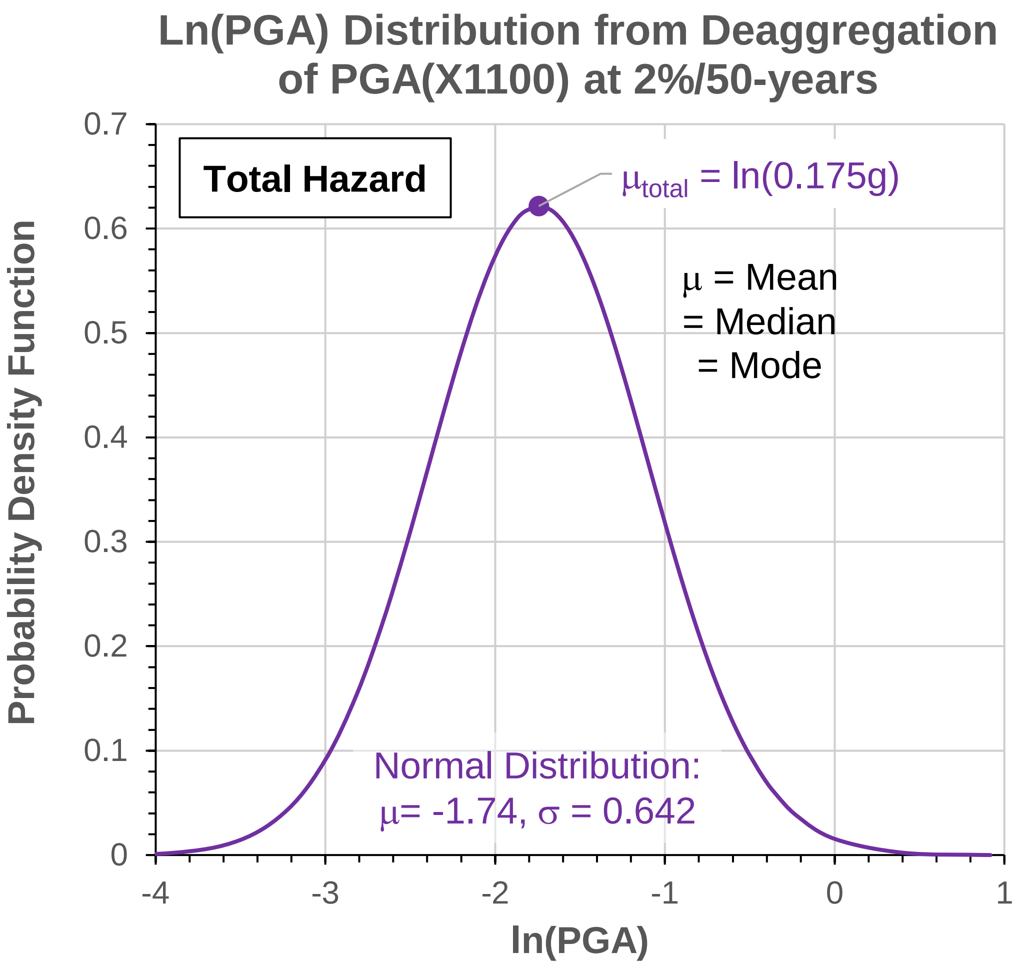
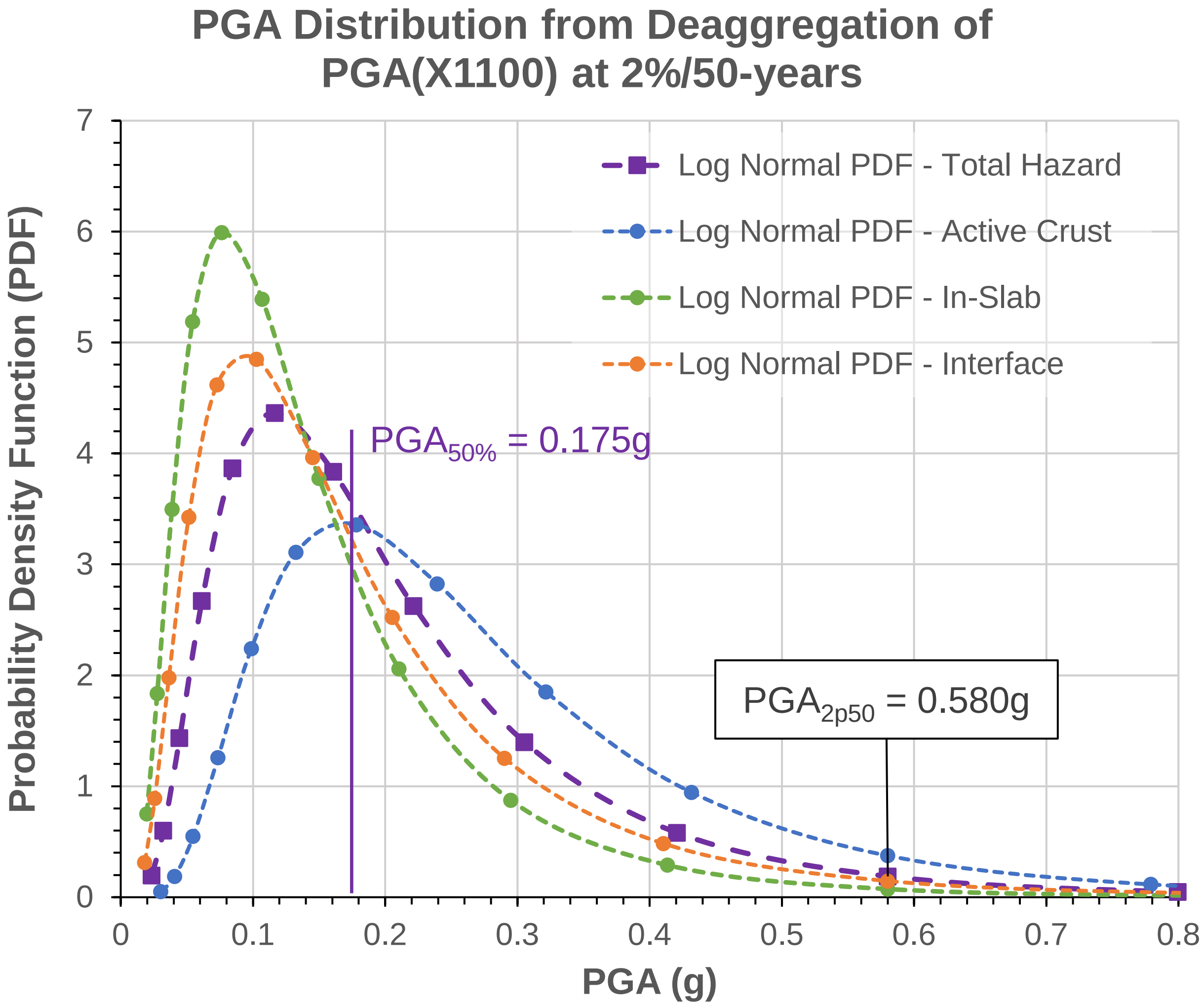


Probability Distribution of *X* from ε Distribution





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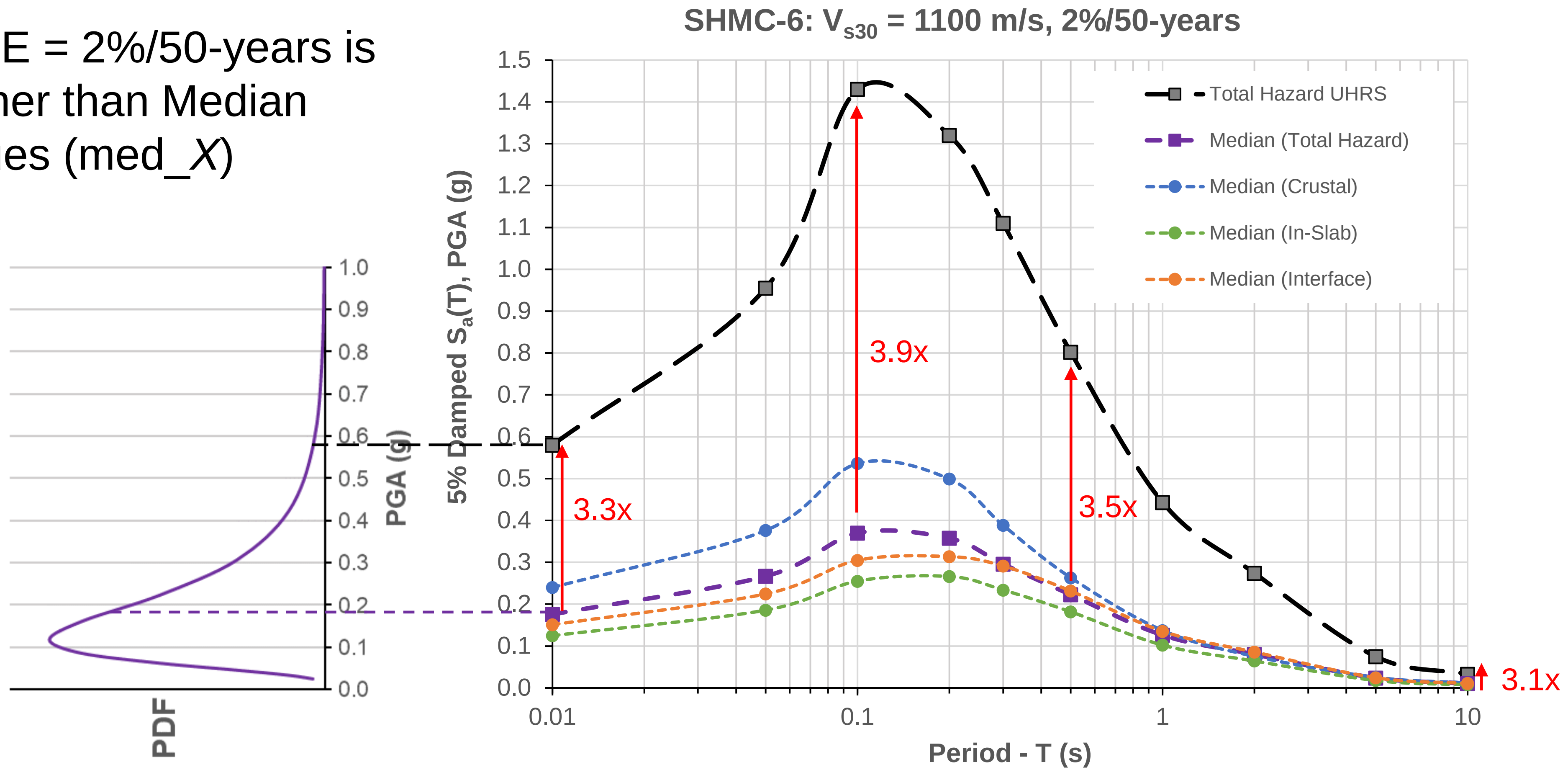
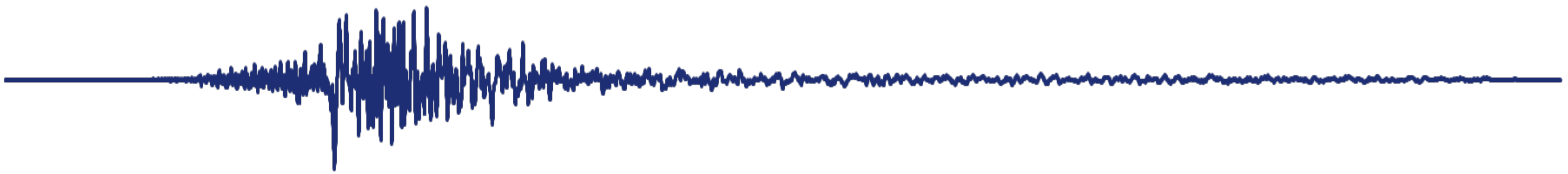
Median Response Spectrum vs UHRS

- UHRS at PoE = 2%/50-years is 3x to 4x higher than Median Hazard Values (med_*X*)





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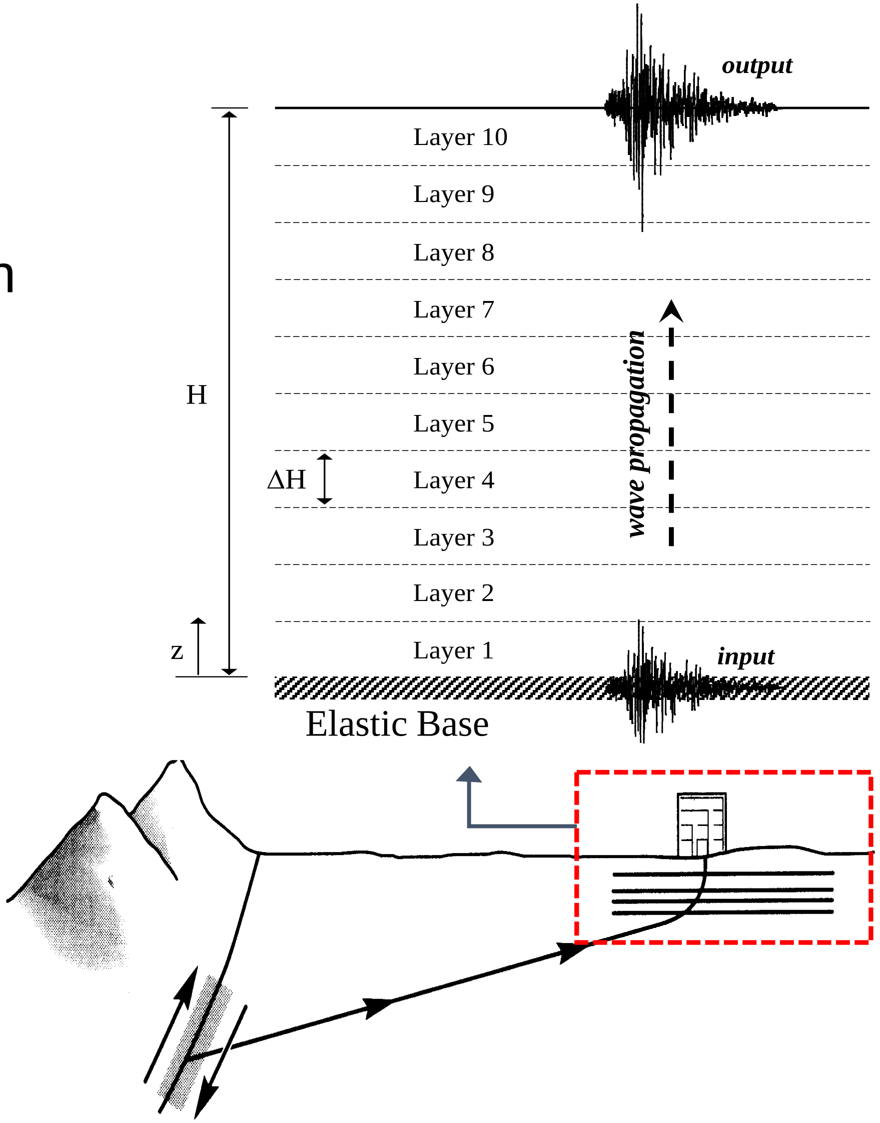
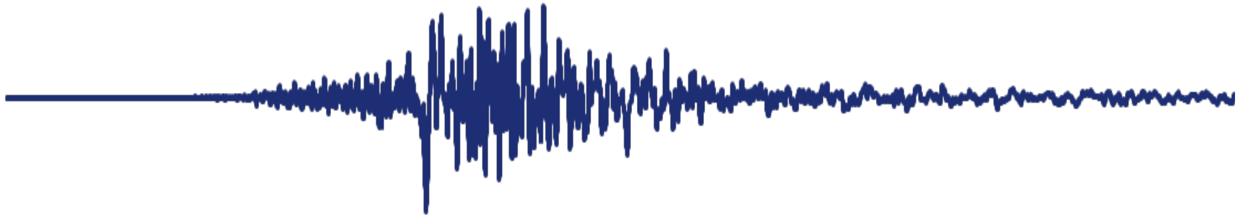
Seismic Site Response Analysis (SSRA)

- Models the response of a multi-layered soil profile to the upward propagation of horizontal shear waves during an earthquake – i.e. an <u>individual event response</u>
- Multiple analyses are run on suite(s) of horizontal acceleration time histories
- Acceleration time histories, a(t), are scaled and/or matched to a target response spectrum for a reference ground condition that represents the conditions within a basal layer that behaves as an elastic material (ideally bedrock)
- Intensity and frequency content of the ground motions altered by dynamic soil properties that vary with shear strain (γ):
  - o Shear stiffness (G) decreases with increasing γ
  - o Hysteretic Damping (D) increases with increasing γ





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Calculating UHRS from SSRA (NBC 2015)

Typical Practice:

1. Scale and/or spectrally match individual event time histories to a probabilistic target UHRS of reference ground condition corresponding to <u>aggregated hazard</u> at design hazard level
2. Conduct deterministic SSRA to generate a suite of amplified response spectra
3. Use mean of amplified $S_a(T)$ for structural design
   - Amplified $S_a(T)$ at any T is depends on how well input $S_a(T)$ matches target $UHRS_{ref}$ at T
   - Amplification effects depend on non-linear soil behaviour; non-linearity increases with increasing shear strain; large shear strains induced by very high <u>aggregated hazard</u> values

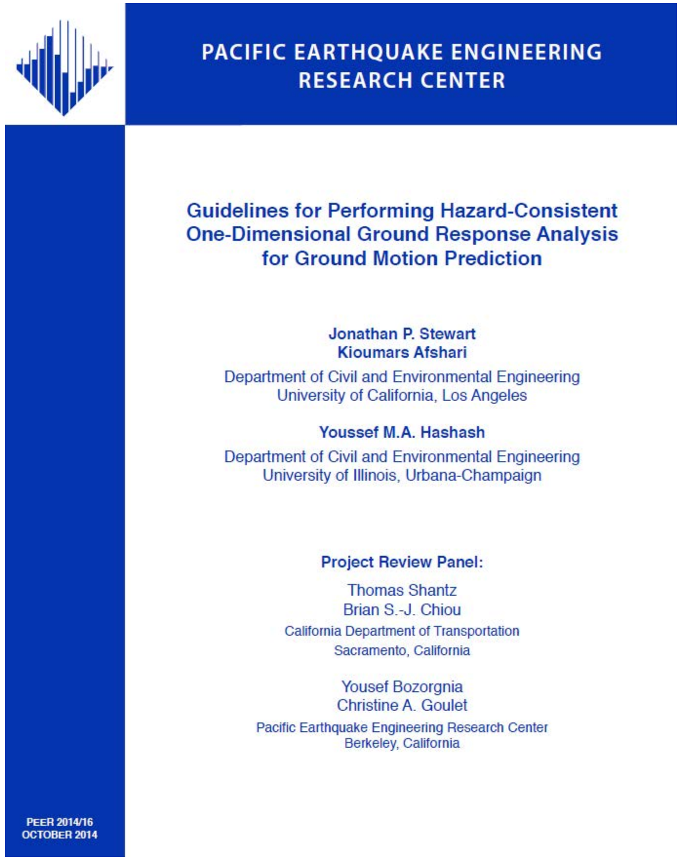
Apply Amplification Function Using "Hybrid Method" (Stewart et al., 2014)

1. & 2. Same as above

3. For each time history, calculate $F(T) = S_a(T)_{out}/S_a(T)_{in}$
4. Amplified $S_a(T)$ = Mean F(T) x Target $UHRS_{ref}$
   - Consistent with F(T) approach in NBC 2015
   - Non-linear amplification effects based on intensity of input motions scaled to target UHRS of <u>aggregated hazard</u> at design hazard level

NBC 2020-Consistent SSRA

- **Pilot Study** conducted by Thurber Engineering and the Earthquake Engineering Research Facility (UBC), peer review by Golder-WSP, funding by EGBC
- **Purpose:** To investigate how SSRA can be implemented within NBC 2020 framework for structural analysis of seismic retrofits for BC schools in accordance with the Seismic Retrofit Guidelines, 2020 Ed.
- **Objectives:**
  - To incorporate SSRA results directly within SHMC-6 allowing probabilistic computation of amplified UHRS – **Rigorous Method**
  - Compare amplified UHRS from rigorous method to **Simplified Methods** of calculating UHRS using SSRA results: *"Hybrid Method"* and *"Modified Hybrid Method"* described by Stewart et al. (2014)


PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Guidelines for Performing Hazard-Consistent One-Dimensional Ground Response Analysis for Ground Motion Prediction

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PEER 2014/16
OCTOBER 2014

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NBC 2020-Consistent SSRA:
Pilot Study on SSRA in SRG 2020

Acknowledgments

- Thurber: McKenzie Douglas, Paul Wilson
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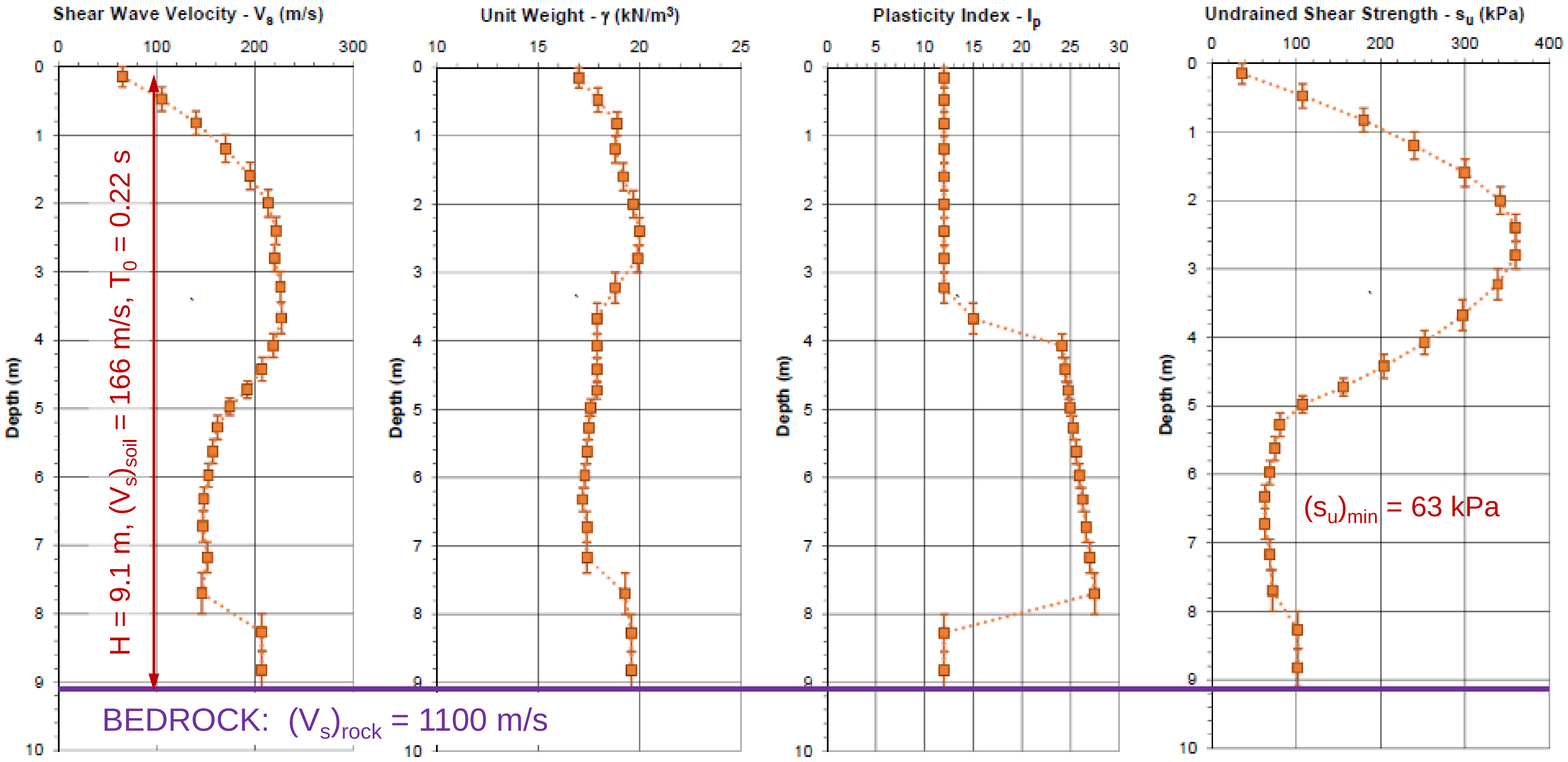
- Golder-WSP: Roberto Olivera
- Engineers & Geoscientists BC: Peter Mitchell
- Natural Resources Canada: Michal Kolaj, Stephen Halchuk
- Graham Taylor (TBG Seismic Consultants)
- Tuna Onur (Onur Seemann Consulting)

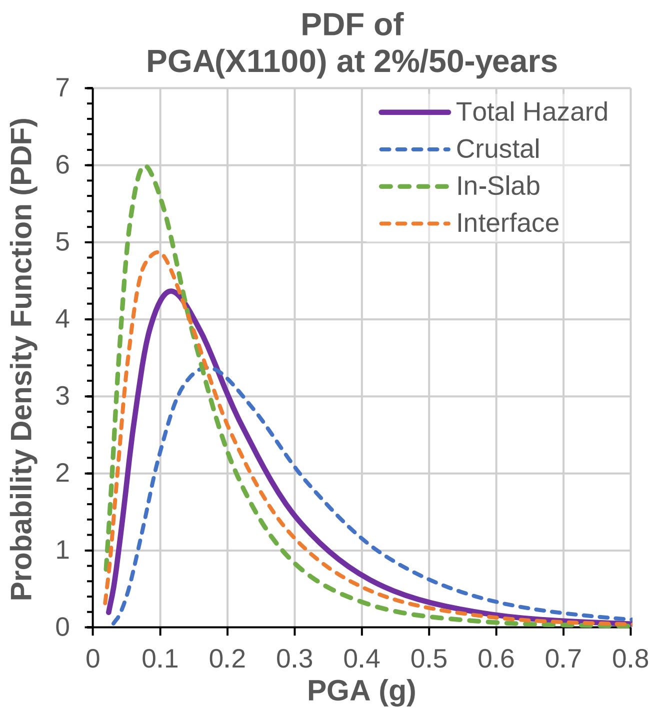
Test Site: Legislative Assembly of BC, Victoria



Calculating UHRS from SSRA (NBC 2020)

Rigorous Method Implemented in SSRA Pilot Study:

1. Scale earthquake acceleration time histories to various PGA_{ref} corresponding to the range of median PGA_{ref} for <u>individual event scenarios</u> within the hazard model
2. Conduct deterministic SSRA to generate suites of $F(T,PGA_{ref})$ for each Tectonic Regime Type (TRT)
3. Replace site terms in the GMMs with lookup tables of mean $F(T,PGA_{ref})$ for each tectonic source
4. Hazard model computes amplified $S_a(T)$ for <u>each event scenario</u> as a function of $F(T,PGA_{ref})$ and the GMM-predicted <u>median</u> PGA_{ref}, then probabilistically aggregates the amplified $S_a(T)$ to generate hazard curves for each T
5. Construct the UHRS at hazard level of interest using the hazard curves



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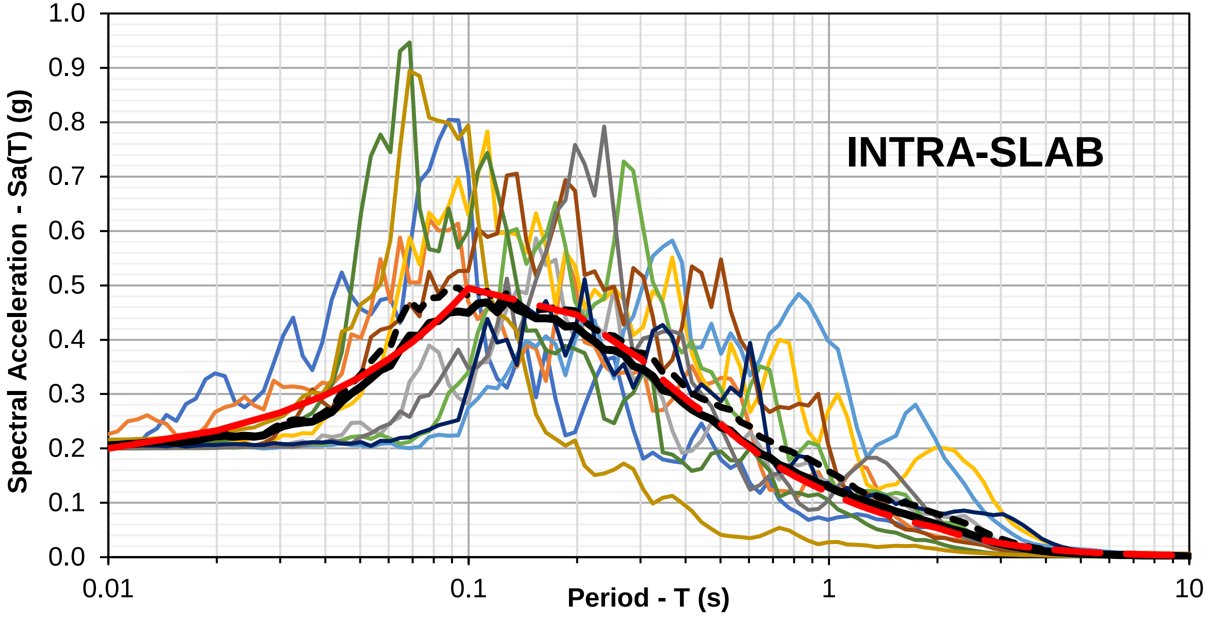
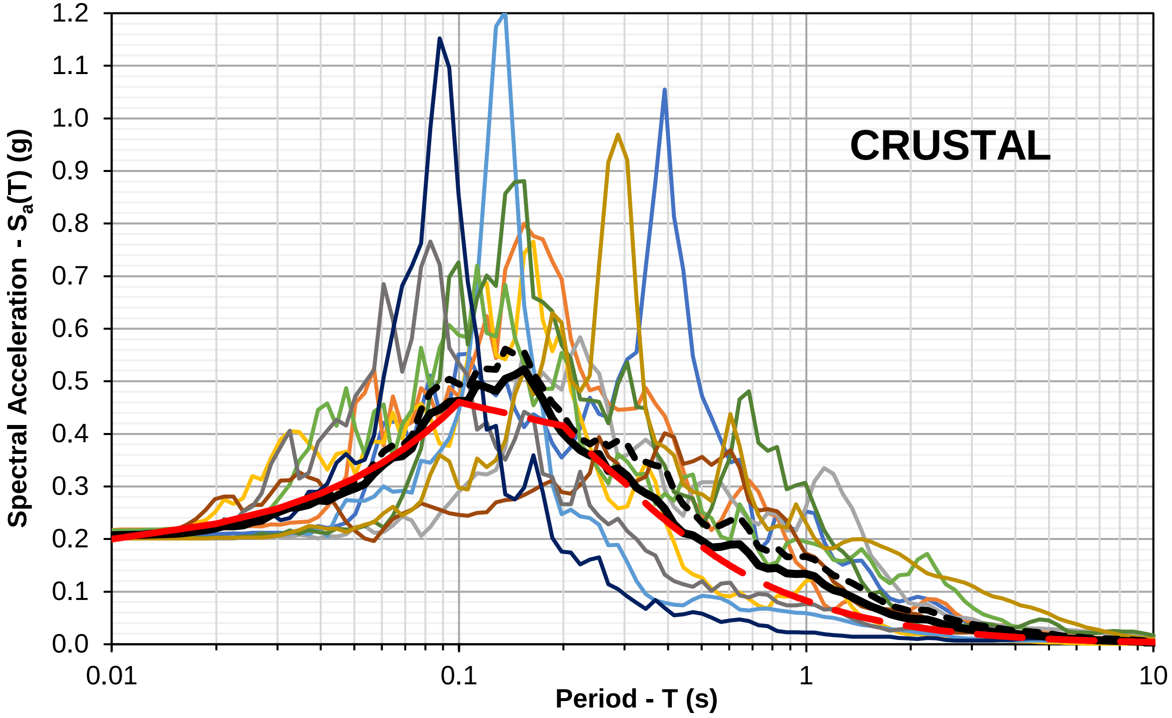
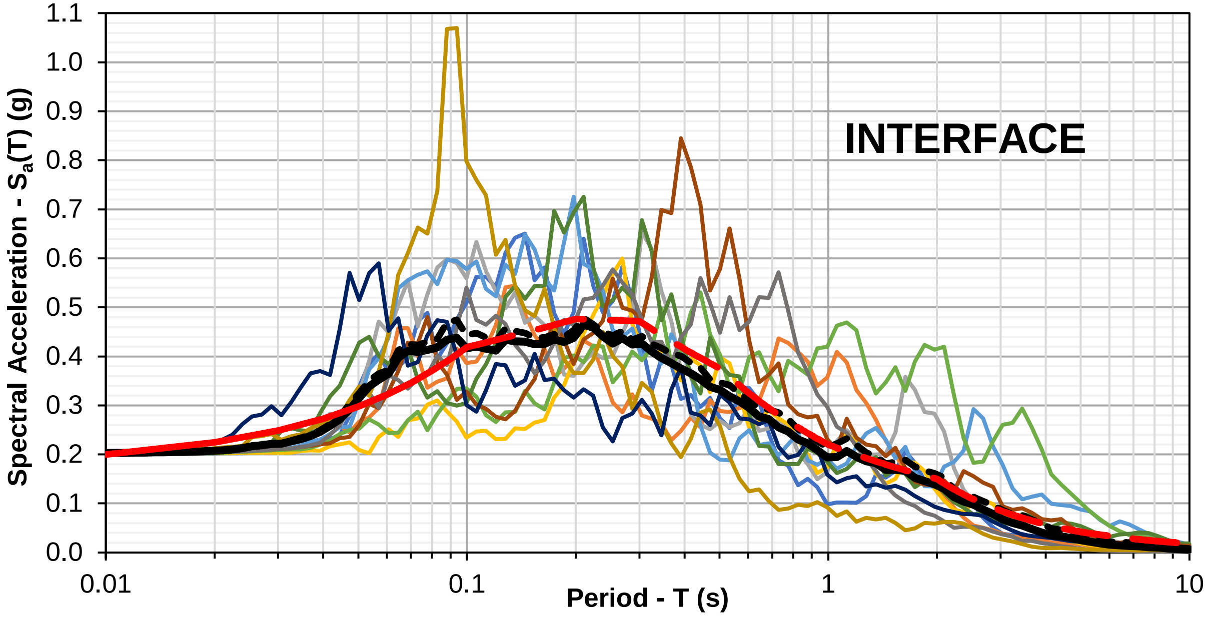
Input Response Spectra (Ref V_{s30} = 1100 m/s)

- Target Response Spectra: 2%/50yrs UHRS for each TRT from SHMC-6:
  Crustal, Intra-Slab, Interface
- Suites of 11 EQ records for each TRT selected by UBC scaling for best fit of $S_a(T)$ geomean to target
- Each suite scaled to multiple intensity levels:
  PGA_{ref} = 0.05g, 0.10g, 0.20g, 0.40g, 0.60g

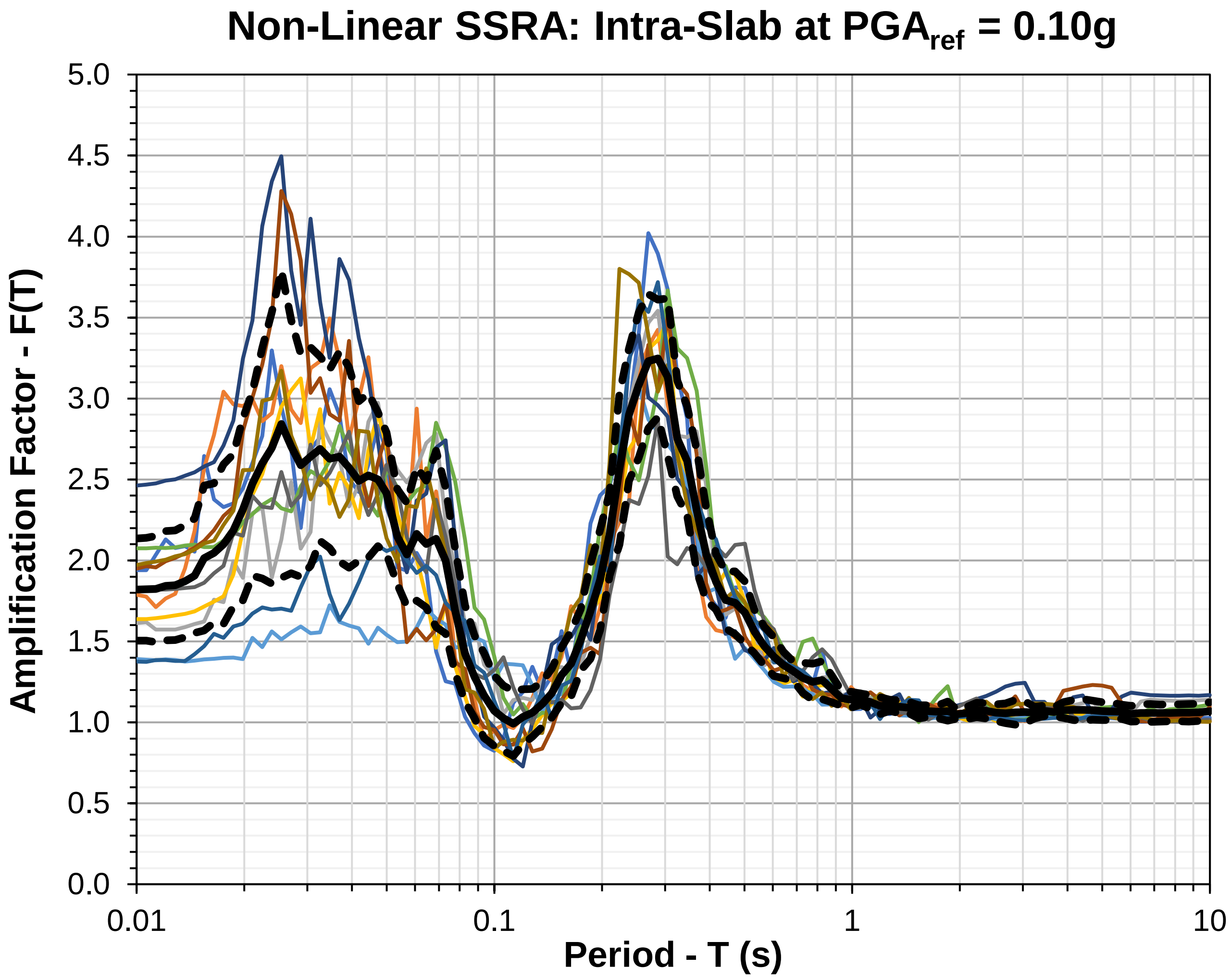


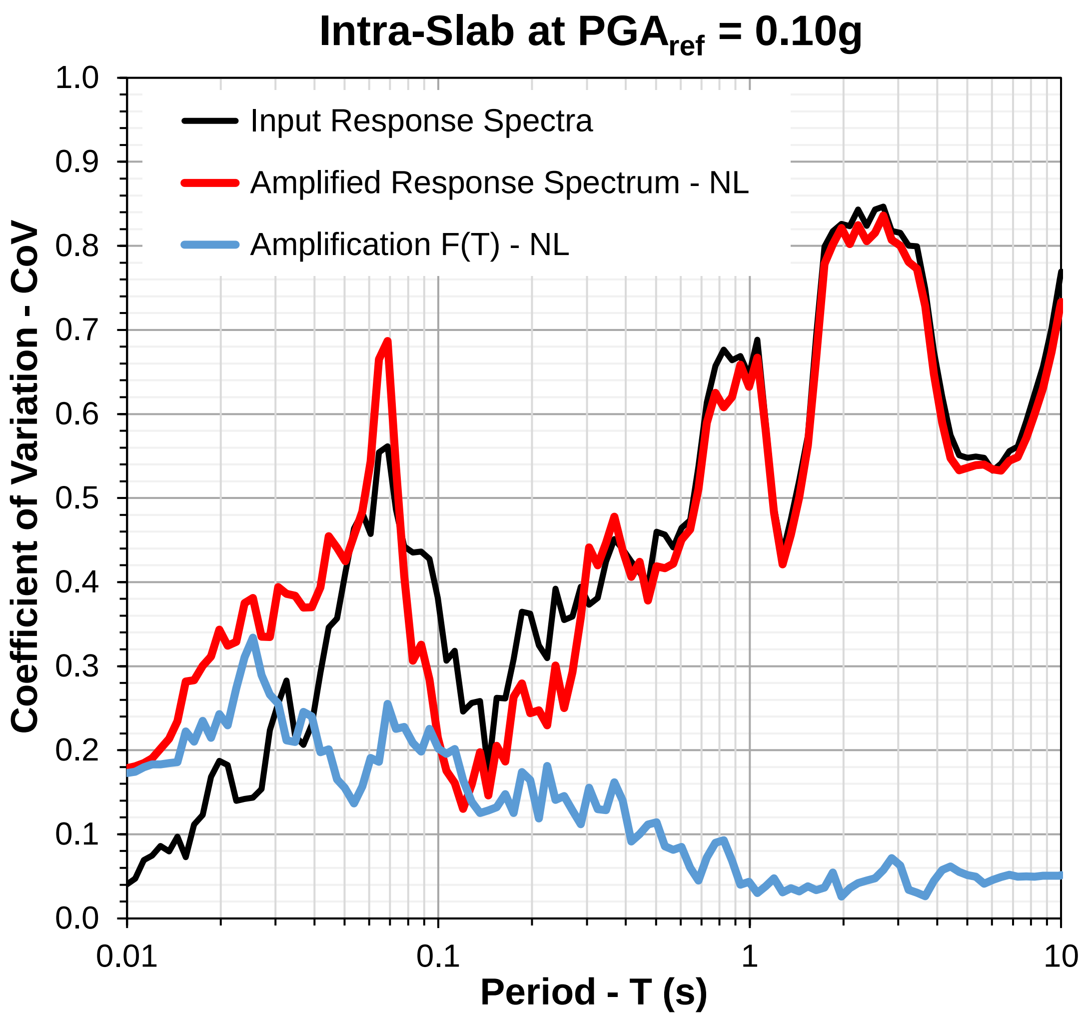




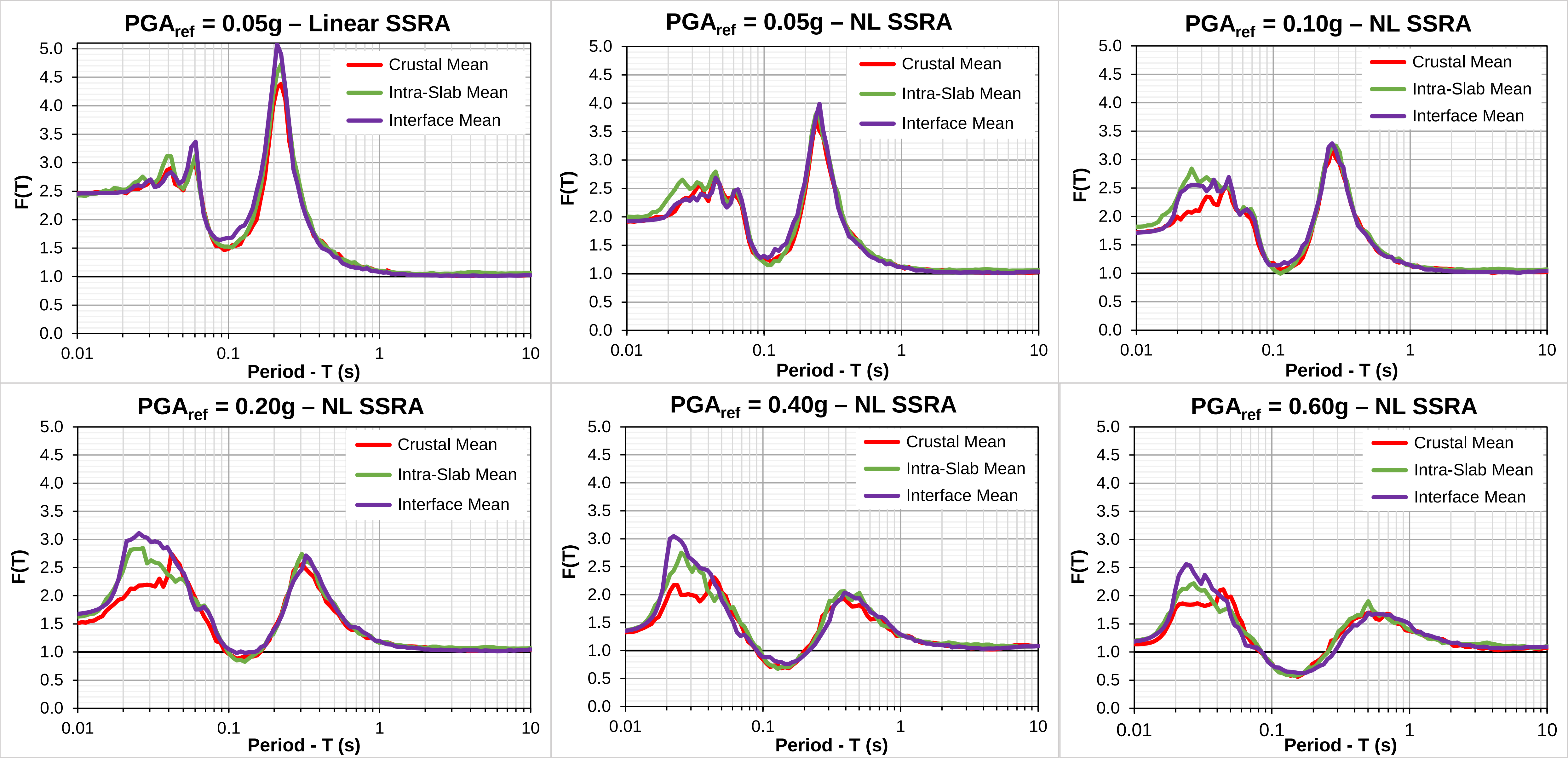
Amplification Function - $F(T,PGA_{ref})$

At each PGA_{ref}, $F(T)_j = S_a(T)_{output}/S_a(T)_{input}$

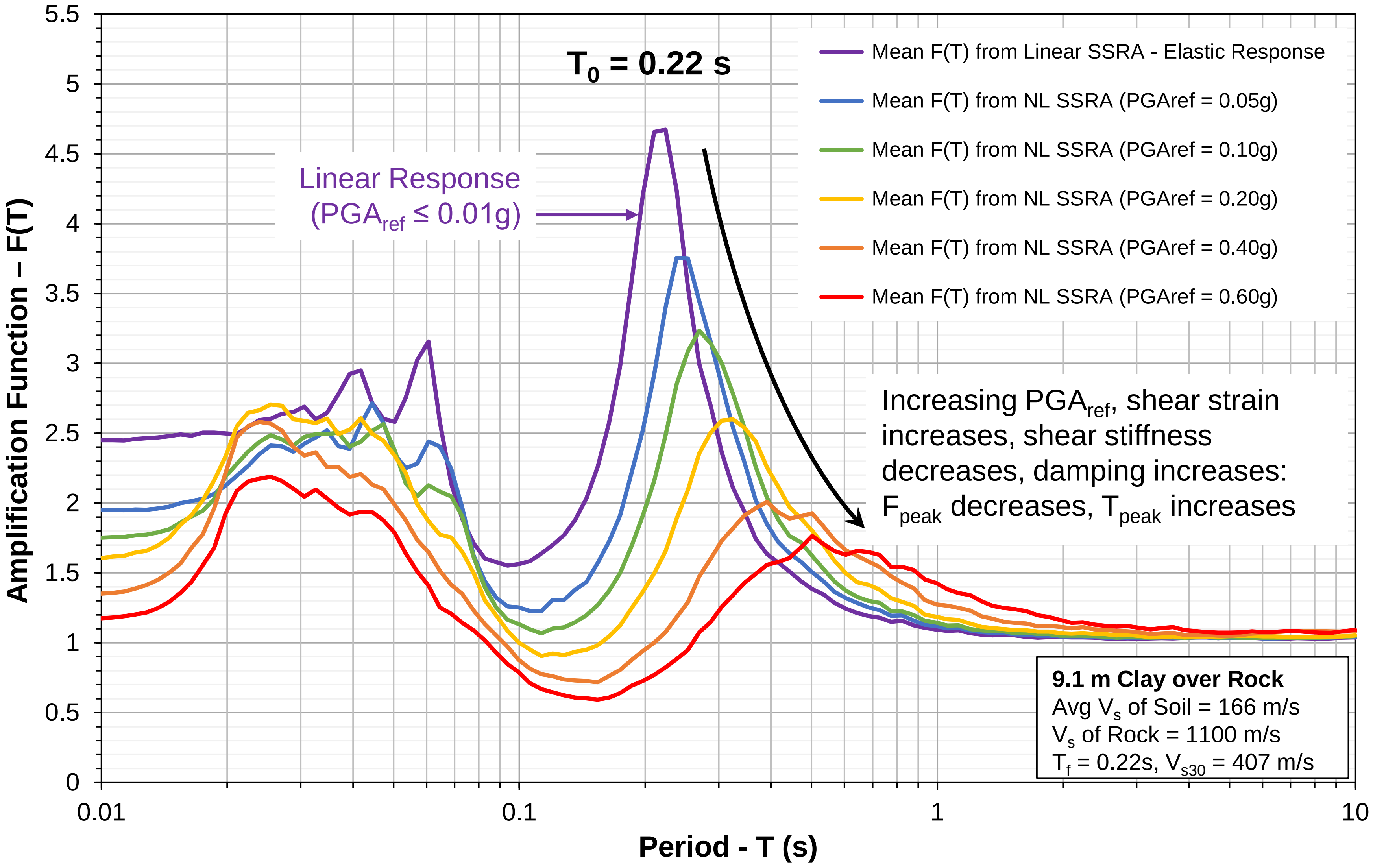




Mean F(T,PGA_{ref}) from SSRA



Mean F(T,PGA_{ref}) from SSRA (All TRT)



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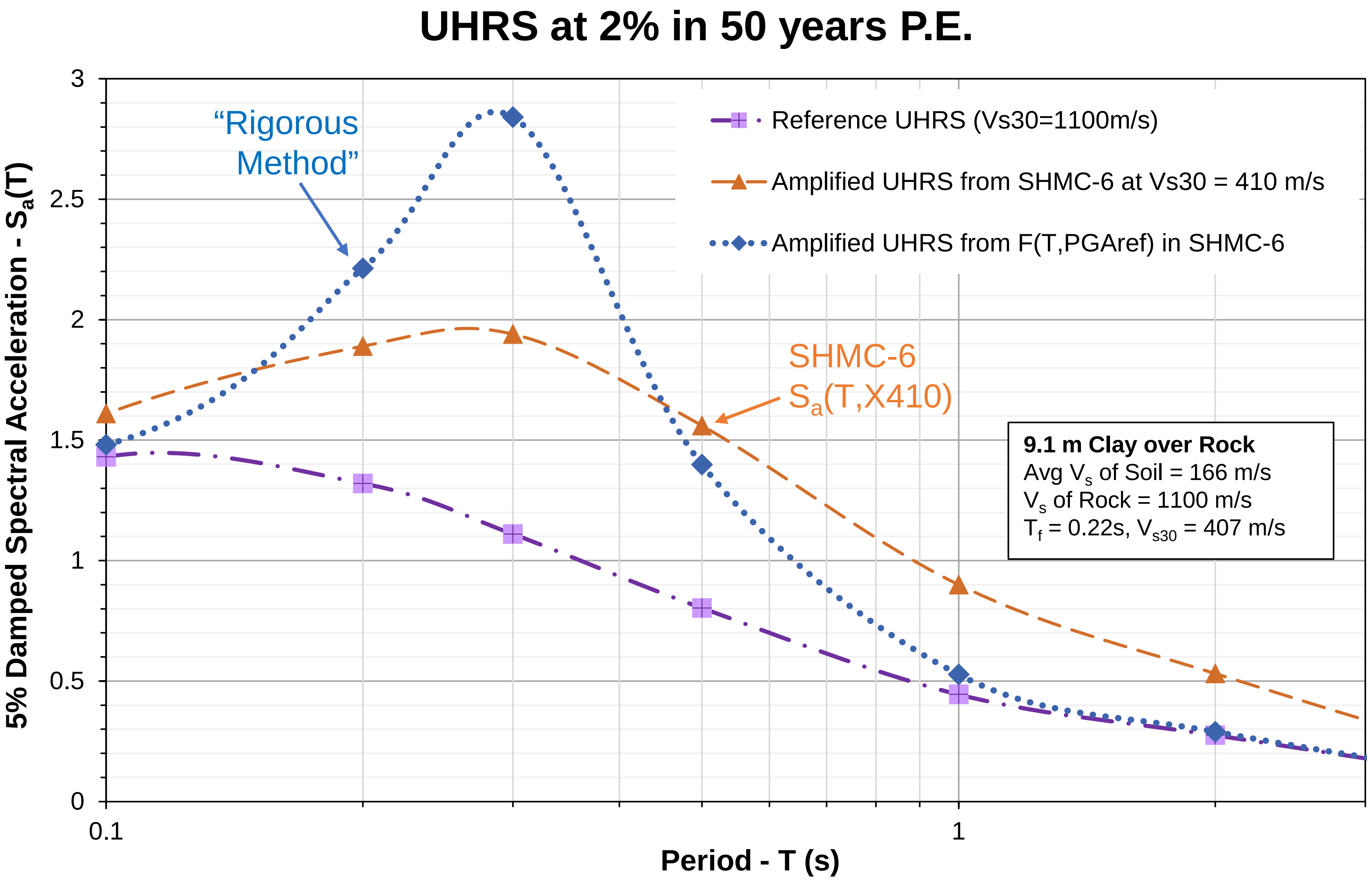
UHRS from $F(T,PGA_{ref})$ in SHMC-6 (Rigorous Method)



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Calculating UHRS from SSRA (NBC 2020)

Simplified Method - “Modified Hybrid” Method (Stewart et al. 2014):

$$\textbf{Amplified } S_a(T) = F(T, Med\_PGA_{ref}) \times UHRS_{ref}$$

- Median PGA_{ref} calculated using mean epsilon ($\bar{\varepsilon}$) from deaggregation of PGA_{ref} at hazard level of interest (e.g. 2%/50-years) and tectonic source-weighted mean sigma ($\bar{\sigma}_{Total}$):

$$\text{eg. } \ln(Med\_PGA_{ref}) = \ln(PGA_{ref\_2p50}) - \bar{\varepsilon}_{2p50} \cdot \bar{\sigma}_{Total}$$

- $F(T, Med\_PGA_{ref})$ calculated from SSRA using time histories scaled so $PGA_j = Med\_PGA_{ref}$

From deaggregation of PGA = 0.580g at 2%/50-years (V_{s30} = 1100 m/s):

Tectonic Regime	Contribution	$\bar{\varepsilon}$(PGA)	$\bar{\sigma}$(PGA)	Median PGA (g)
Crustal	44%	1.51	0.590	0.240
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Total Hazard	**100%**	**1.87**	**0.642**	**0.175**

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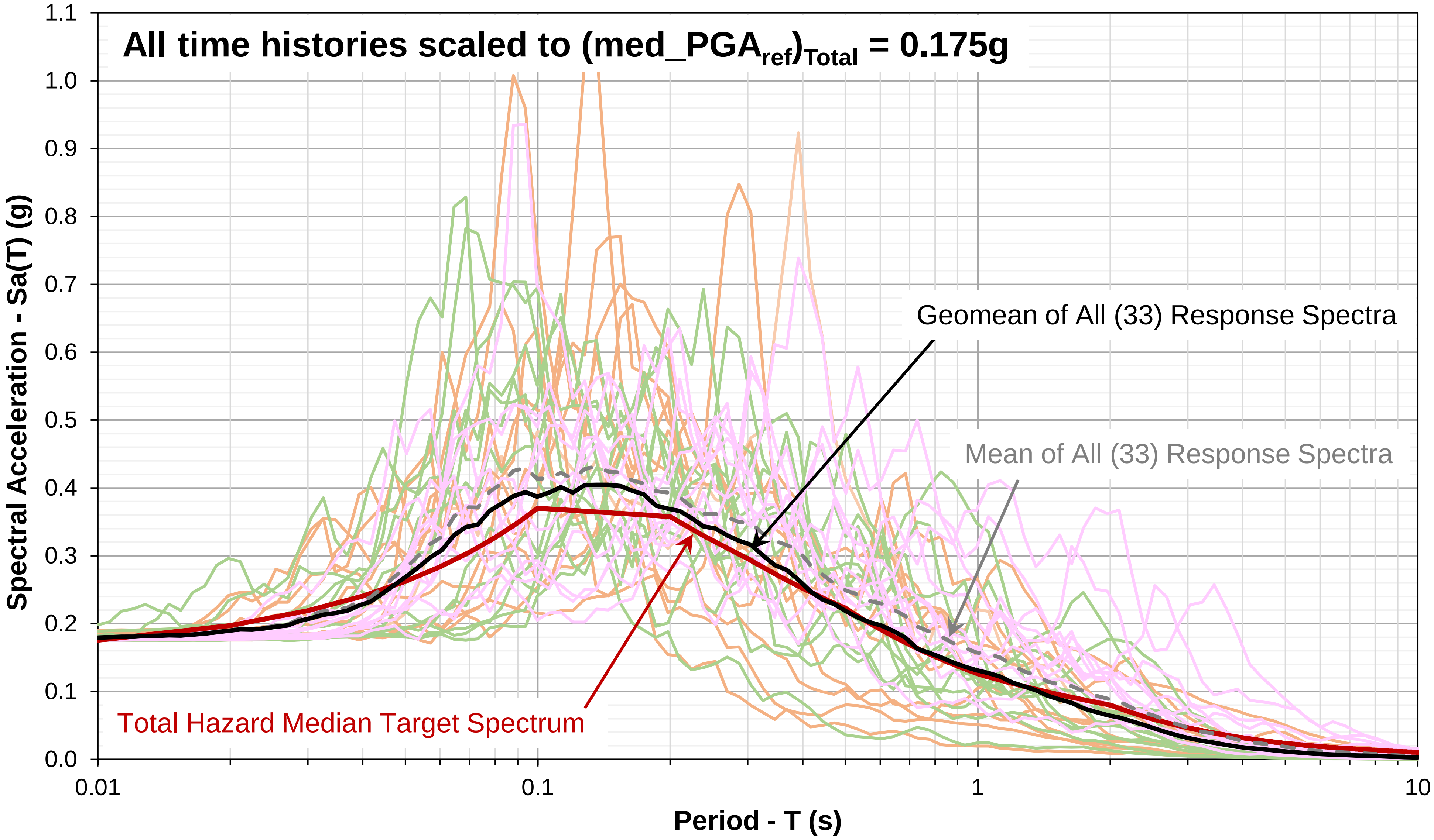
"Modified Hybrid" Method – Input Time History Scaling



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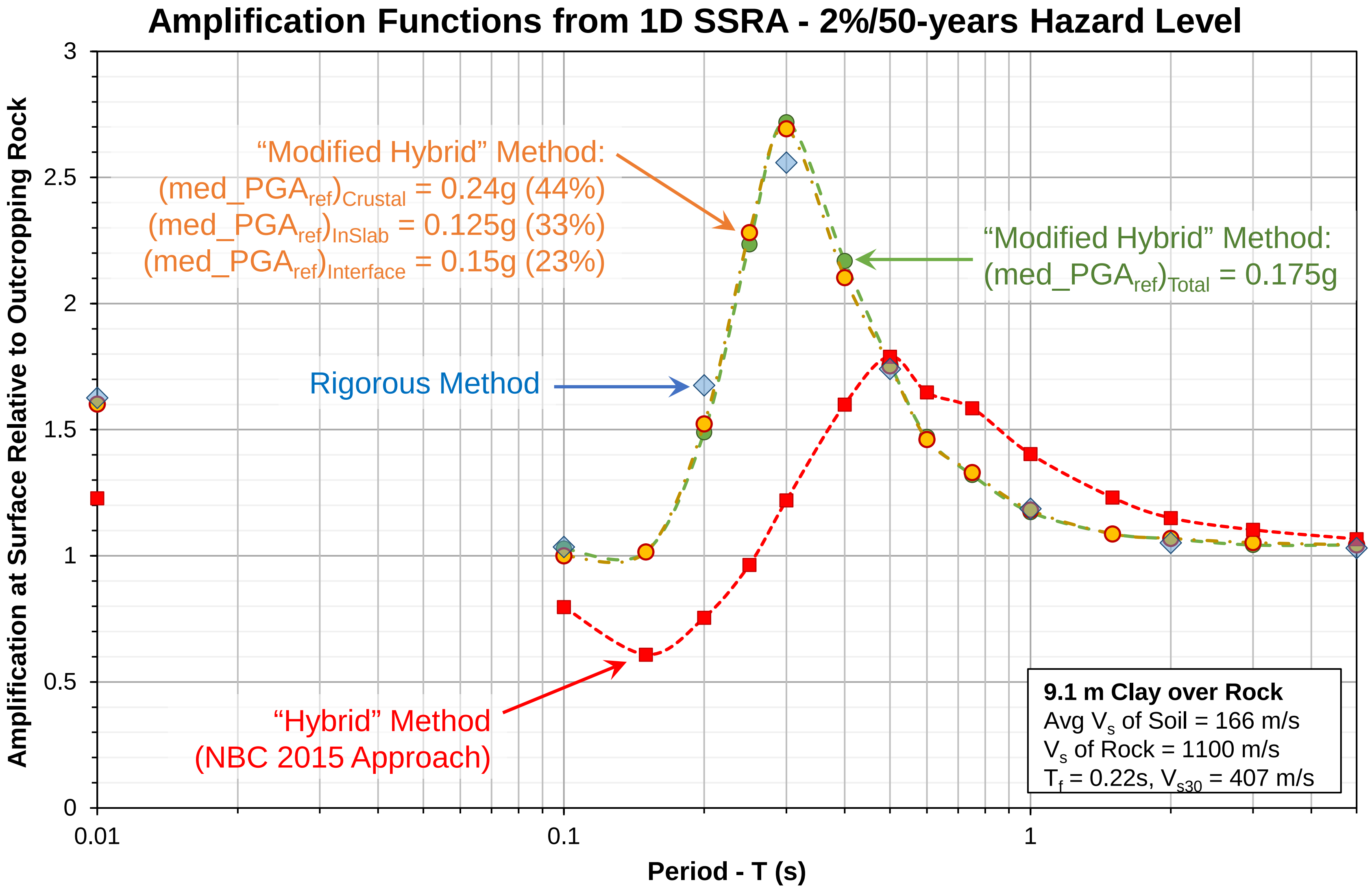
Mean F(T) from Rigorous & Simplified Methods



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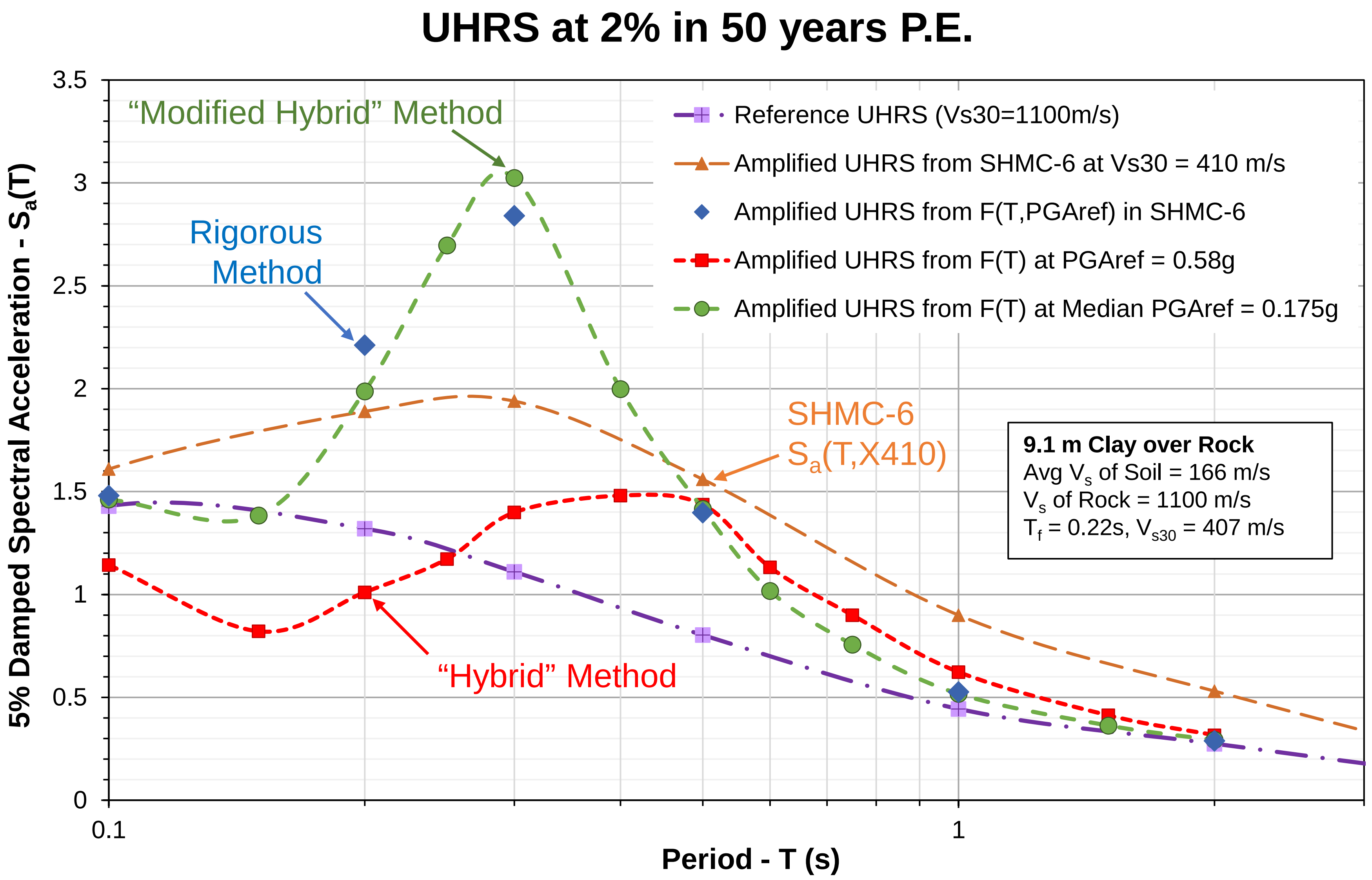
UHRS from Rigorous & Simplified Methods



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Summary - NBC 2020 vs NBC 2015 Amplification

NBC 2015

- $F(T, PGA_{ref})$ for each Site Class provided in the code
- PGA_{ref} (= PGA_C in Western Canada) is the “intensity measure” used to model non-linear response
- PGA_C is a probabilistic hazard value on the aggregated hazard curve
- Since PGA_C >> PGA_i of individual event scenarios, $F(T, PGA_{ref})$ for high PGA_{ref} tends to overpredict non-linearity and damping and so underpredicts non-linear amplification

NBC 2020

- Each GMM uses site terms to estimate amplification of rock ground motion values predicted for individual event scenarios within SHMC-6
- Linear amplification relative to a rock reference condition calculated based on V_{s30} of site
- Non-linear amplification is a function of the median prediction of a short-period intensity measure for the reference condition (typ. PGA_{rock}) at the event scenario level
- Amplified hazard values for each event scenario are probabilistically aggregated

Summary – NBC 2020-Compatible SSRA

1. Reference Ground Condition – assign X_V consistent with elastic basal layer in analysis
2. Median Target Spectrum for reference condition at design hazard level - construct using suite of site-specific deaggregation data for X_v at design hazard level: $\ln(med\_x_{ref}) = \ln(X_{ref}) - \bar{\varepsilon}(x_{ref}) \cdot \bar{\sigma}(x)$
3. Time History Selection – scale TRT-relevant time histories to $(med\_PGA_{ref})_{TRT}$; geomean of suite should be close to target spectrum for each TRT
4. Input Time Histories: i) TRT-specific suite scaled to $(med\_PGA_{ref})_{TRT}$; or ii) All time histories scaled to $(med\_PGA_{ref})_{Total}$
5. Run SSRA and calculate $F(T)_j = S_a(T)_{out}/S_a(T)_{in}$ for each time history
6. Mean Amplification Function: $\bar{F}(T)_{Total} = \Sigma\, c_{TRT} \cdot \bar{F}(T)_{TRT}$, where c_{TRT} is % contribution of each TRT, $\bar{F}(T)_{TRT}$ is mean (conservative) or geomean of all $F(T)_j$ in the TRT-specific suite
7. Amplified UHRS at design hazard level: $S_a(T) = \bar{F}(T)_{Total} \cdot S_a(T)_{ref}$

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Questions?

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