Non-Ergodic Site Response in Seismic Hazard Analysis

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Objectives

Understand differences between non-ergodic and ergodic site response

Present framework for developing site-specific GMPE for use in ground motion hazard analysis

Effects on hazard

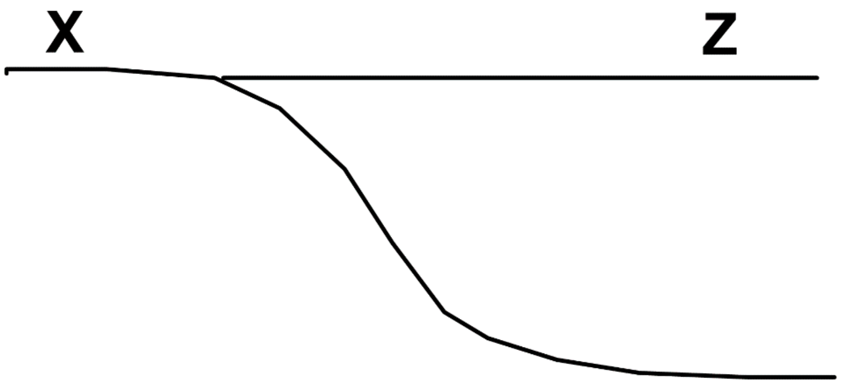
Takes some effort, but tools available … and worth it

Outline

- Ergodic site amplification
- Non-ergodic (location-specific) site amplification
- Implementation in PSHA
- Summary

Notation

- IM = intensity measure
- X = Reference site IM
- Z = soil site IM
- Y = Z / X
  (site amplification)



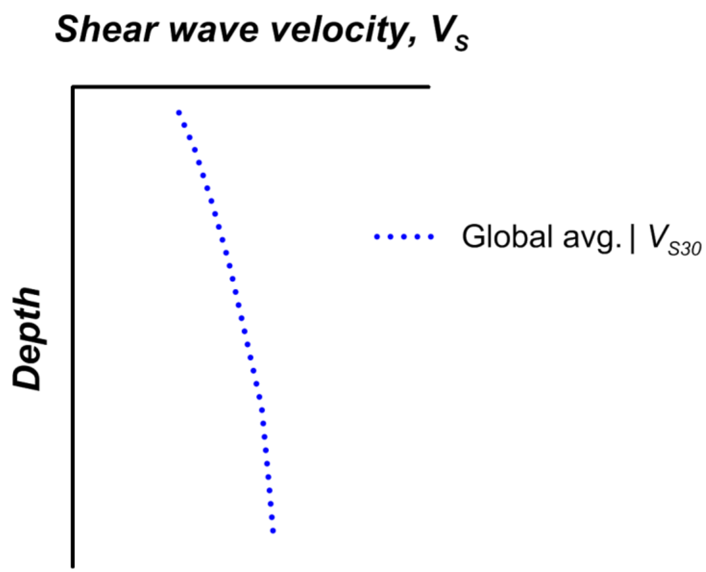
Ergodic Models

- *Ergodic*: Ground motions evaluated from diverse (global) data set
- Examples:
  - V_{S30}- and depth-dependent site terms in GMPEs
  - Site amplification coefficients in building codes

GMPE

$$\ln Z = F_E + F_P + F_S + \varepsilon_n \sigma_{\ln Z}$$

Ergodic source & path



F_S: ergodic effect of site

Two components:

$F_S = F_{lin} + F_{nl}$

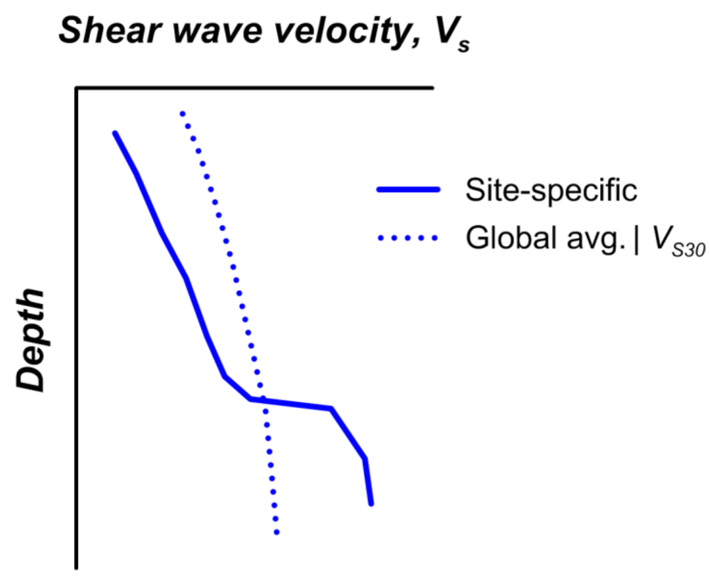
GMPE

$$\ln Z = F_E + F_P + F_S + \varepsilon_n \sigma_{\ln Z}$$

Ergodic source & path

F_S: ergodic effect of site

Actual for site *j*: $F_S + \eta_{Sj}$



GMPE

$$\ln Z = F_E + F_P + F_S + \varepsilon_n \sigma_{\ln Z}$$

Ergodic source & path

F_S: ergodic effect of site

Actual for site *j*: $F_S + \eta_{Sj}$

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

Between-event variability

$\sigma_{\ln Z}$: ergodic total standard deviation

GMPE

$$\ln Z = F_E + F_P + F_S + \varepsilon_n \sigma_{\ln Z}$$

Ergodic source & path

***F**$_S$*: ergodic effect of site

Actual for site *j*: $F_S + \eta_{Sj}$

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

$\sigma_{\ln Z}$: ergodic total standard deviation

Within-event variability

$$\phi_{P2P}^2 + \phi_{S2S}^2 + \phi_{\ln Y}^2$$

Modified from Al Atik et al. (2010)

Importance of σ

Consider example site

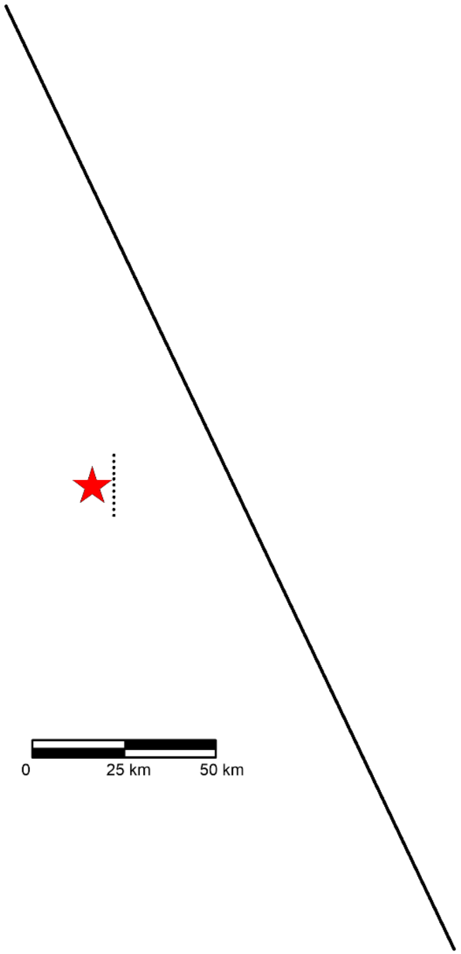


Figure: P. Zimmaro.

Importance of σ

Consider example site

Hazard with as-published ergodic σ & sensitivity

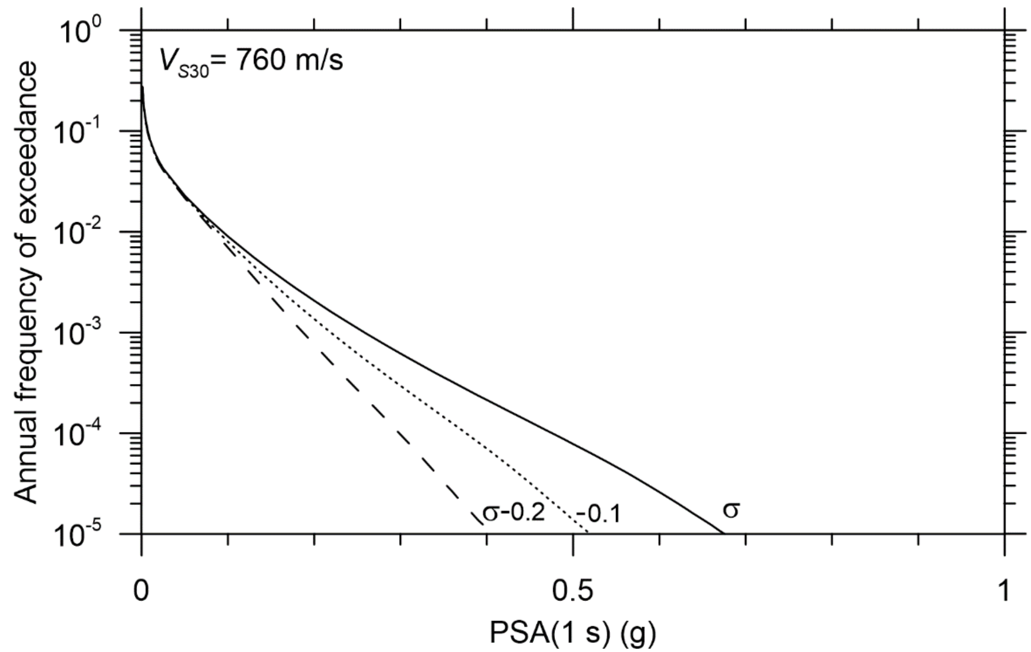


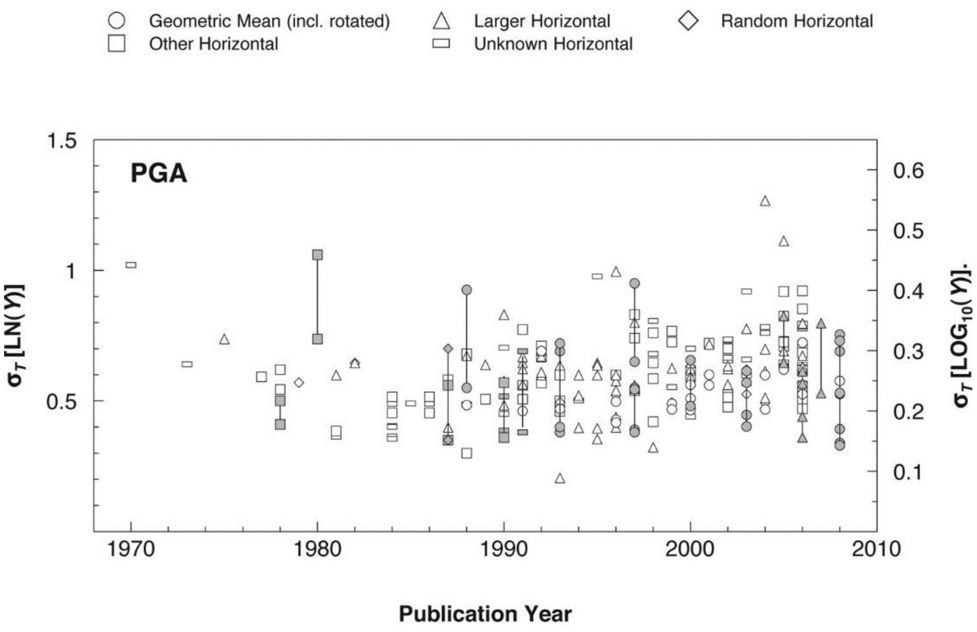
Figure: P. Zimmaro. Similar to Bommer and Abrahamson, 2006

Importance of σ

Consider example site

Hazard with as-published ergodic σ & sensitivity

Ergodic σ difficult to reduce as GMPEs evolve…



After Strasser et al., 2009

Outline

- Ergodic site amplification
- **Non-ergodic (location-specific) site amplification**
- Implementation in PSHA
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Non-Ergodic Site Amplification

- *Non-Ergodic*: Amplification is site-specific
  - Bias removal
  - Reduced dispersion
- Evaluation from:
  - On-site recordings
  - Geotechnical simulations
- Site response model: μ_{lnY}, ϕ_{lnZ}

Dispersion reduction

Recall $\phi^2_{\ln Z} = \phi^2_{P2P} + \phi^2_{S2S} + \phi^2_{\ln Y}$

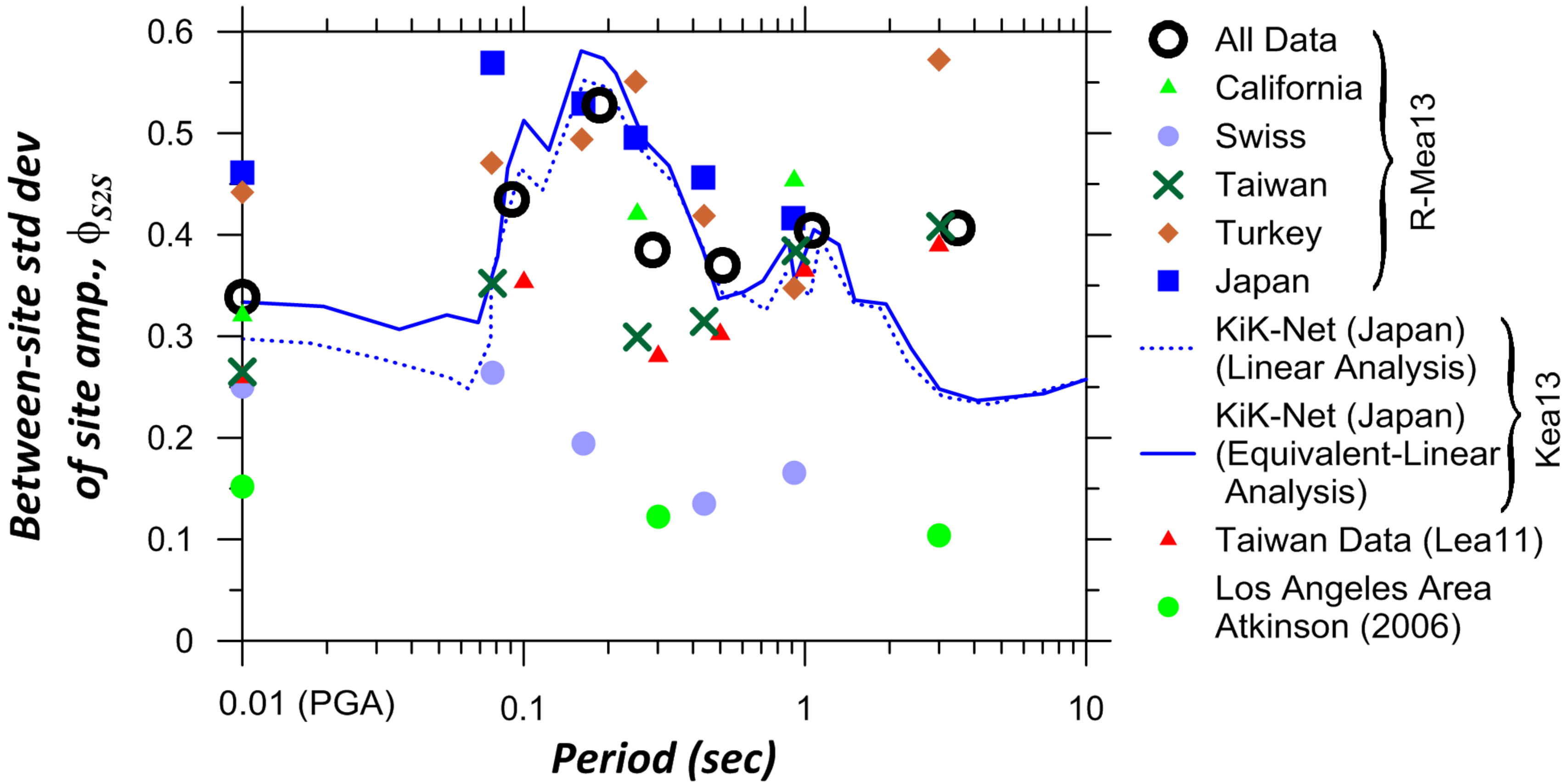
ϕ_{lnZ} from GMPE

If site effect non-ergodic, can remove S2S-component:

Approach 1: use $\approx \phi^2_{\ln Z} - \phi^2_{S2S}$

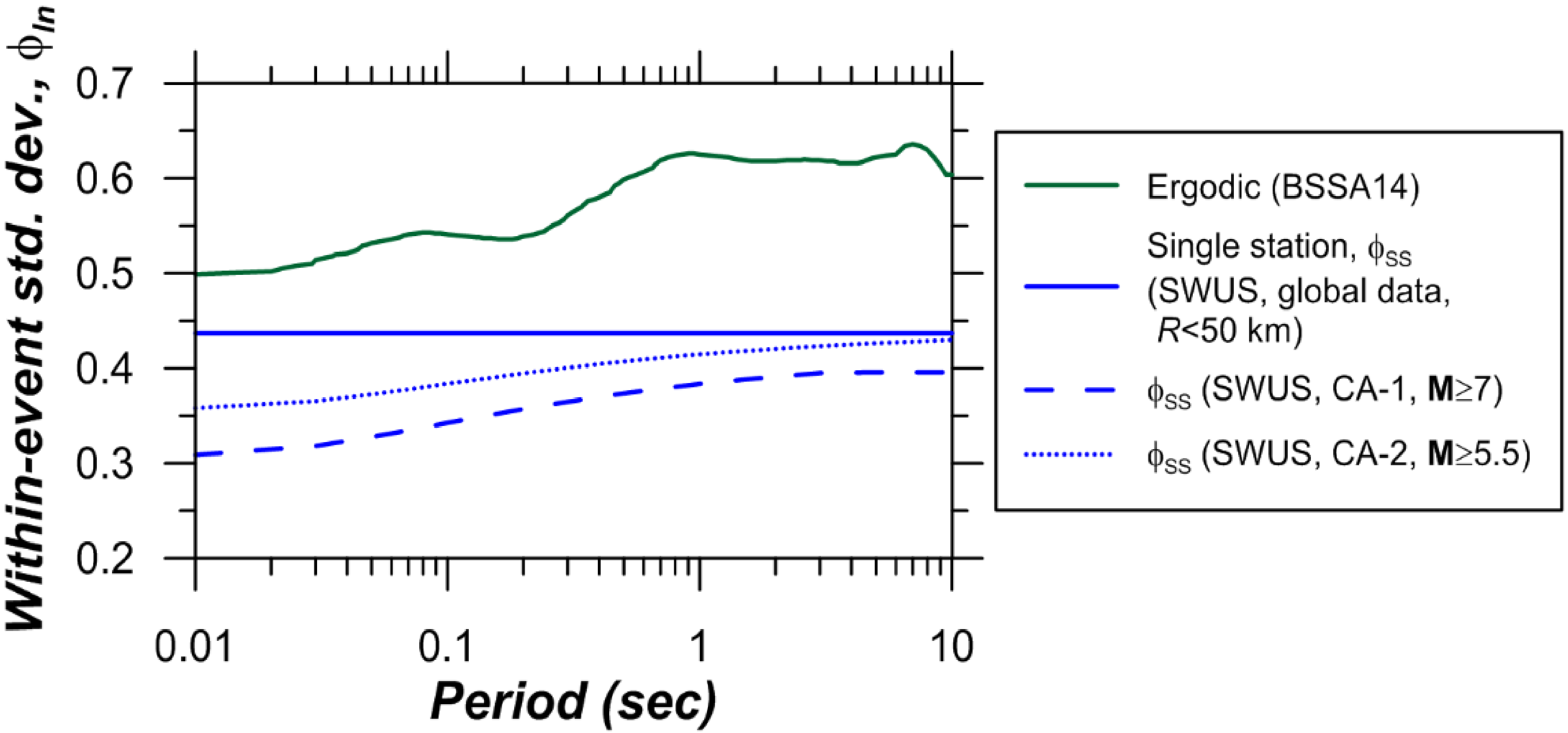
Approach 2: replace $\phi^2_{P2P} + \phi^2_{S2S}$ with ϕ^2_{SS}

Approach 1

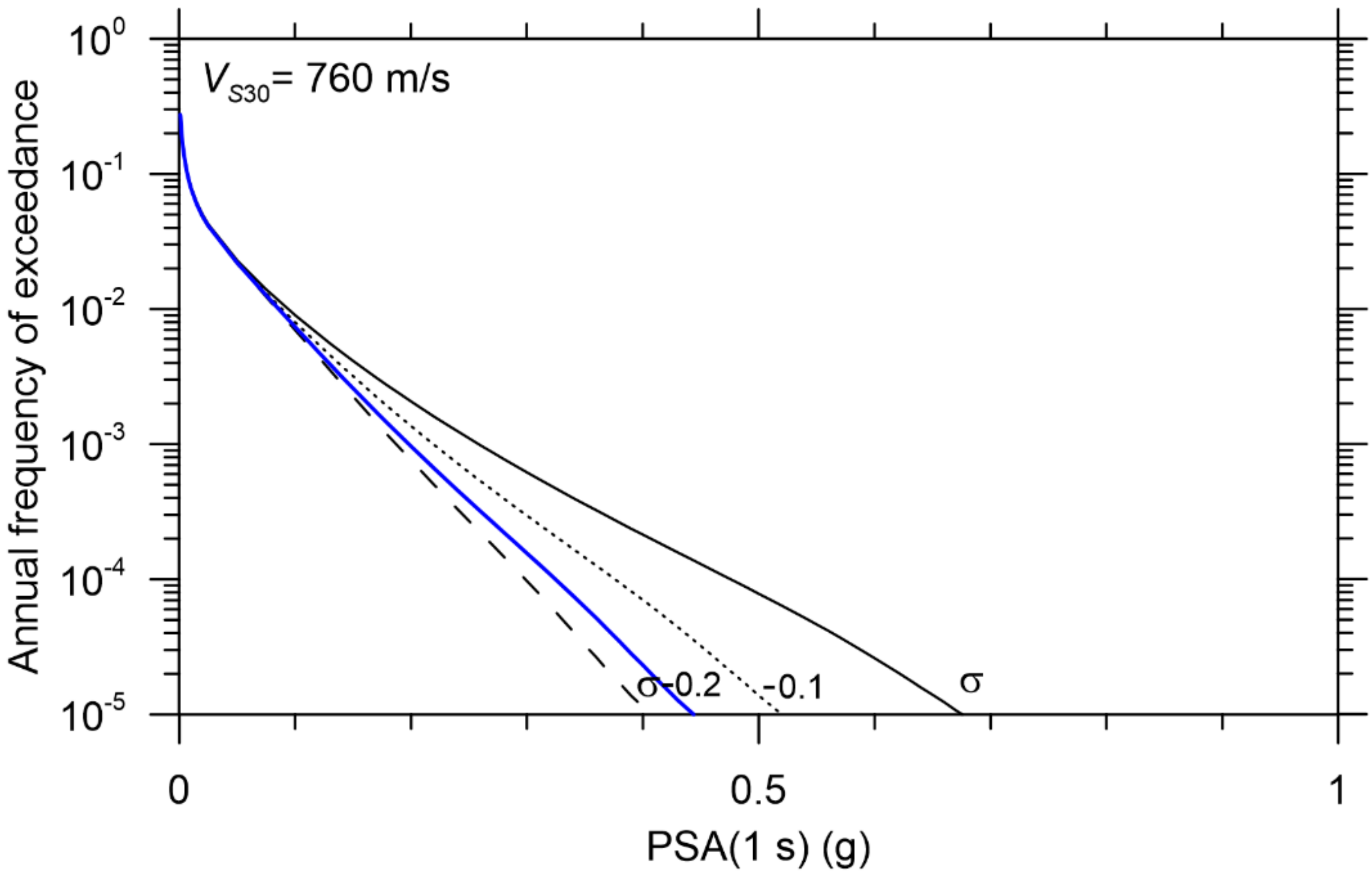


0.6
0.5
0.4
0.3
0.2
0.1
0
0.01 (PGA)
0.1
1
10
Period (sec)
Between-site std dev of site amp., ϕ_{S2S}
All Data
California
Swiss
Taiwan
Turkey
Japan
R-Mea13
KiK-Net (Japan) (Linear Analysis)
KiK-Net (Japan) (Equivalent-Linear Analysis)
Kea13
Taiwan Data (Lea11)
Los Angeles Area Atkinson (2006)

Approach 2



GMPE (ergodic) vs single-station (ϕ_{SS}) (GeoPentech, 2015)



V_{S30}= 760 m/s
Annual frequency of exceedance
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
σ-0.2
-0.1
σ
0
0.5
1
PSA(1 s) (g)

Evaluation from Recordings

Install sensors at Site *j*

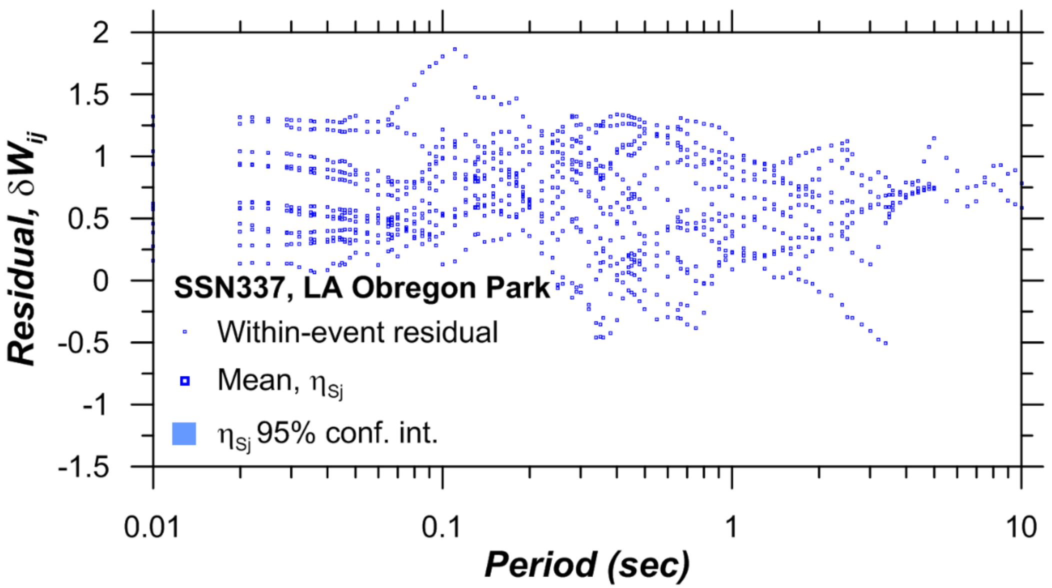
Record eqks in **M**-R range of GMPE (Site *j* and others)

Compute residuals:

$$R_{ij} = \ln z_{ij} - \mu_{\ln Z,ij}$$

Partition residuals:

$$R_{ij} = \eta_{Ei} + \delta W_{ij}$$



Evaluation from Recordings

Install sensors at Site *j*

Record eqks in **M**-R range of GMPE (Site *j* and others)

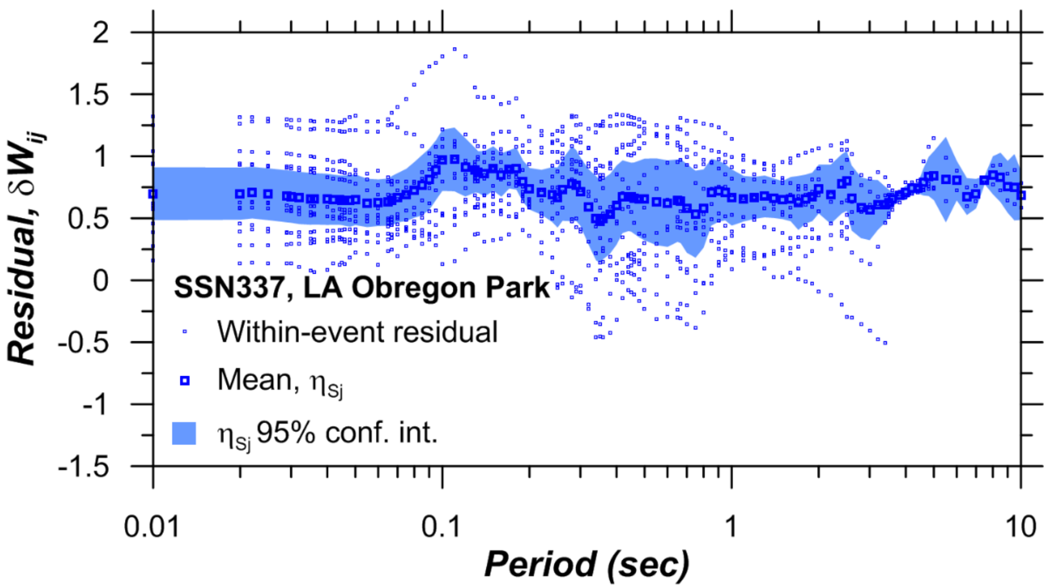
Compute residuals:

$$R_{ij} = \ln z_{ij} - \mu_{\ln Z,ij}$$

Partition residuals:

$$R_{ij} = \eta_{Ei} + \delta W_{ij}$$

Mean of δW_{ij} is $\sim \eta_{Sj}$



Evaluation from Recordings

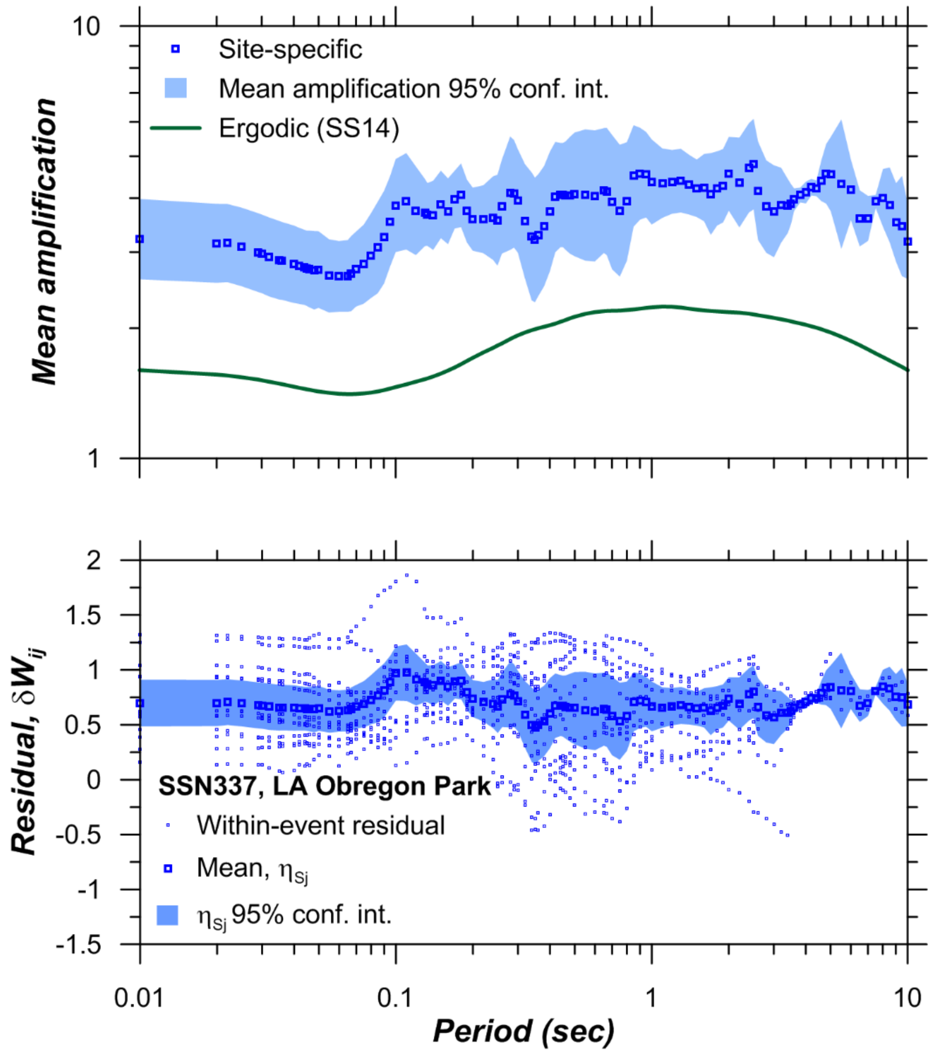
Mean linear site response:

$$F_{lin} + \eta_{Sj}$$

Ergodic linear site term

F_{nl} term can be added from simulations

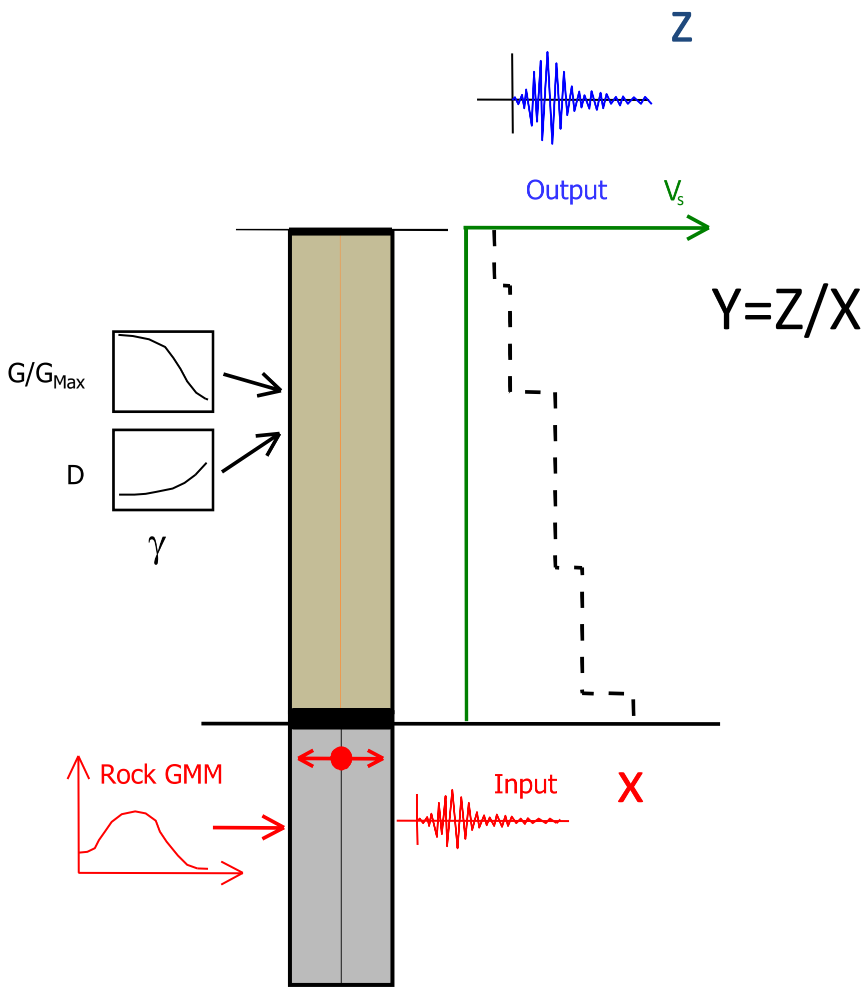
Adjusts mean ground motion $\mu_{\ln Z}$



Evaluation from Simulations

Geotechnical 1D GRA

What is simulated, what is not.



Evaluation from Simulations

Geotechnical 1D GRA

What is simulated, what is not.

Use range of input motions, X.
For each, compute Y=Z/X

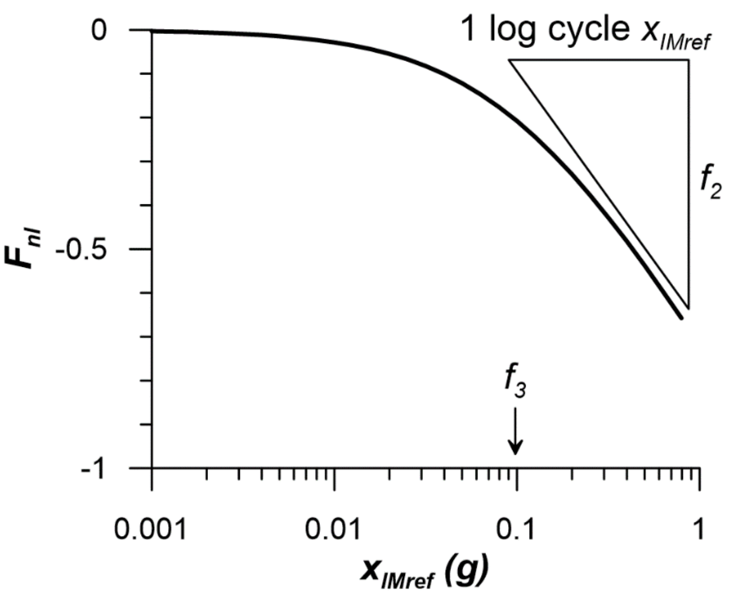
(Detailed procedures in 2014 PEER report)

Limited effectiveness for many sites (e.g., Thompson et al. 2012)

Site Response Model

Site-specific amplification function

$$\mu_{\ln Y} = \underbrace{f_1}_{F_{lin}} + \underbrace{f_2 \ln\left(\frac{x_{IMref} + f_3}{f_3}\right)}_{F_{nl}}$$

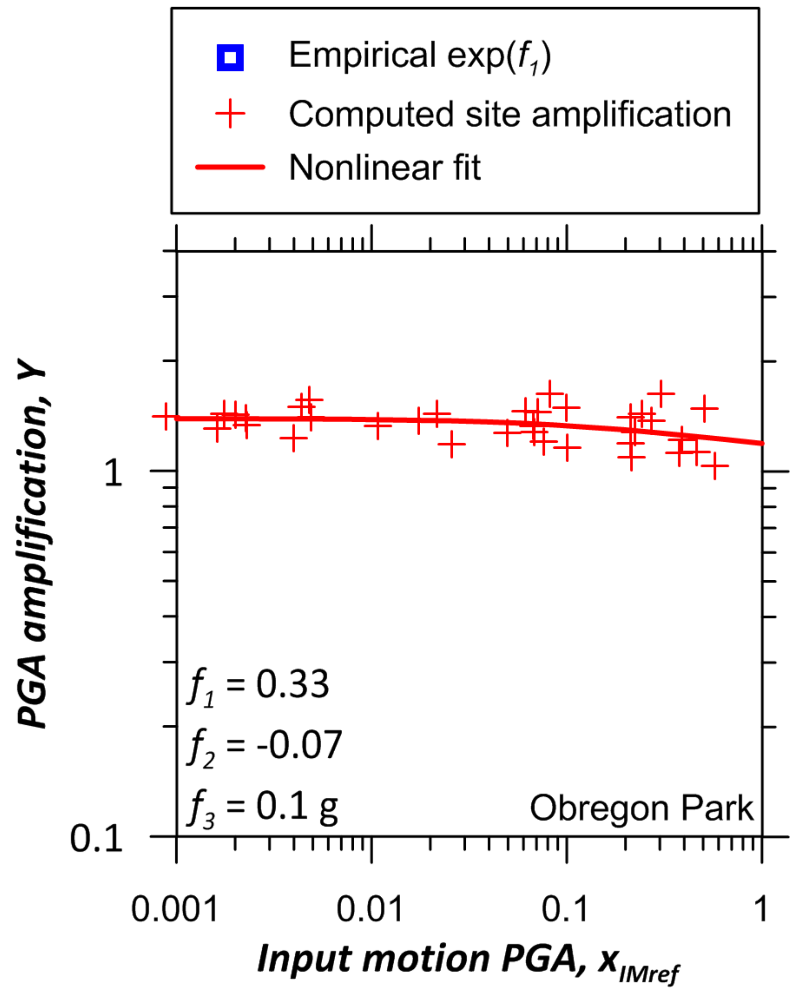


Site Response Model

Site-specific amplification function

Fit GRA results

Approximate fits possible if fewer runs



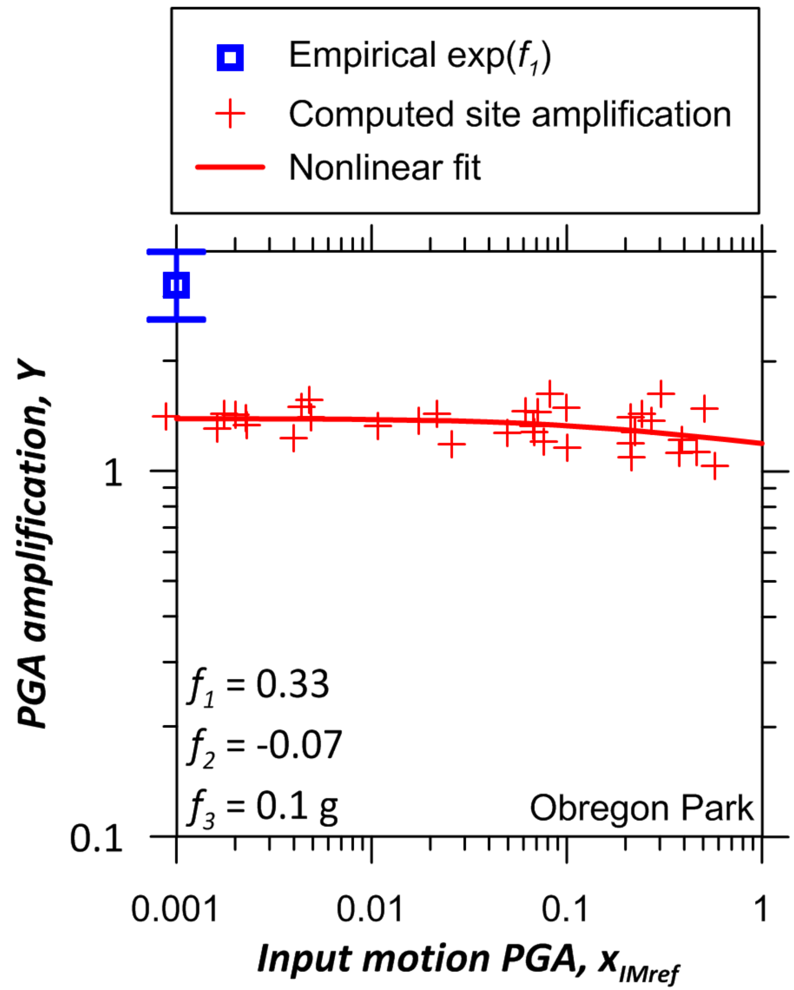
Site Response Model

Site-specific amplification function

Fit GRA results

Approximate fits possible if fewer runs

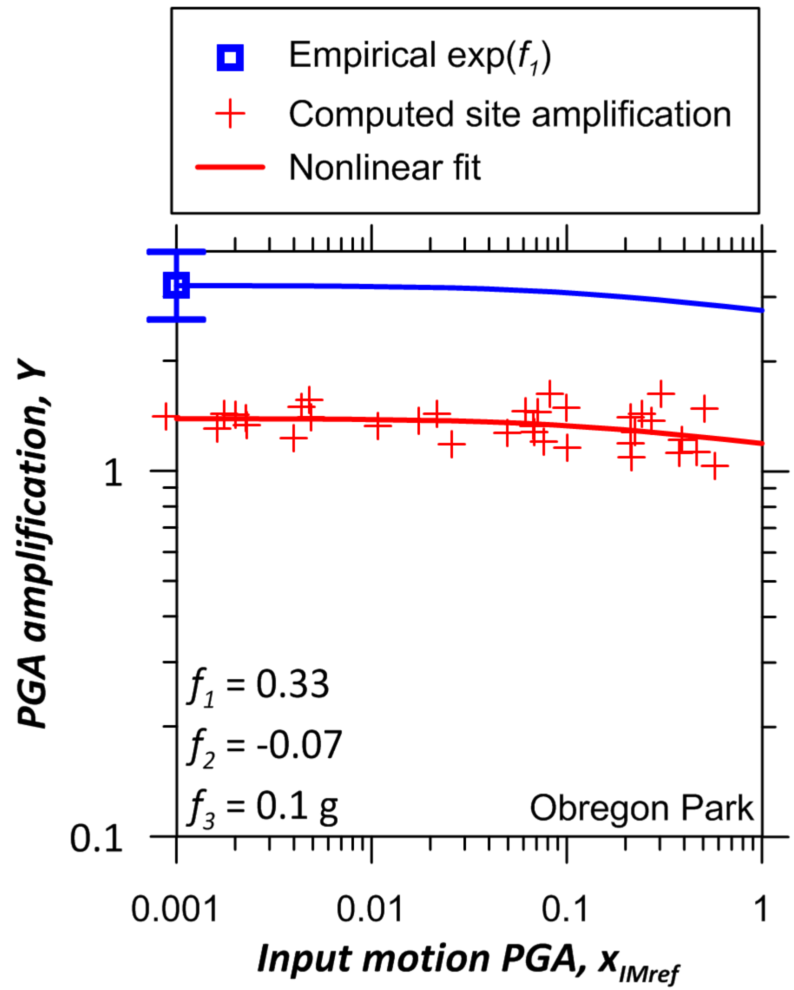
As available, note empirical amplification



Site Response Model

Site-specific amplification function

- Fit GRA results
- Approximate fits possible if fewer runs
- As available, note empirical amplification
- Shift to match empirical for weak motion (semi-empirical approach)



Site Response Model

Site-specific amplification function

$$\mu_{\ln Y} = f_1 + f_2 \ln\left(\frac{x_{IMref} + f_3}{f_3}\right)$$

Standard deviation term

$\phi_{\ln Z}$ reduced from $\phi_{\ln X}$ due to:

- Nonlinearity

$$\phi_{\ln Z} = \sqrt{\left(\frac{f_2 x}{x + f_3} + 1\right)^2 \left(\phi^2_{\ln X} - F\phi^2_{S2S}\right) + \phi^2_{\ln Y}}$$

Site Response Model

Site-specific amplification function

$$\mu_{\ln Y} = f_1 + f_2 \ln\left(\frac{x_{IMref} + f_3}{f_3}\right)$$

Standard deviation term

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$$\phi_{\ln Z} = \sqrt{\left(\frac{f_2 x}{x + f_3} + 1\right)^2 \left(\phi_{\ln X}^2 - F\phi_{S2S}^2\right) + \phi_{\ln Y}^2}$$

Approach 1

Site Response Model

Site-specific amplification function

$$\mu_{\ln Y} = f_1 + f_2 \ln\left(\frac{x_{IMref} + f_3}{f_3}\right)$$

Standard deviation term

$\phi_{\ln Z}$ reduced from $\phi_{\ln X}$ due to:

- Nonlinearity
- Non-ergodic ϕ_{ln}

$$\phi_{\ln Z} = \sqrt{\left(\frac{f_2 x}{x + f_3} + 1\right)^2 \phi_{SS}^2 + \phi_{\ln Y}^2}$$

Approach 2

Site Response Model

Site-specific amplification function

$$\mu_{\ln Y} = f_1 + f_2 \ln\left(\frac{x_{IMref} + f_3}{f_3}\right)$$

Standard deviation term

$\phi_{\ln Z}$ reduced from $\phi_{\ln X}$ due to:

- Nonlinearity
- Non-ergodic ϕ_{ln}

Include uncertainty in site amplification, $\phi_{\ln Y} \approx 0.3$

$$\phi_{\ln Z} = \sqrt{\left(\frac{f_2 x}{x + f_3} + 1\right)^2 \left(\phi_{\ln X}^2 - F\phi_{S2S}^2\right) + \phi_{\ln Y}^2}$$

Site Response Model

Site-specific amplification function

Standard deviation term

Epistemic uncertainty

Should consider center & range of possible:

- Mean amplification functions
- $\phi_{\ln Z}$ models

Outline

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Hybrid

term from Cramer, 2003, and others

For any given probability, *P*: $\ln(z) = \ln\left(\bar{Y} \middle| x_{IMref}\right) + \ln(x)$

Mean site amplification given x from hazard curve

Read from hazard curve

Dominant approach in practice (basis for building code ground motions)

Convolution

Bazzurro and Cornell, 2004

Given: (1) Hazard curve for reference condition

$$P\left(X > x \mid \Delta t\right)$$

(2) Site amplification function: $\mu_{\ln Y} = f\left(x_{IMref}\right) \quad \phi_{\ln Y}$

$$P\left(Z > z \mid \Delta t\right) = \int_0^\infty P\left(Y > \frac{z}{x} \mid x_{IMref}\right) f_X\left(x\right) dx$$

Simple probability operation given PDF for Y

Abs. value of slope of hazard curve

Advantage relative to hybrid: uncertainty in *Y* considered

Hybrid & Convolution - Summary

Advantages:

- Simple to implement. Only requires rock PSHA and amplification model.

Drawbacks:

- PSHA based on σ_{lnX} not σ_{lnZ}
- No allowance for non-ergodic standard deviation
- Controlling sources and epsilons based on rock GMPE
- Nonlinearity driven by X hazard ($\varepsilon_X > 0$).

Modify GMPE in hazard integral

- Mean: $\mu_{\ln Z} = \mu_{\ln X} + \mu_{\ln Y} \mid x_{IMref}$
- Adjusted $\phi_{\ln Z}$

By default, x_{IMref} taken as mean value ($\varepsilon = 0$)

Pending technical issue: correlation of z and x_{IMref} (unknown presently)

Consider epistemic uncertainties using logic trees – high uncertainty sites should have wider bounds

OpenSHA Implementation

Non-ergodic site response GMPE can be selected as 'intensity measure relation'

Select GMPE for reference condition and its V_{S30}

V_{S30} and depth parameters for site

Coefficients entered for mean and st dev site model for range of periods.

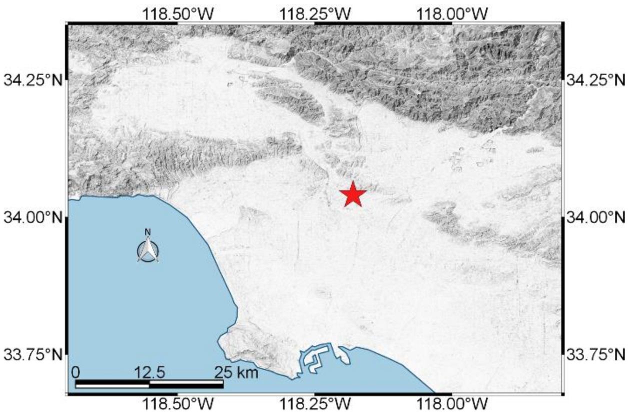
Fitted interpolation between periods with specified coefficients

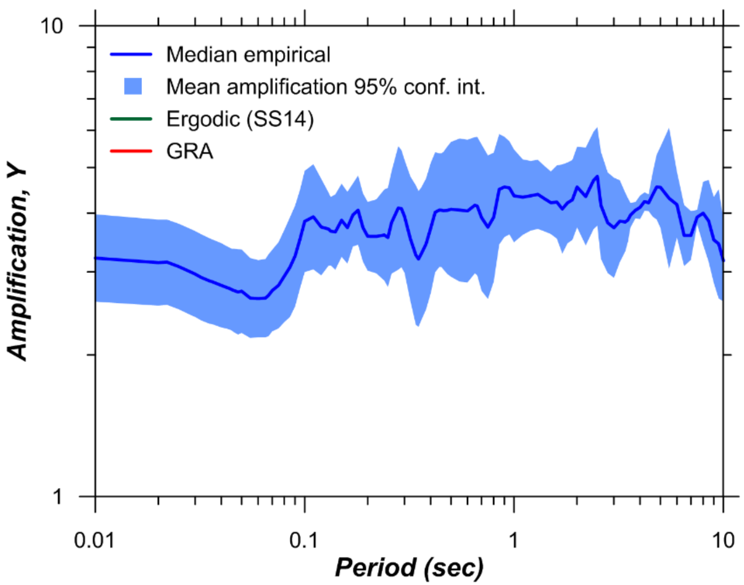
Option to adjust to ergodic model at long periods.

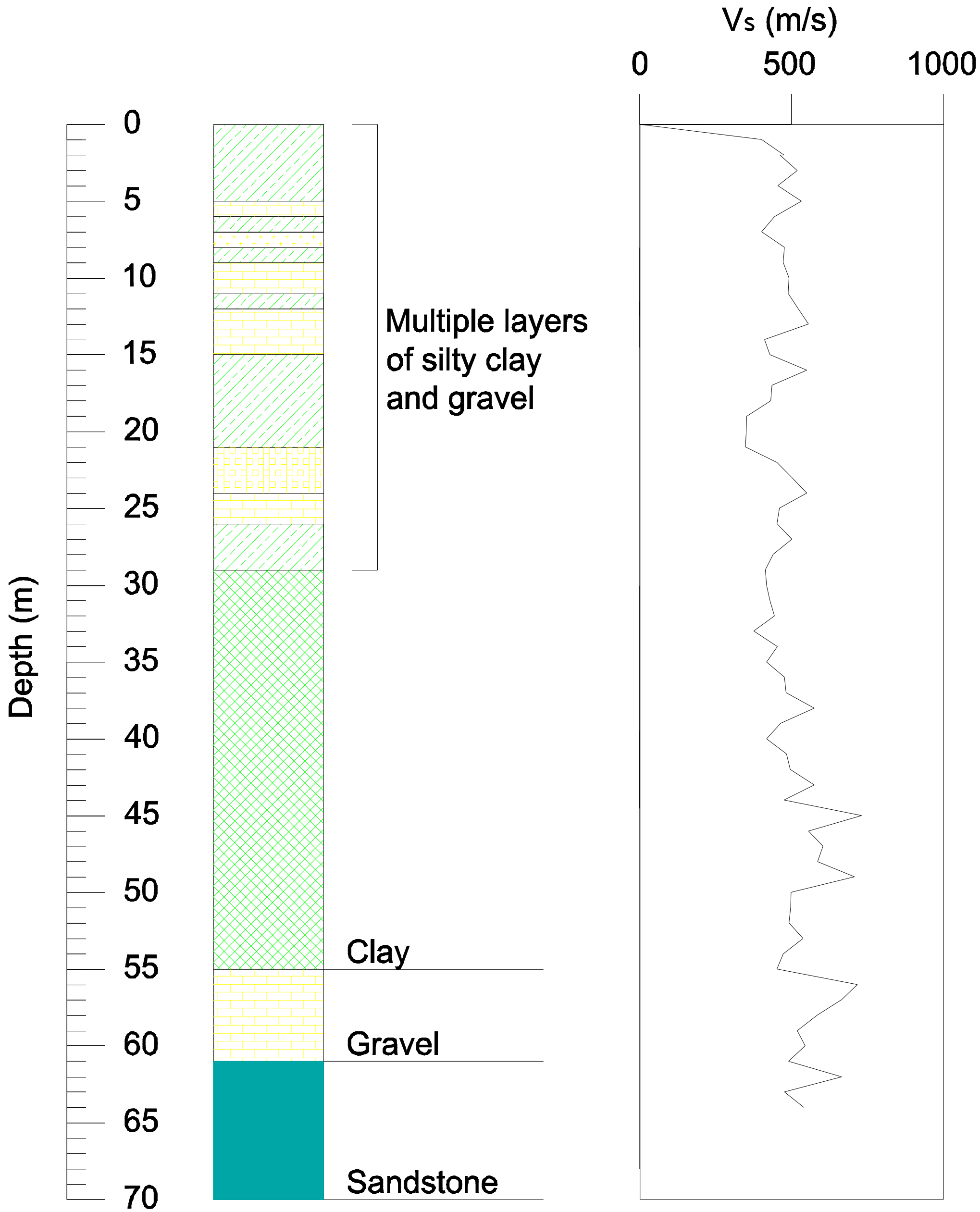
http://www.opensha.org/

Example Applications

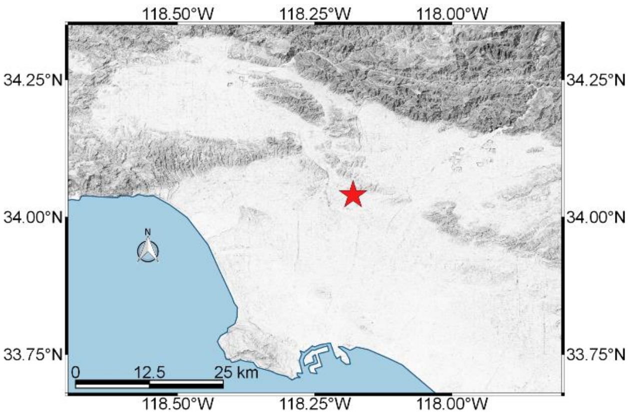
Los Angeles – Obregon Park

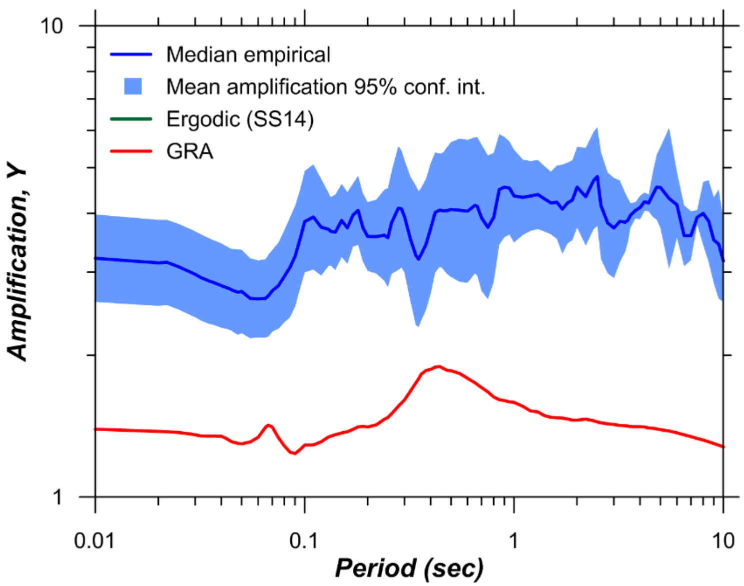


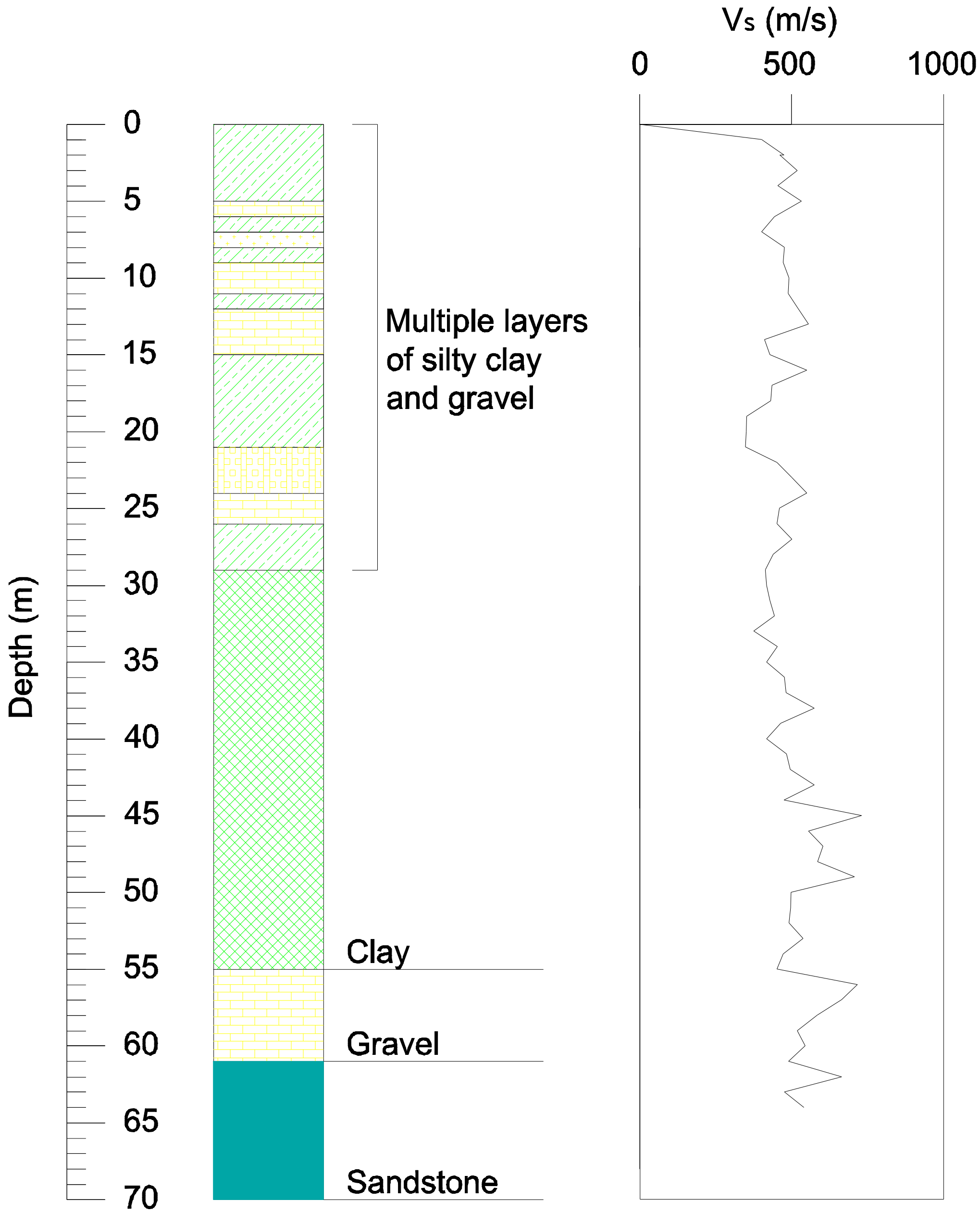




Los Angeles – Obregon Park







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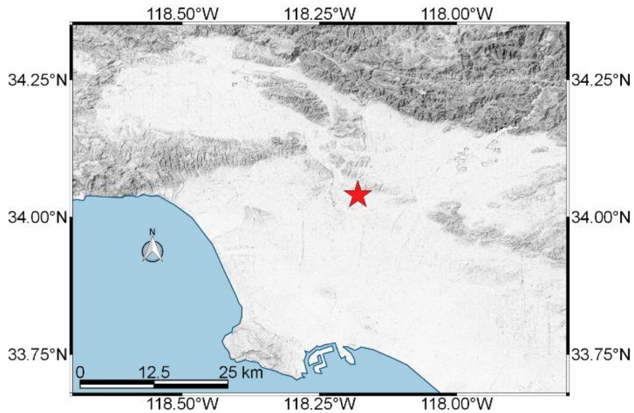
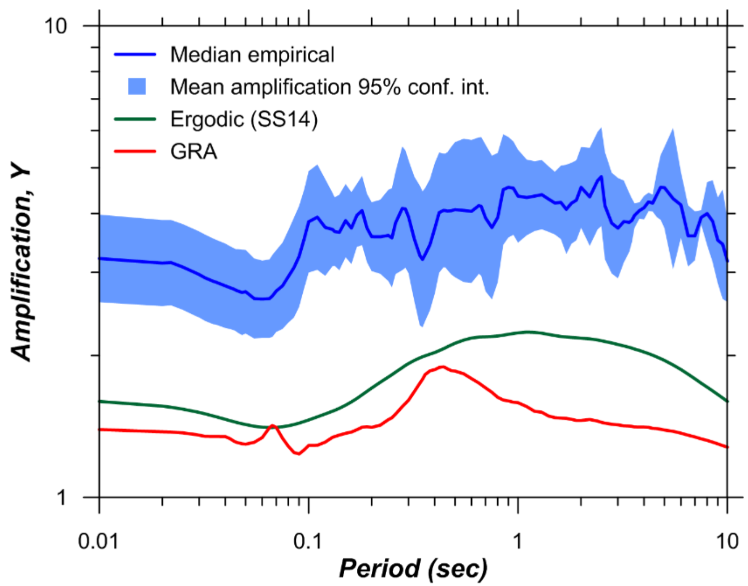
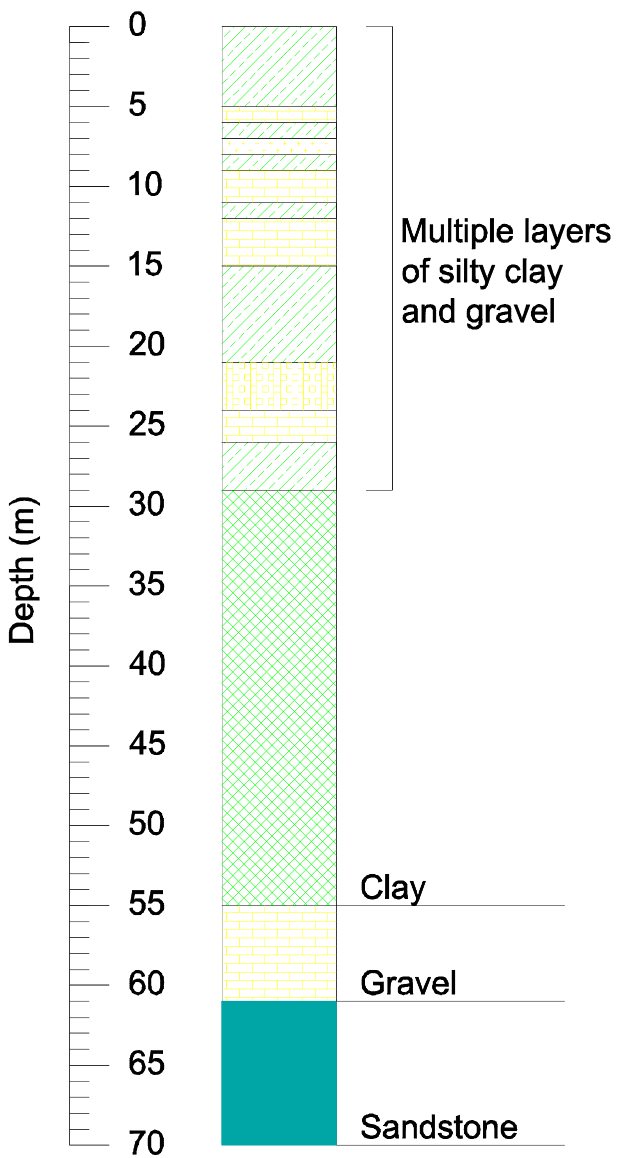
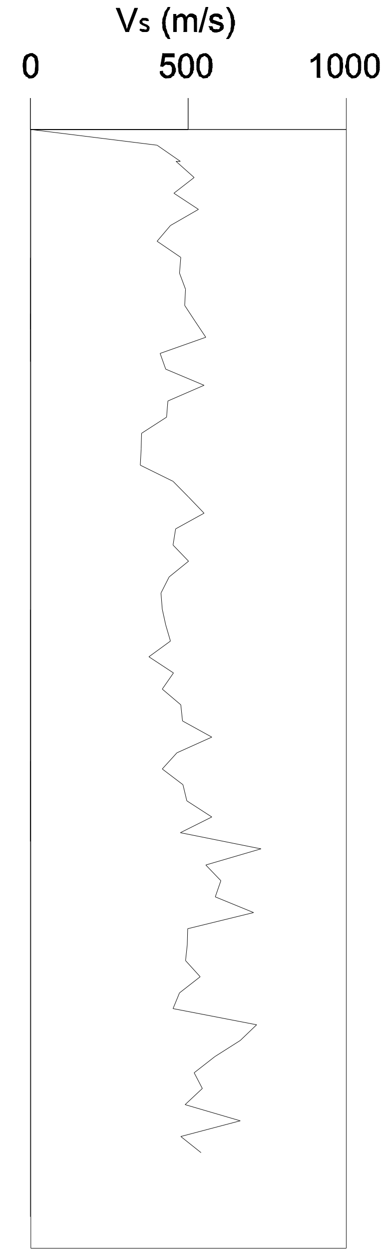


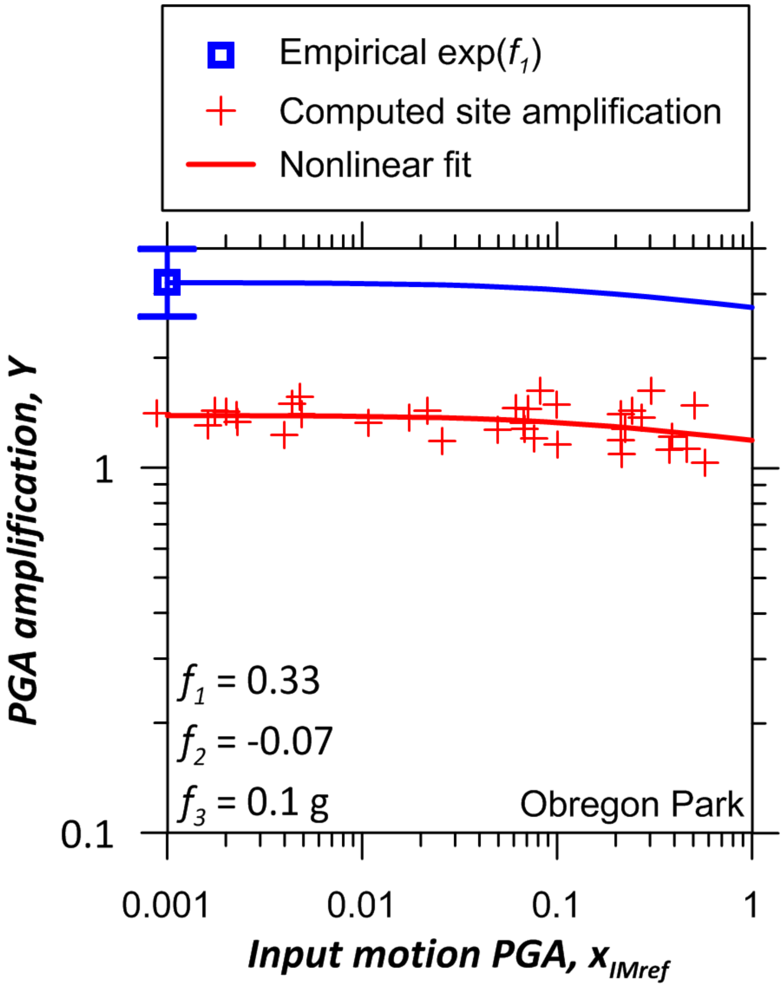




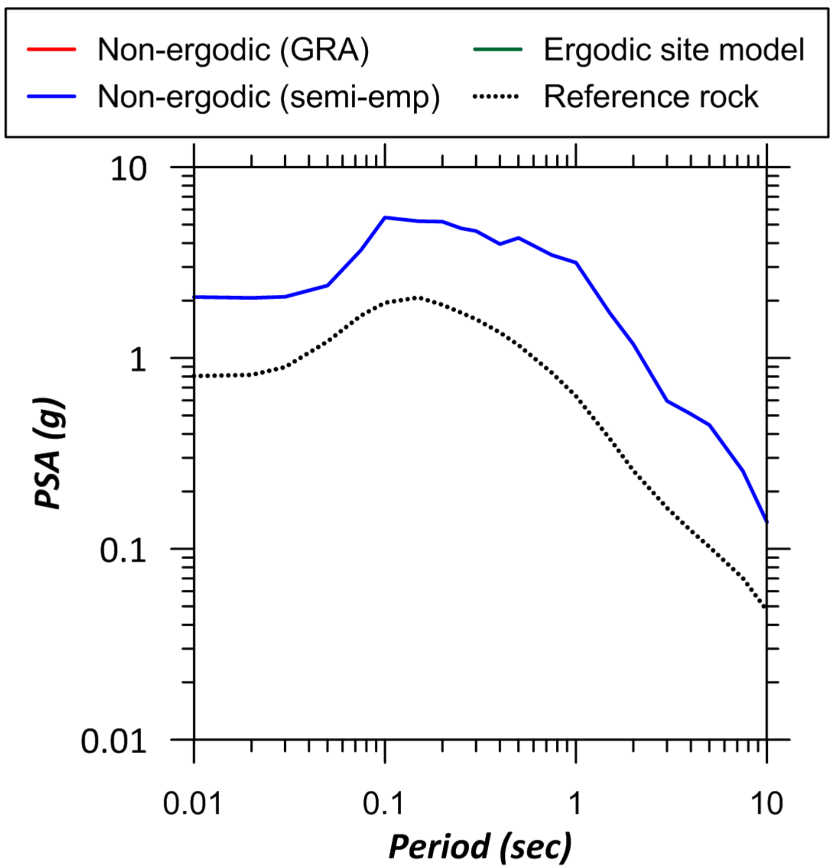


Los Angeles – Obregon Park

Simulations for nonlinear parameters:



UHS: 2% Prob. exc. 50 yr



Los Angeles – Obregon Park

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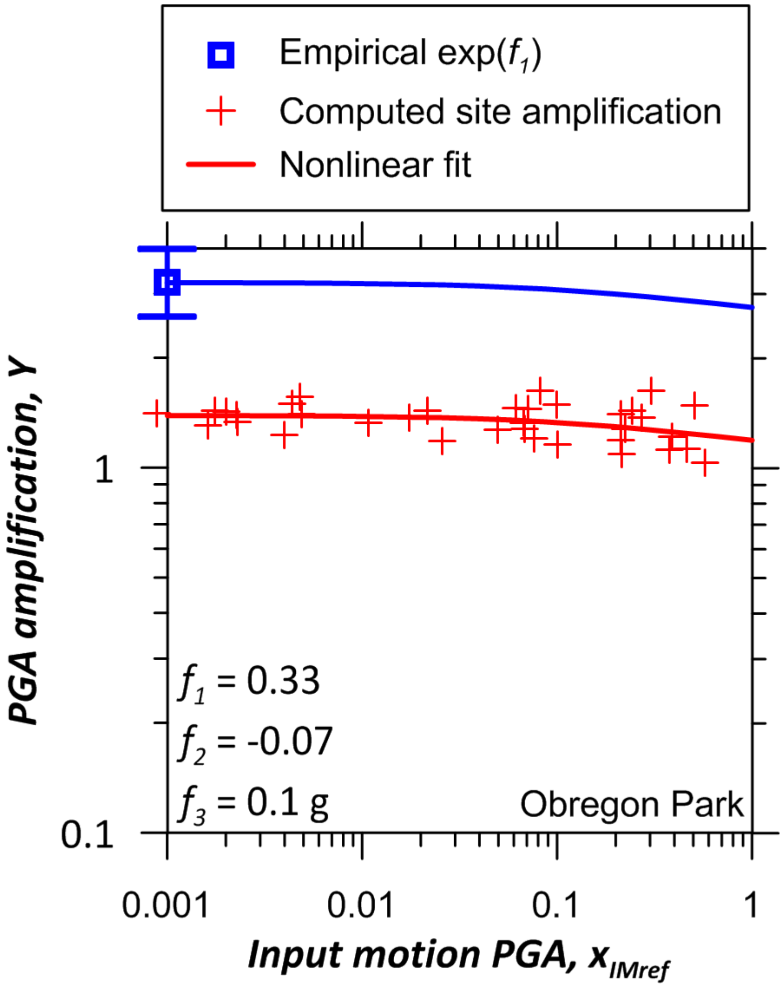

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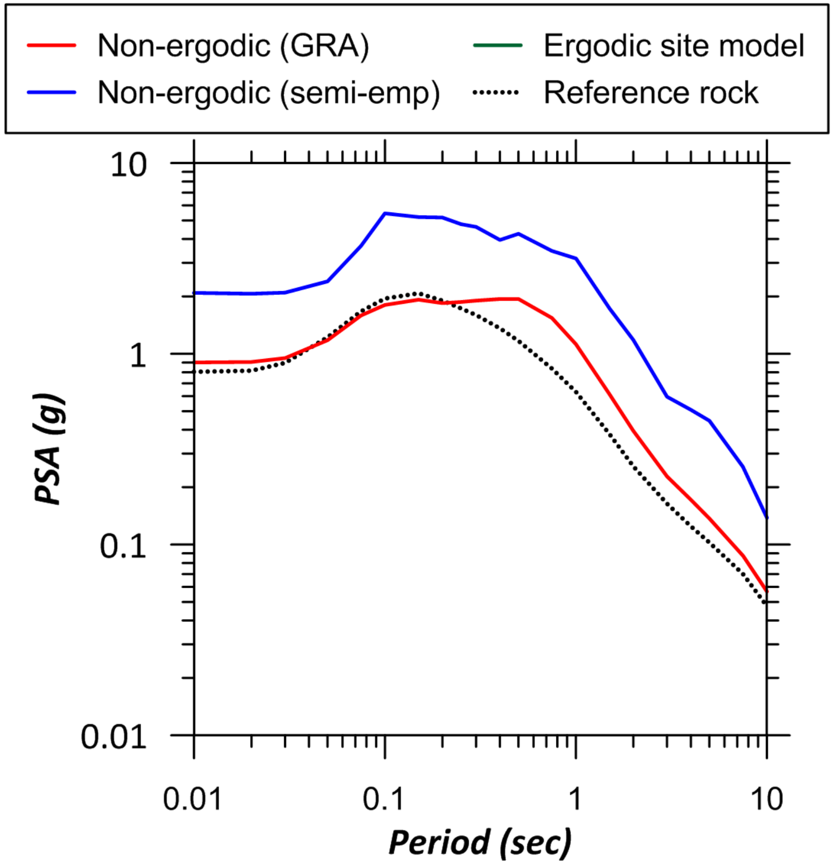

Los Angeles – Obregon Park

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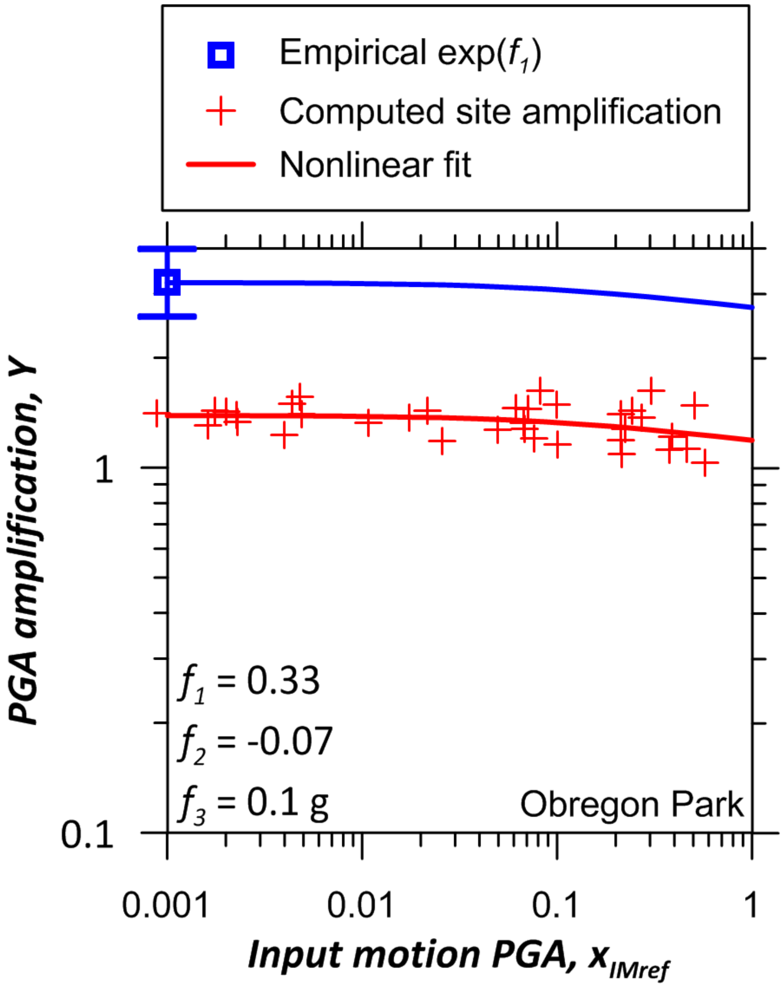

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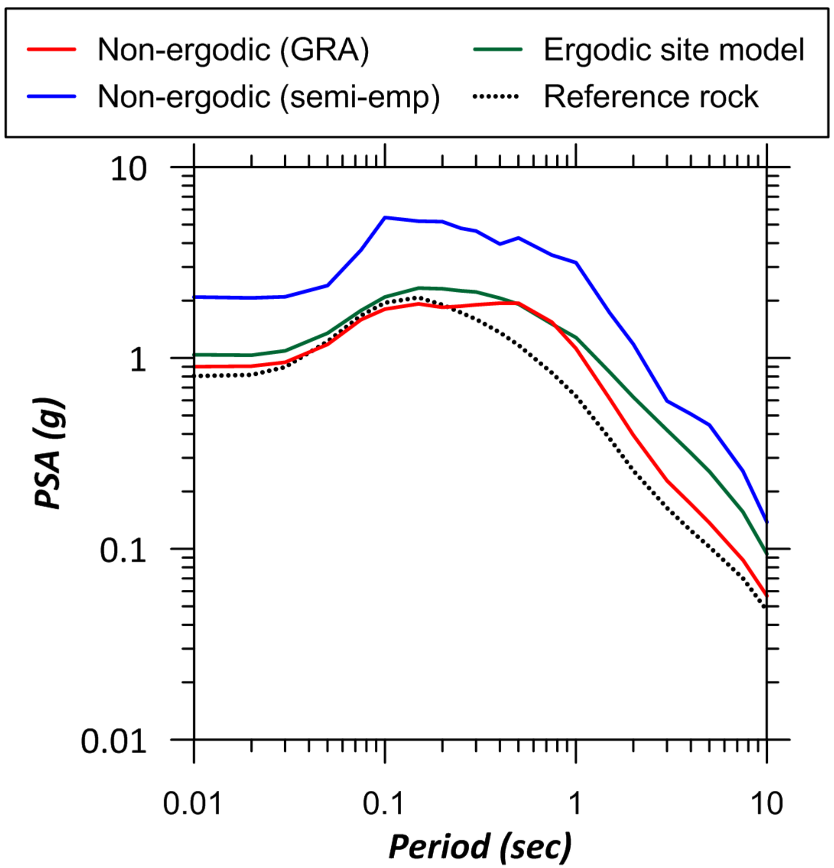
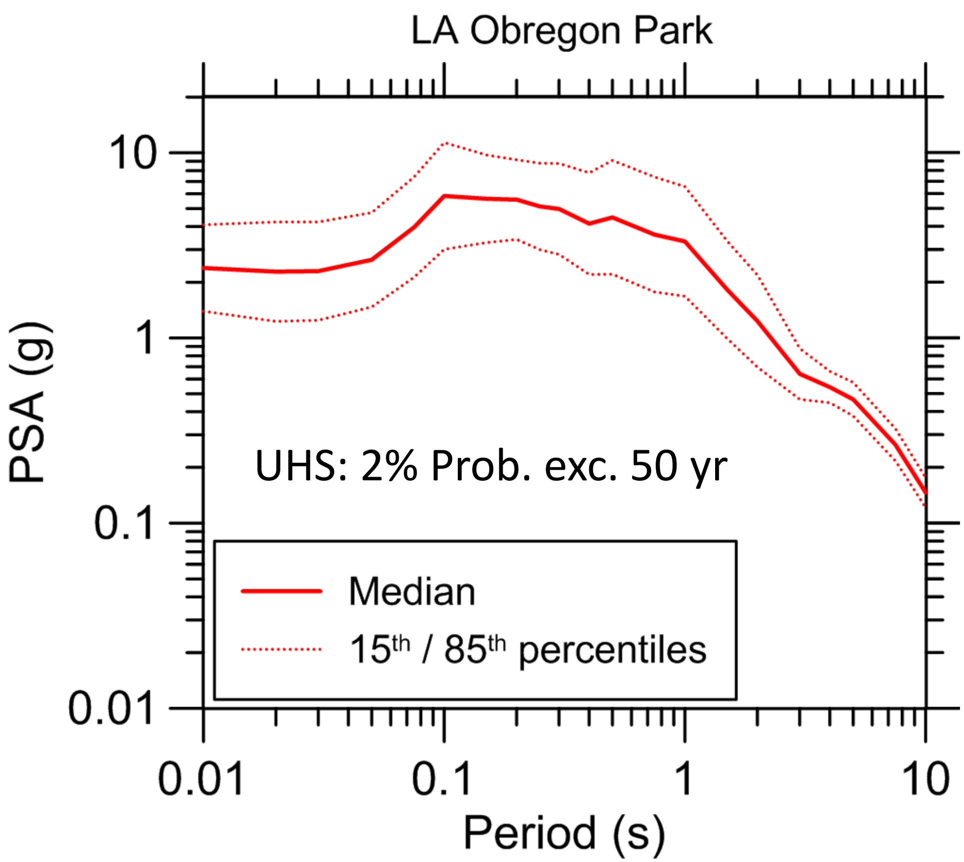


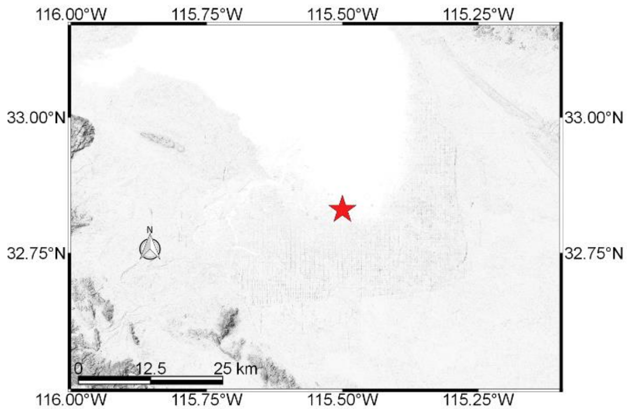
Los Angeles – Obregon Park

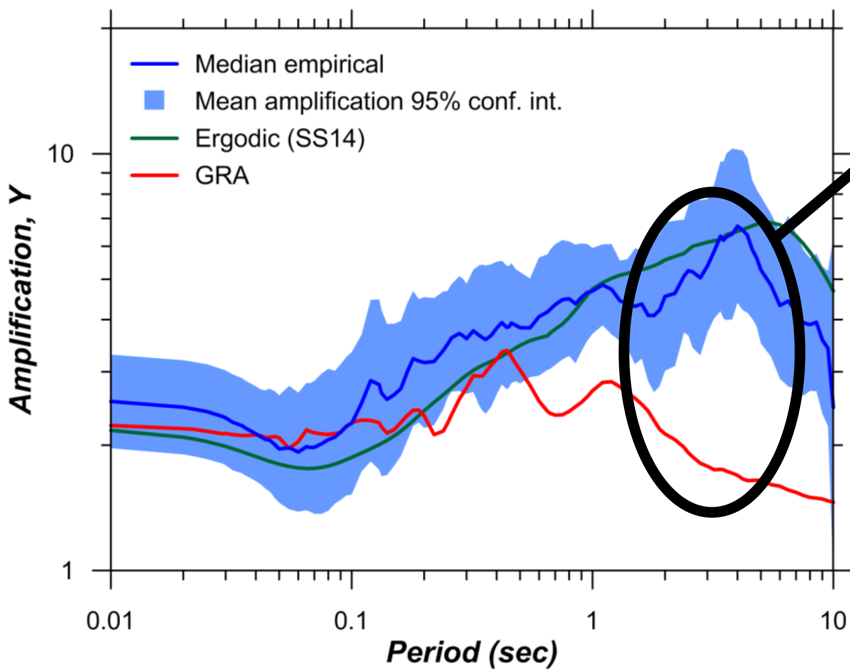
Epistemic uncertainties in hazard from:

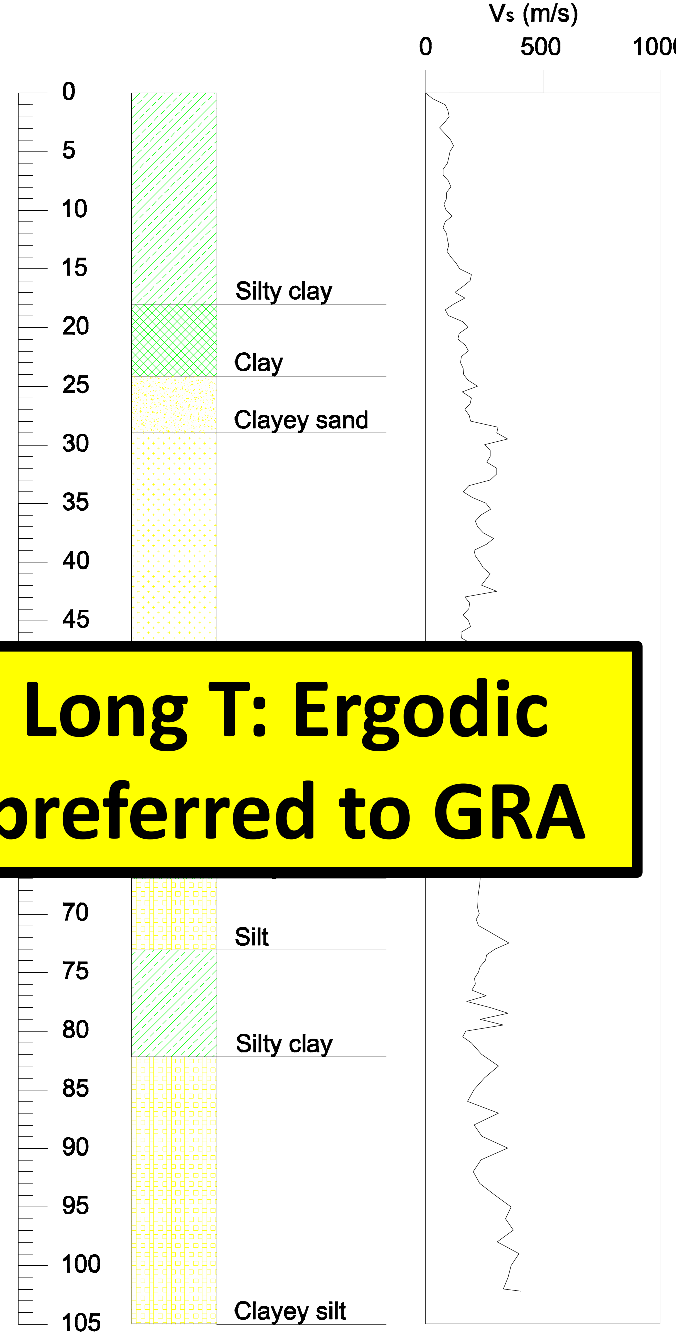
1. Uncertain semi-empirical mean hazard $\mu_{\ln Y} \pm se_{\ln Y}$
2. Alternate $\phi_{\ln Z}$ models



El Centro Array #7





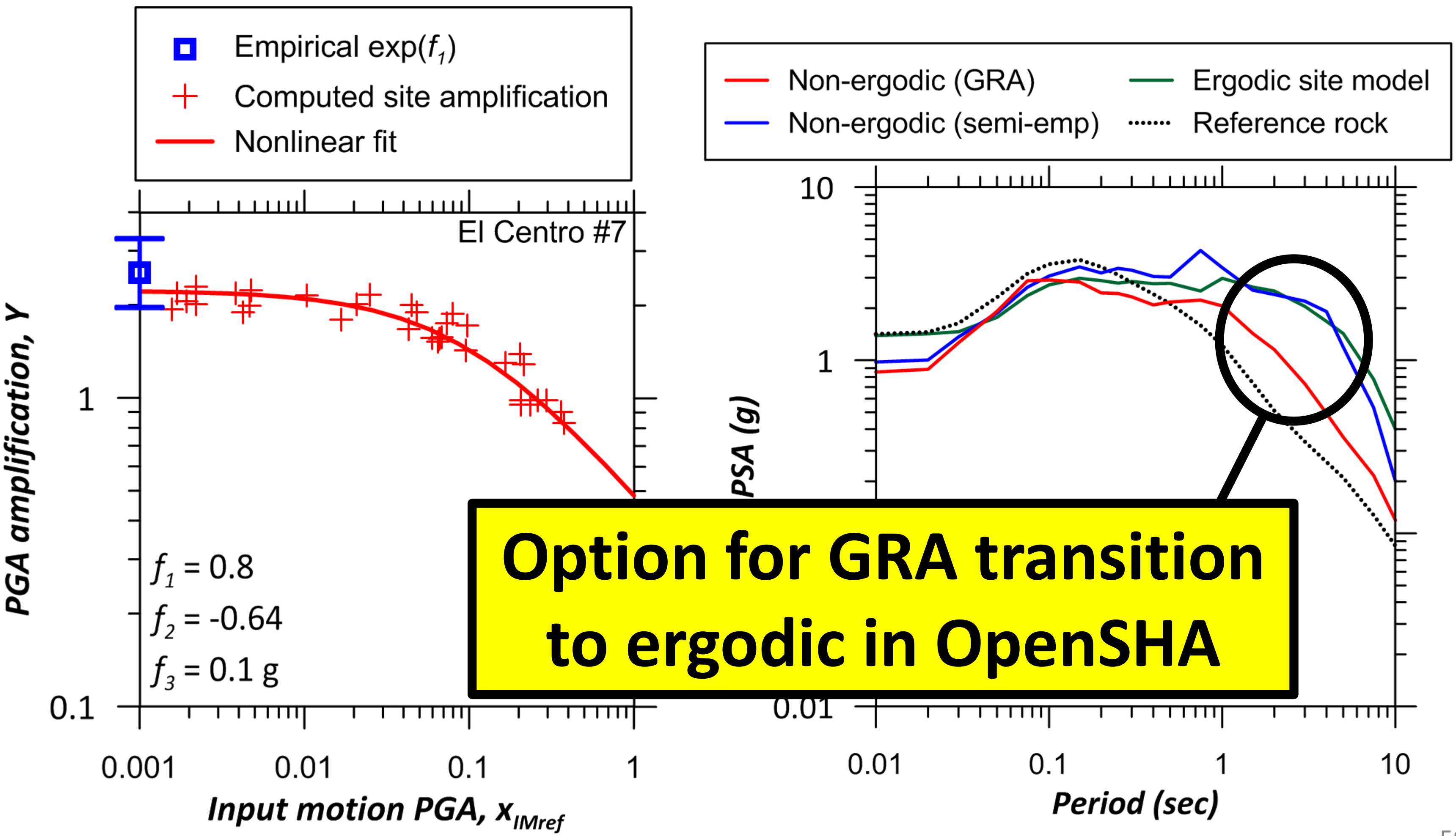


Long T: Ergodic preferred to GRA

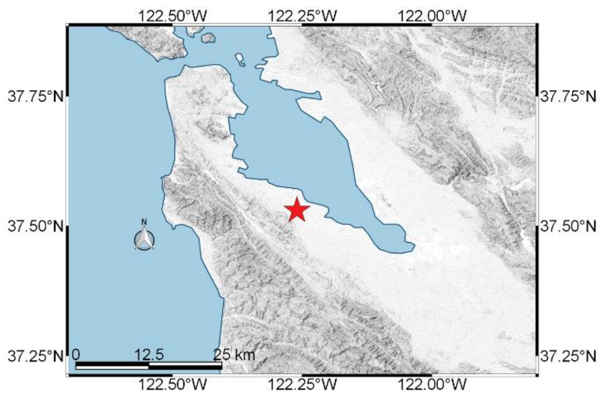
El Centro Array #7

Simulations for nonlinear parameters:

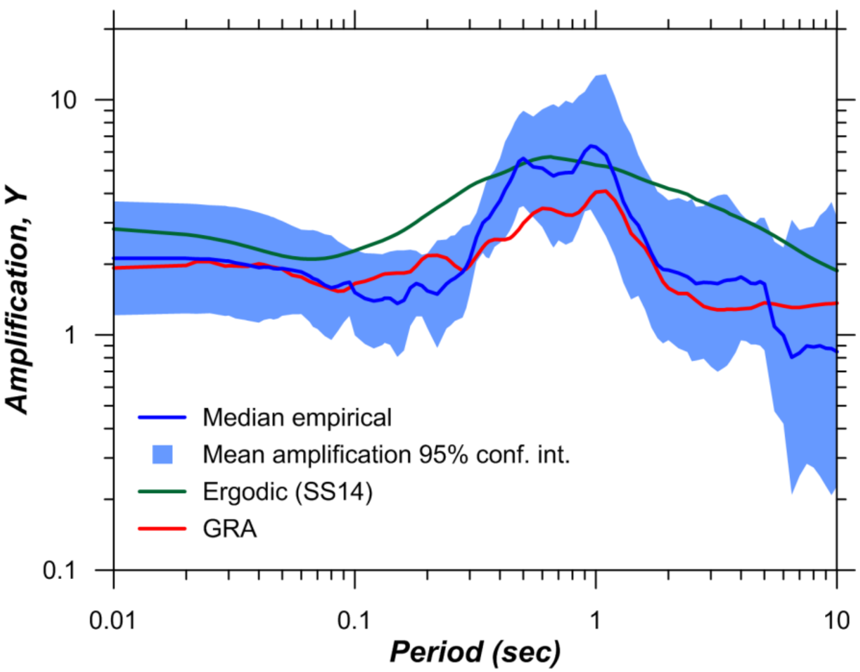
UHS: 2% Prob. exc. 50 yr



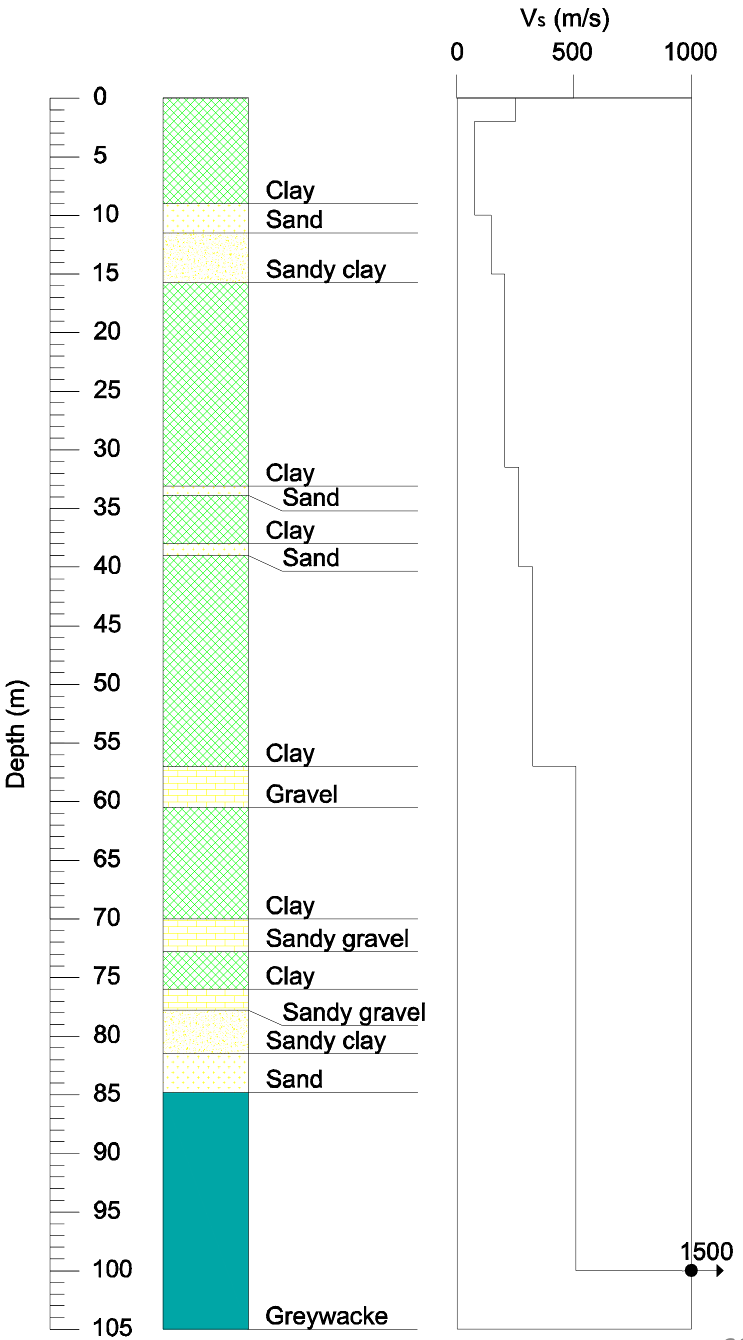
Apeel #2



122.50°W
122.25°W
122.00°W
37.75°N
37.50°N
37.25°N
0
12.5
25 km



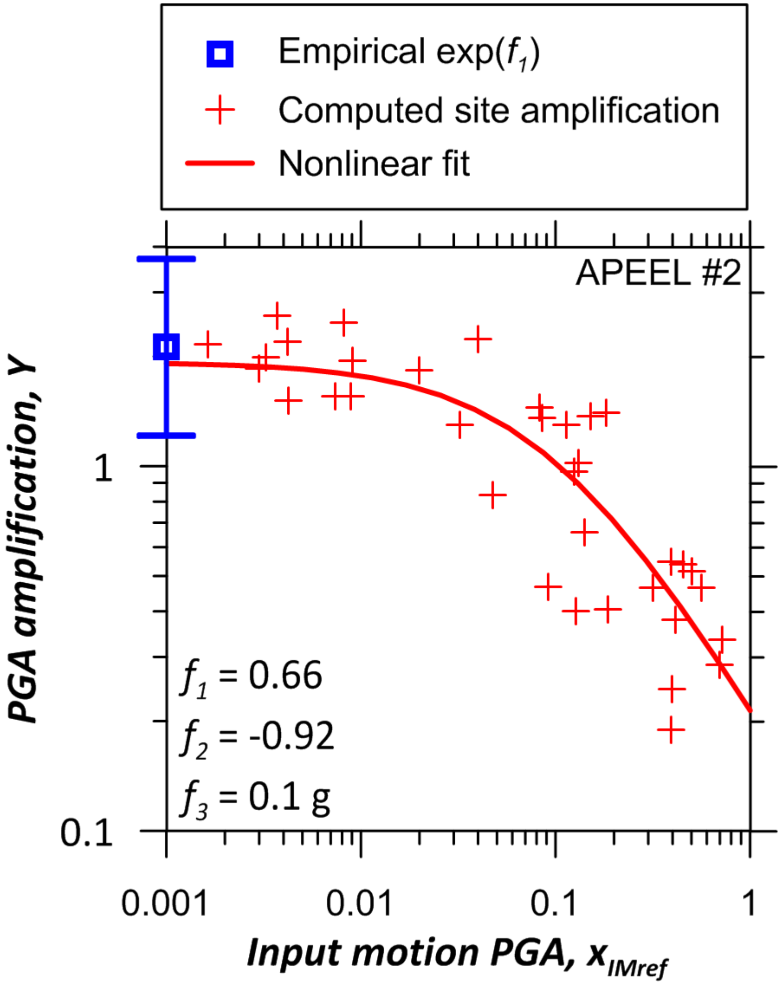
Amplification, Y
Period (sec)
0.01
0.1
1
10
Median empirical
Mean amplification 95% conf. int.
Ergodic (SS14)
GRA



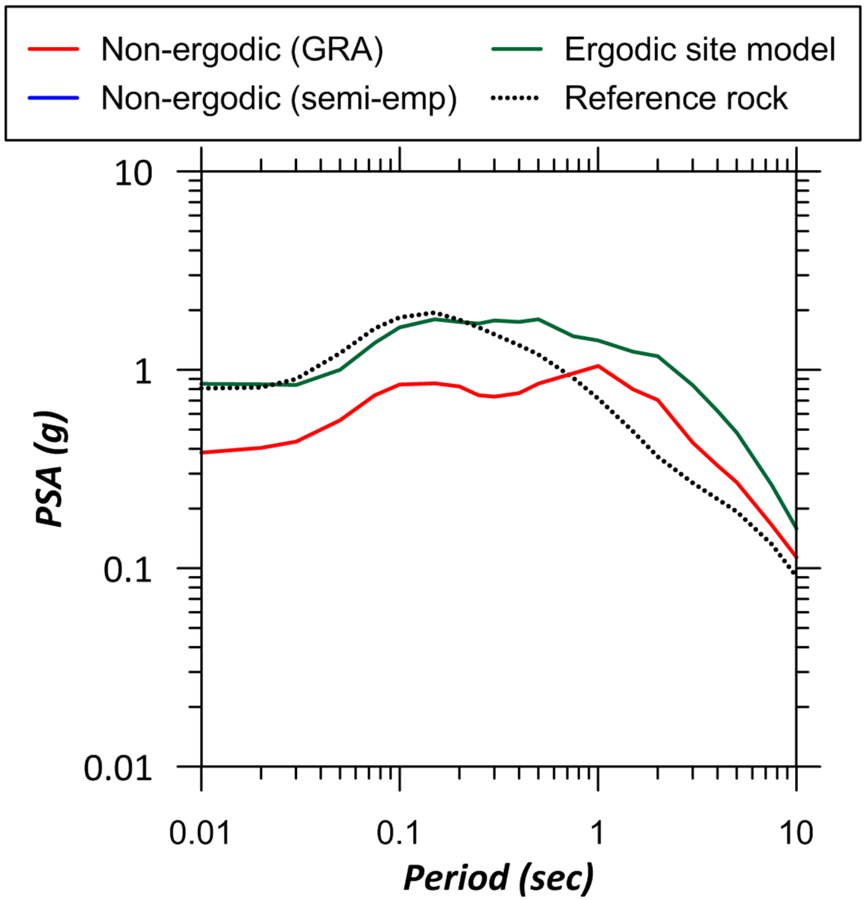
Vs (m/s)
0
500
1000
1500
Depth (m)
Clay
Sand
Sandy clay
Clay
Sand
Clay
Sand
Clay
Gravel
Clay
Sandy gravel
Clay
Sandy gravel
Sandy clay
Sand
Greywacke

Apeel #2

Simulations for nonlinear parameters:

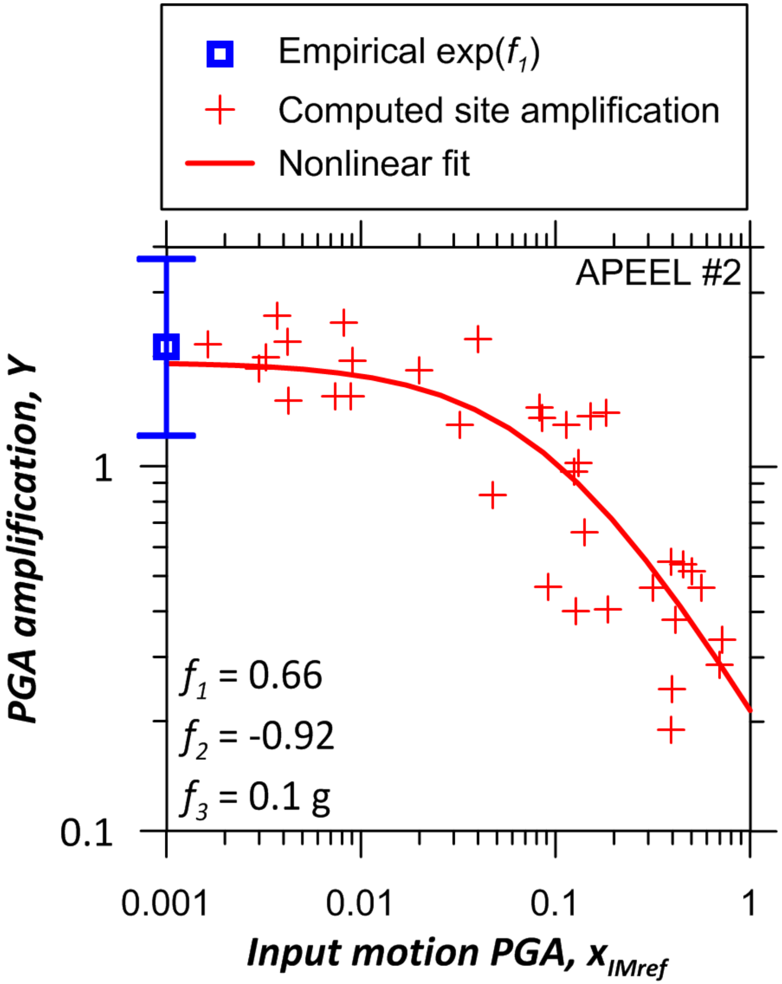


UHS: 2% Prob. exc. 50 yr

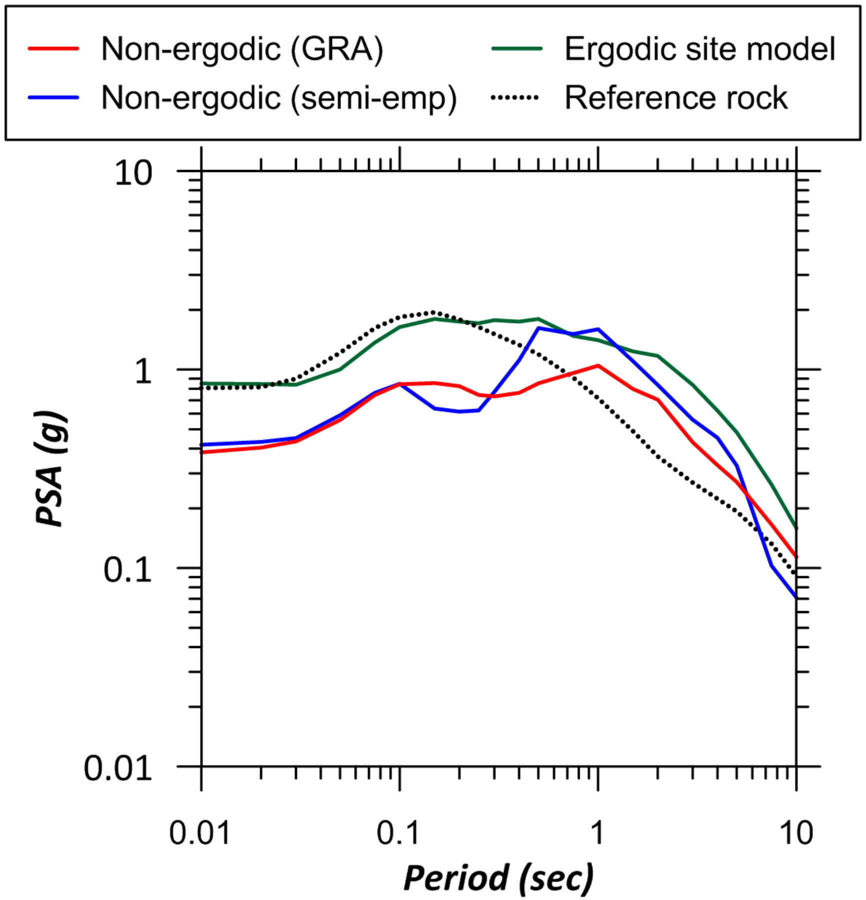


Apeel #2

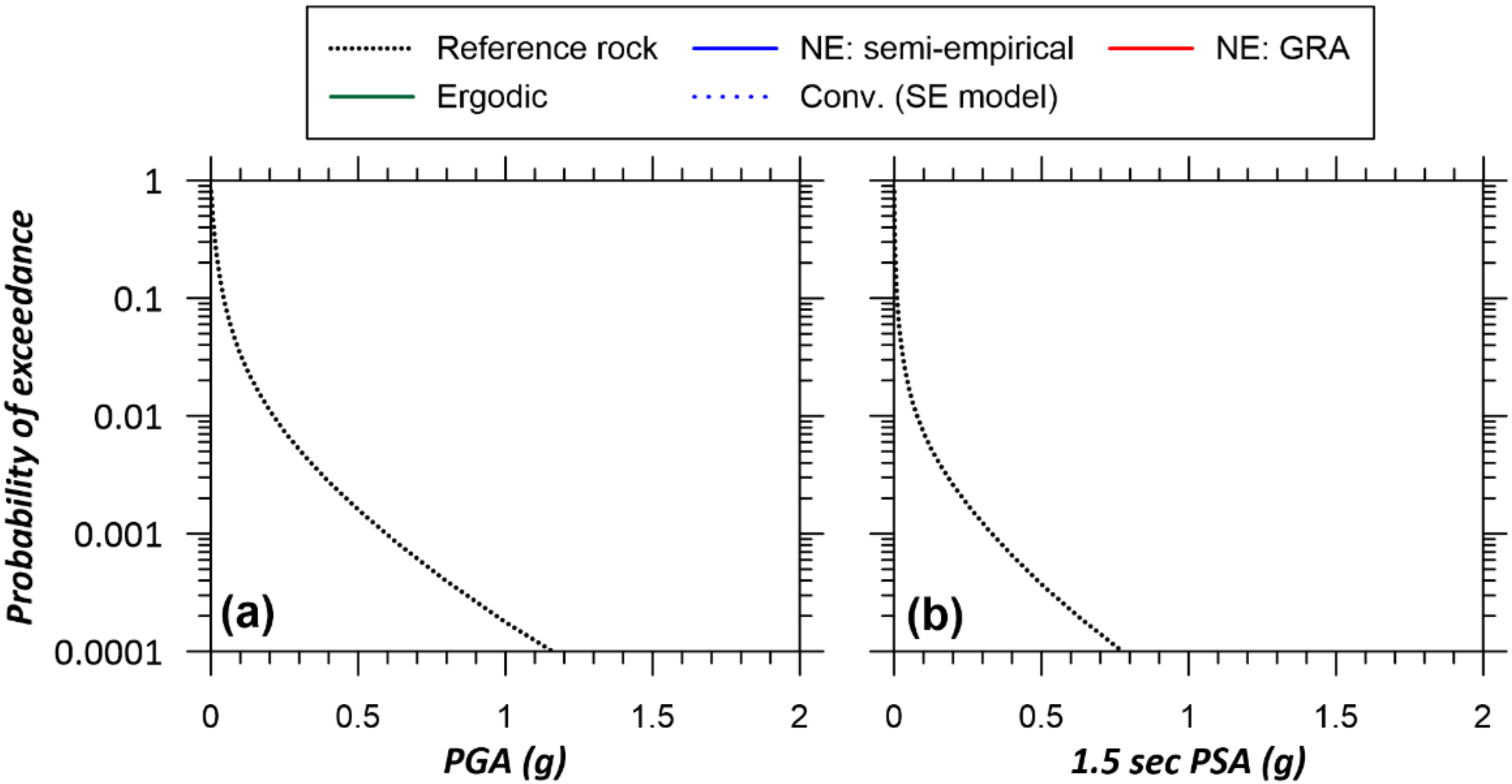
Simulations for nonlinear parameters:



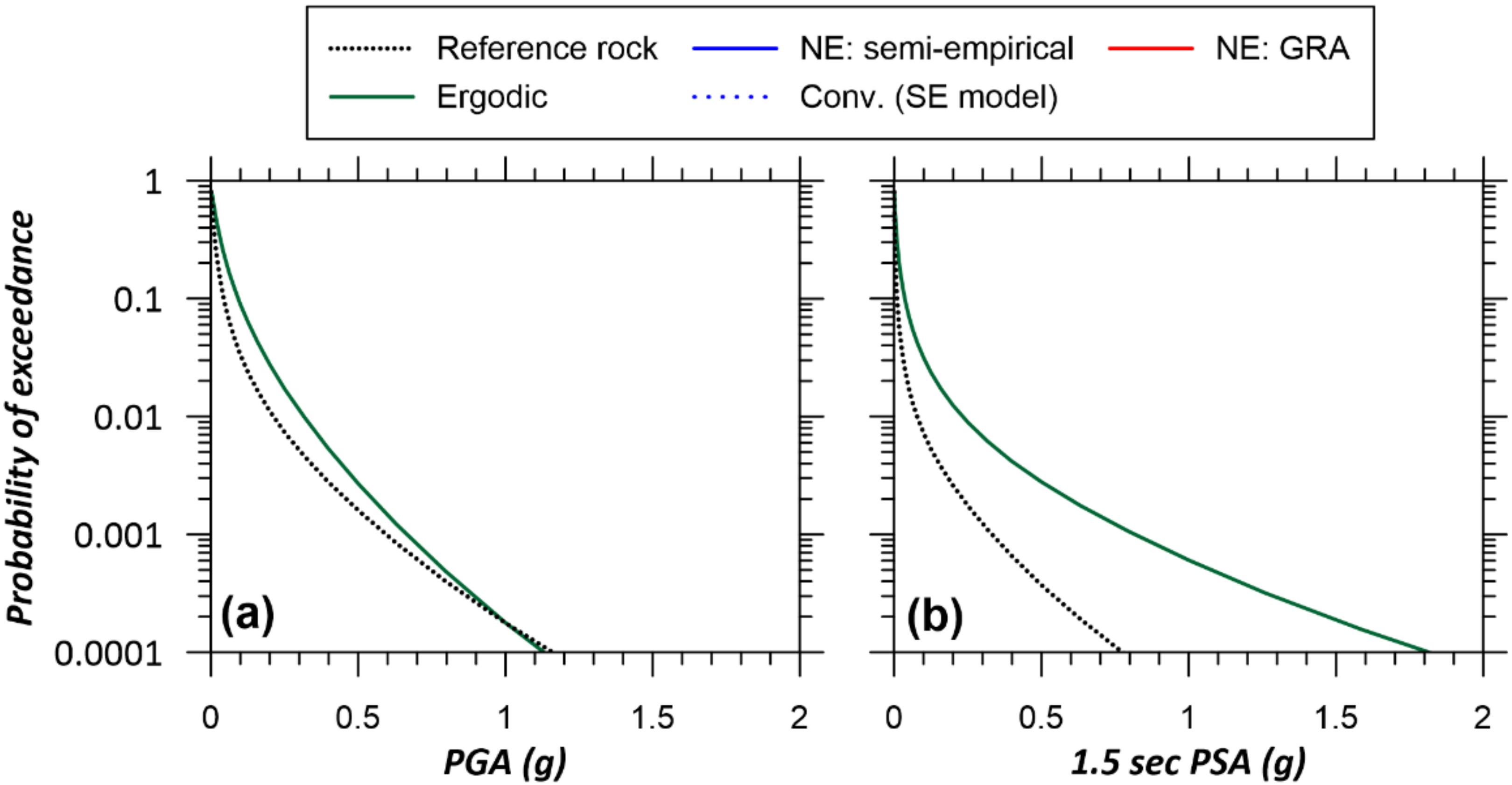
UHS: 2% Prob. exc. 50 yr



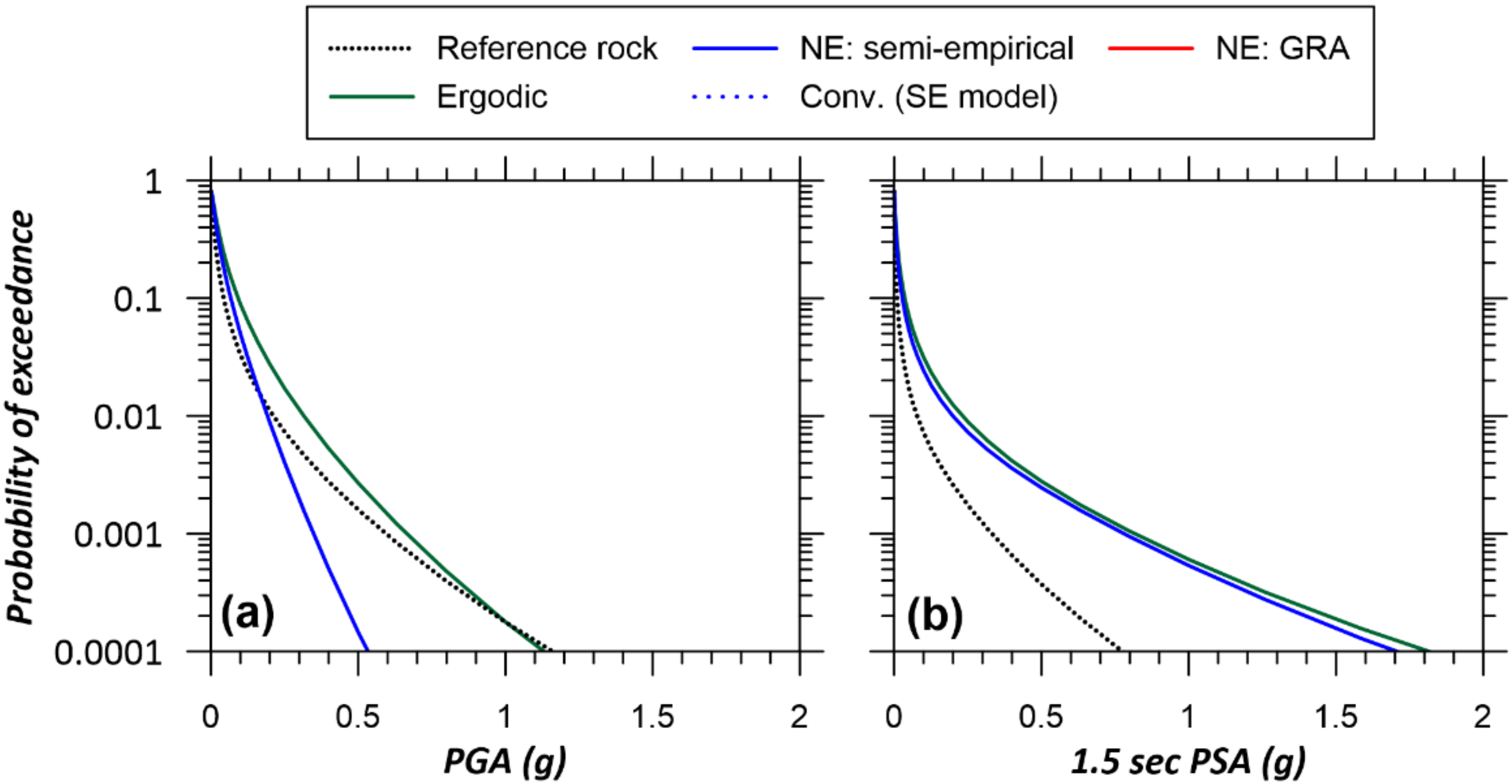
Apeel #2: Hazard Curves



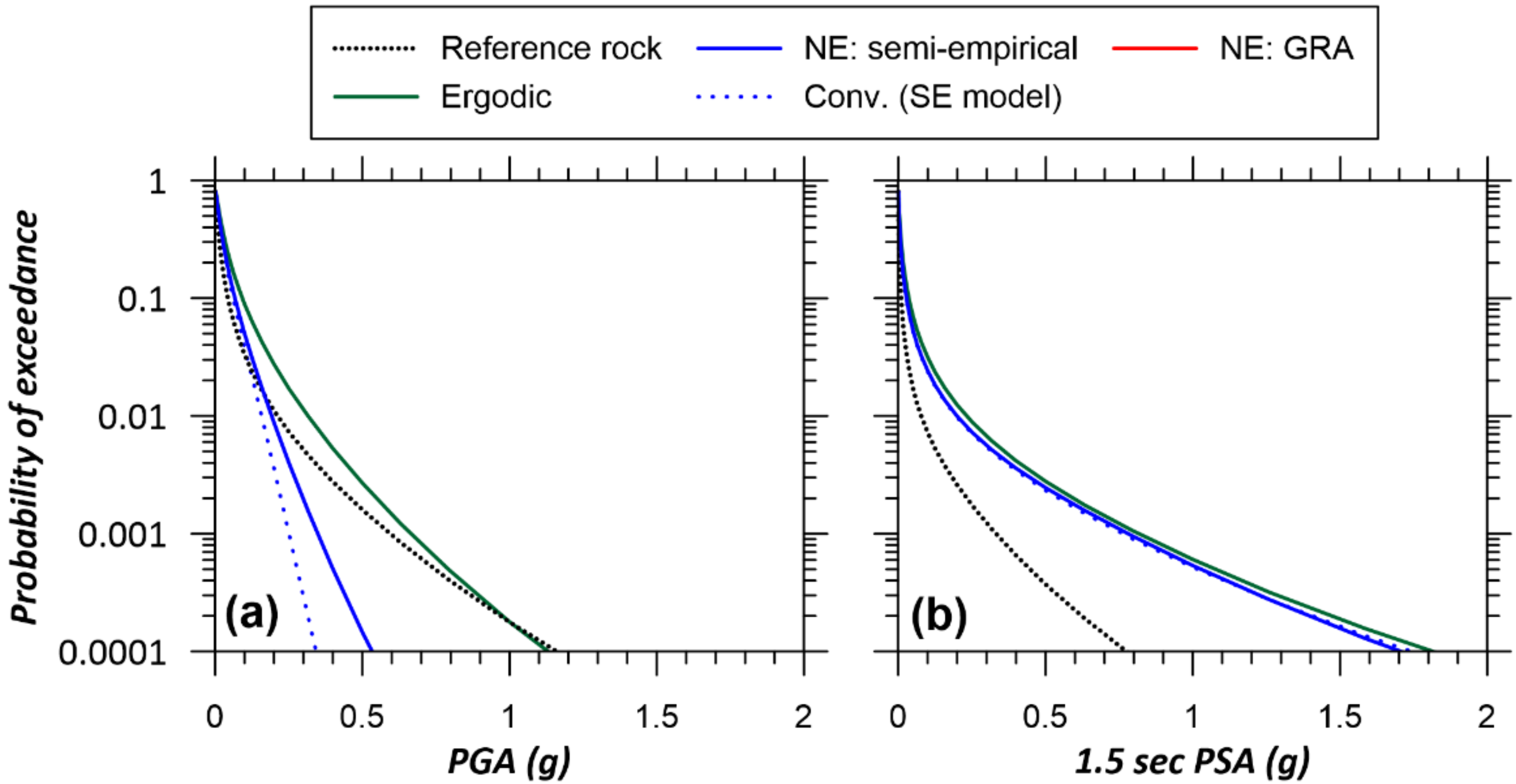
Apeel #2: Hazard Curves



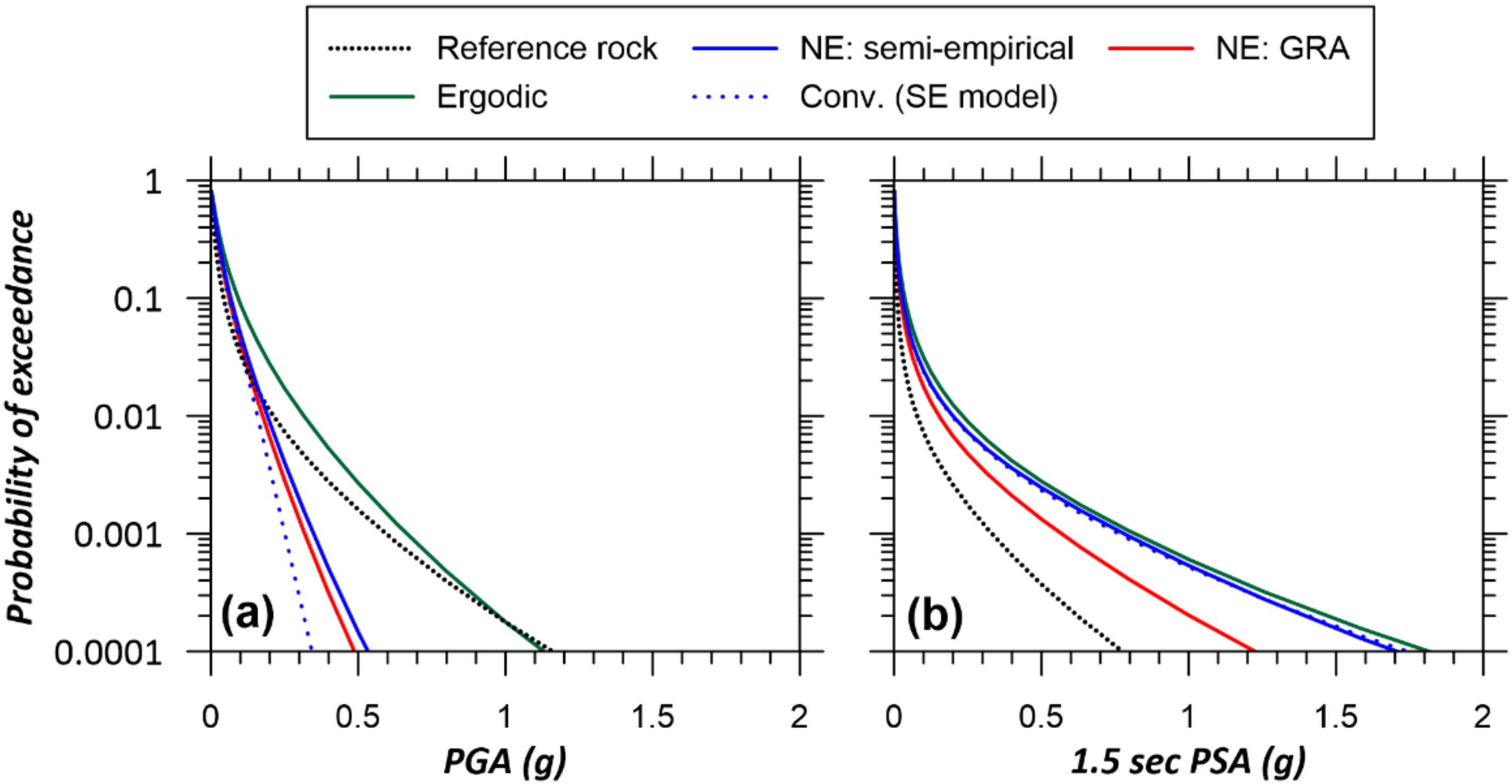
Apeel #2: Hazard Curves



Apeel #2: Hazard Curves



Apeel #2: Hazard Curves



Summary

- Ergodic (global) models easy to use, but sacrifice:
  - Precision. Loss of site-specific features.
  - Dispersion. Site-to-site variability must be included in hazard analysis.

Summary

- Non-ergodic amplification preferred
  - Mean can capture site-specific features, such as site period
  - Lower ϕ will tend to reduce hazard

Summary

- Best applied as site-specific GMPE
  - Nonlinear effects accurately modelled
  - Changes in ϕ applied
  - Enabled by non-ergodic option in OpenSHA
- Most recent site-specific analyses for major projects use convolution

Summary

- Use of on- or near-site recordings preferred for linear response (semi-empirical)
- GRA drawbacks:
  - Biased at long periods
  - Short-period accuracy depends on geologic complexity.

Summary

- More knowledge $\rightarrow$ lowered aleatory variability. Most often will reduce hazard appreciably
- If hazard matters in our risk analyses, we should be adopting these practices

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