Advances in Site Response Analysis to Improve Predictions for Design-Level Ground Motions

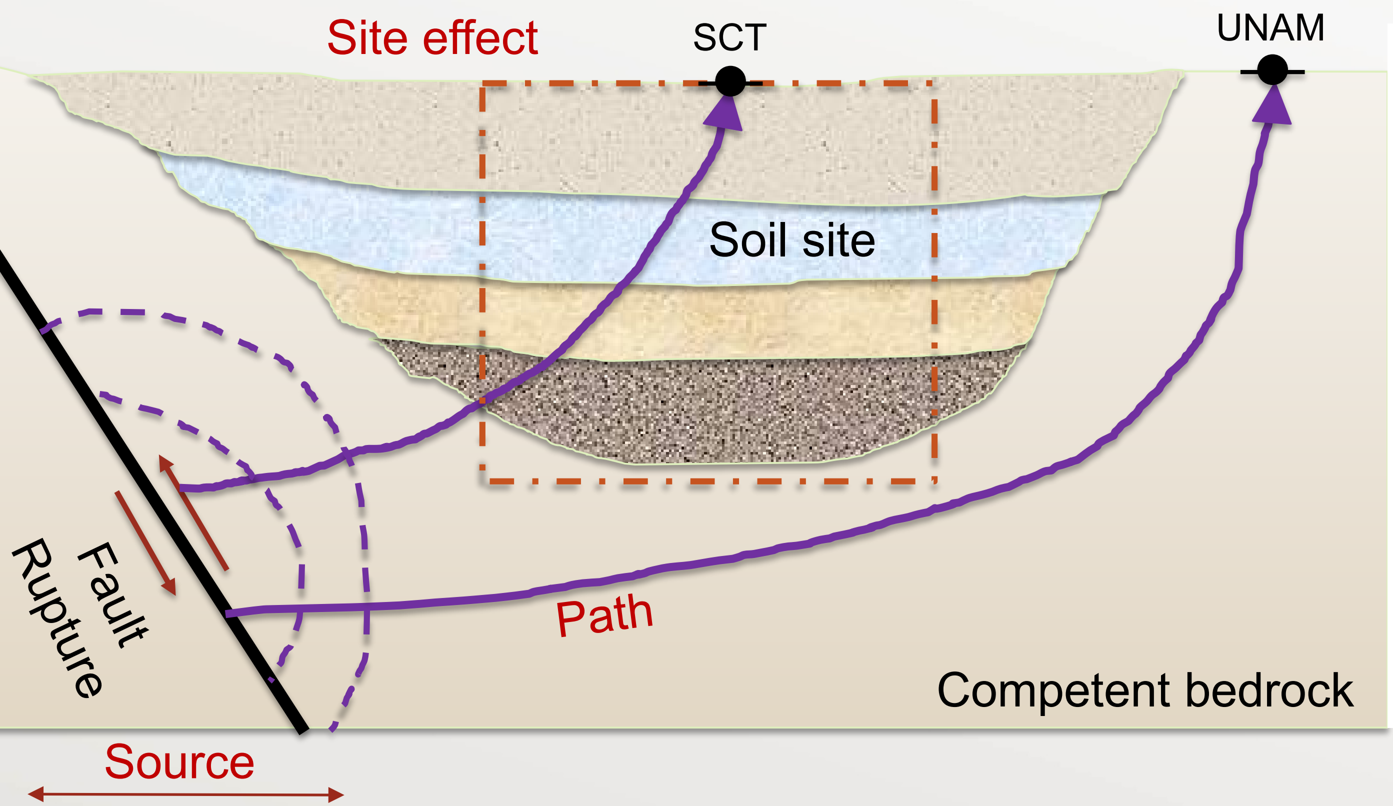
Prof. Ellen M. Rathje, Ph.D., P.E.

Janet S. Cockrell Chair in Engineering
Dept. of Civil, Arch., and Env. Engineering
University of Texas at Austin

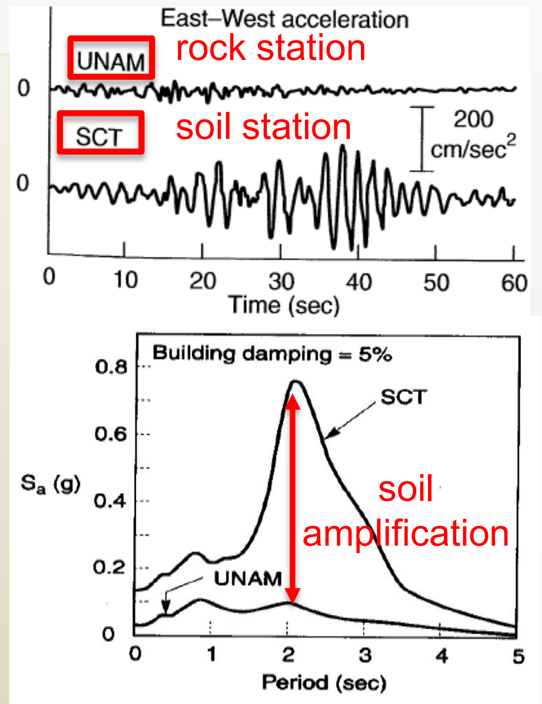
Dr. George Zalachoris, Dr. Yumeng Tao
Dr. Albert Kottke, Dr. Boqin Xu

Funding provided by Nuclear Regulatory Commission

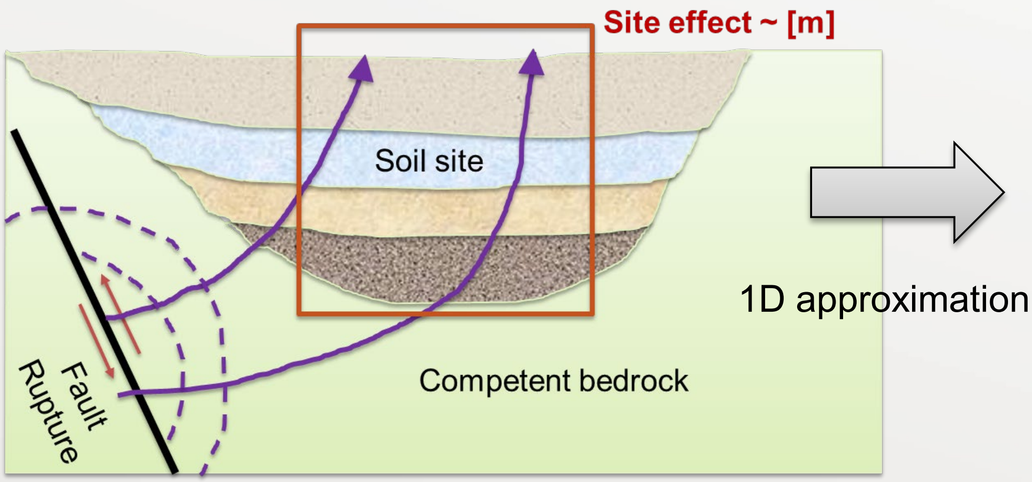
Site Effects and Site Response Analysis

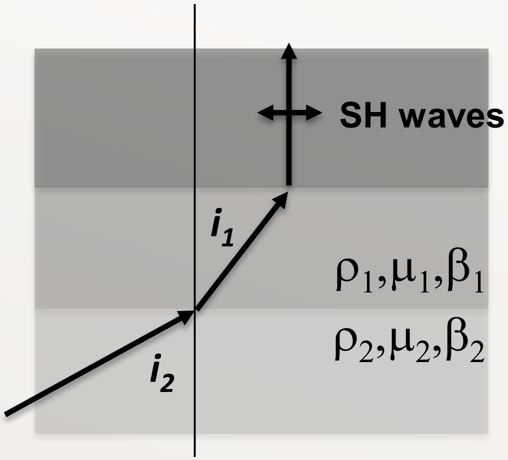


1985 Mexico City Earthquake



One-Dimensional (1D) Site Response Analysis





$$\frac{\sin i_1}{\beta_1} = \frac{\sin i_2}{\beta_2}$$

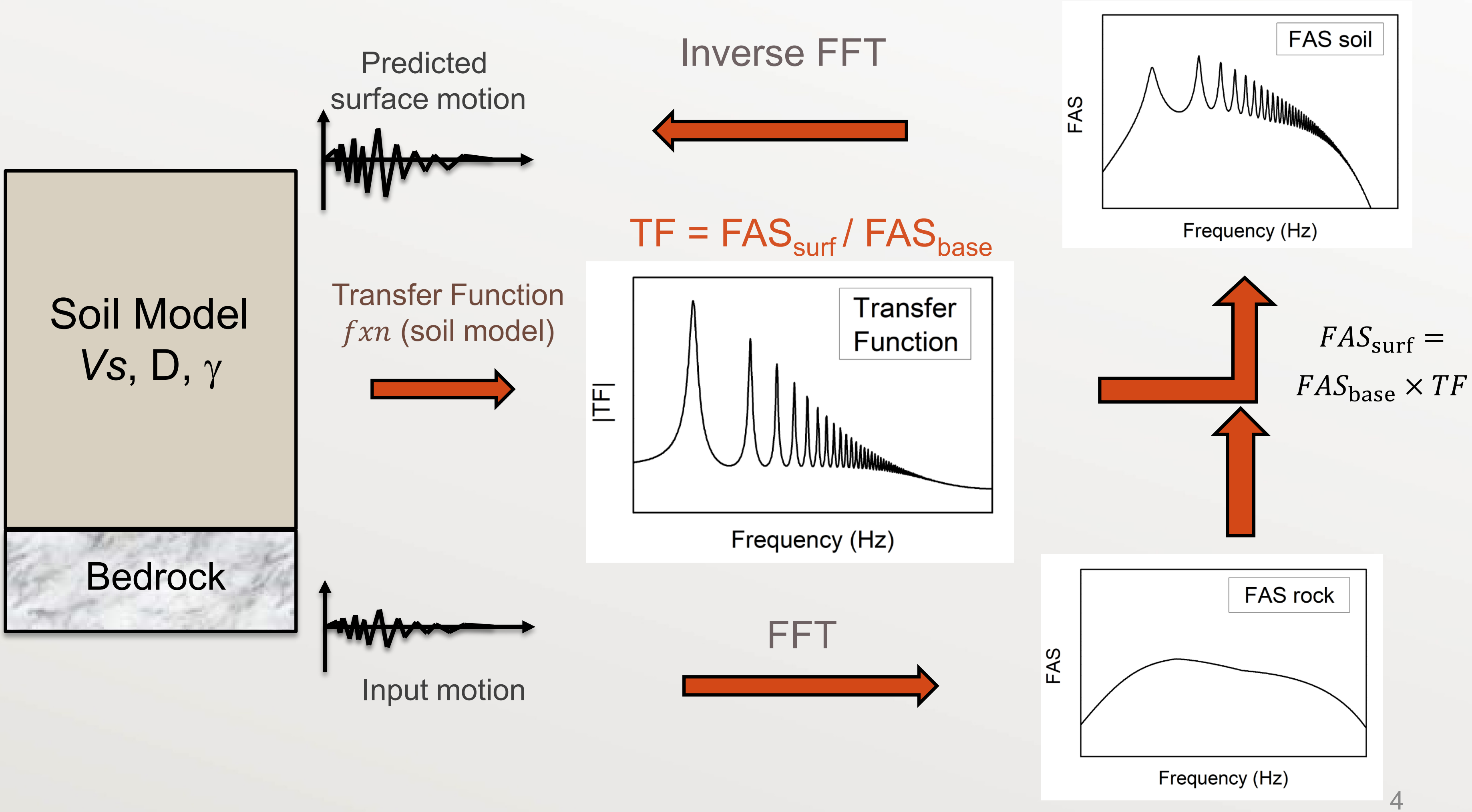
$$\beta_1 < \beta_2$$

<u>SH1D Assumption</u>

- All layer boundaries are horizontal and extend infinitely
- Soil response is predominantly controlled by vertically propagating, horizontally polarized SH waves

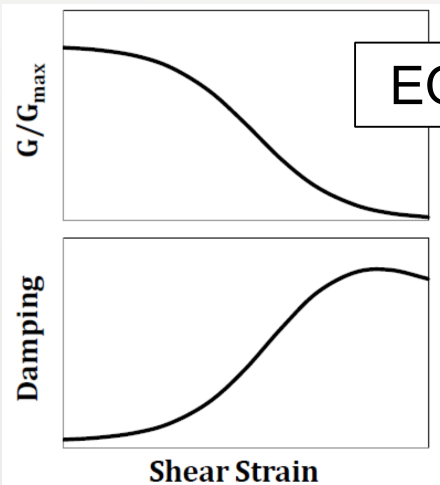
One-Dimensional (1D) Site Response Analysis

Frequency Domain (Shake-type) Approach



Modeling Nonlinear Soil Behavior

Equivalent-linear soil properties

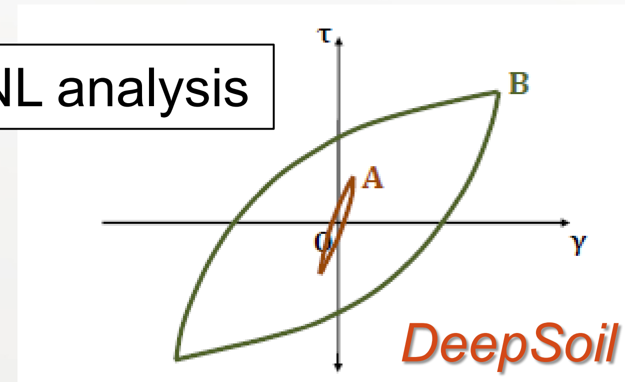


EQL analysis

Strata

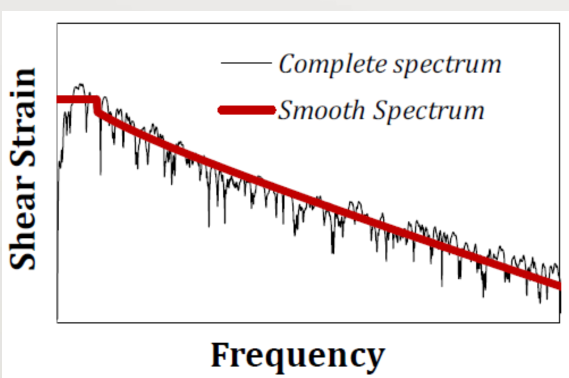
Nonlinear hysteretic soil behavior

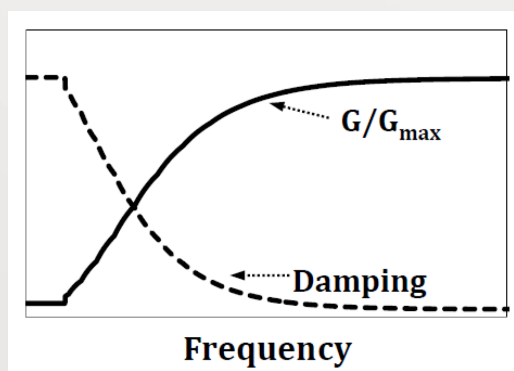
NL analysis



DeepSoil

Frequency-dependent shear strains





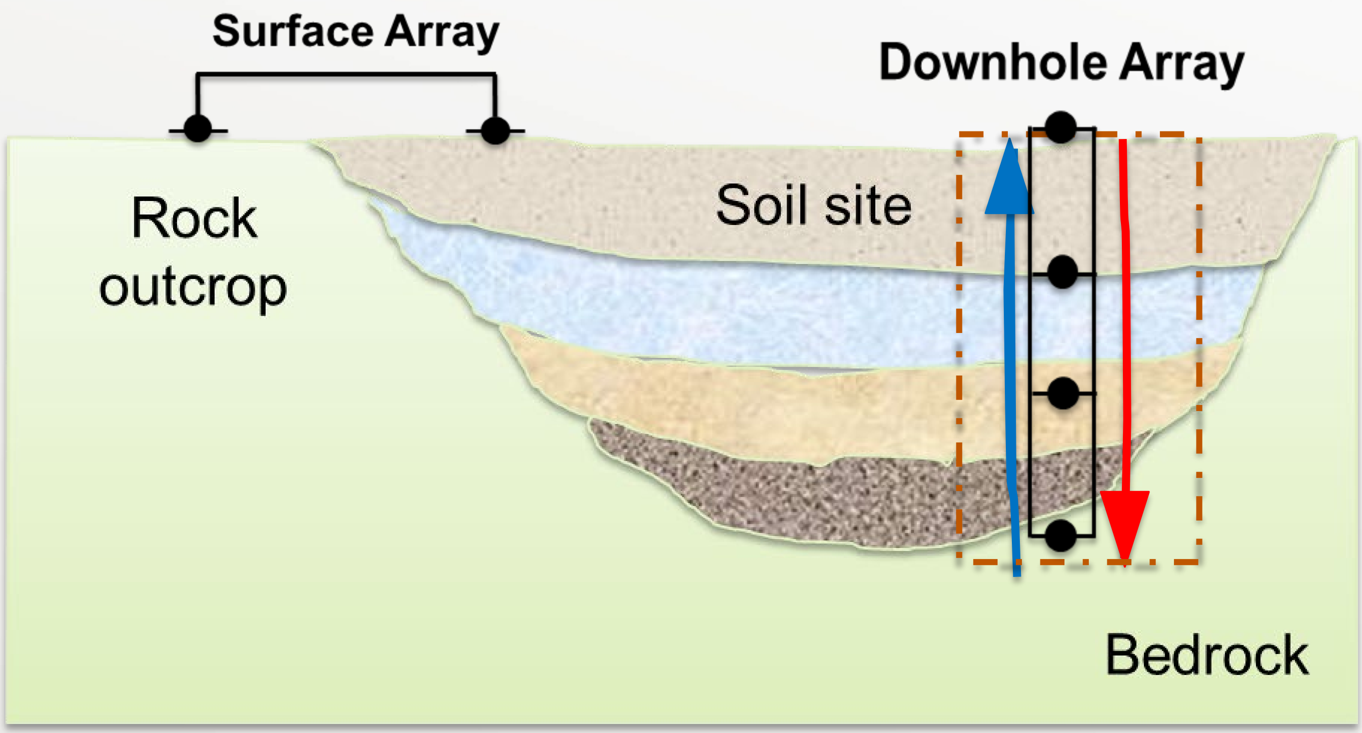
EQL-FD analysis

Strata

Outline

- ***Accuracy of 1D Site Response Analysis***
  - Use *small-strain* motions from downhole arrays to investigate validity of 1D analysis
- ***Large-Strain Site Response***
  - Use *large-strain* motions from downhole arrays to assess the accuracy of site response analysis for large-intensity, design level ground motions
- ***Strata Tool for Site Response Analysis***
  - Open-source code for site response analysis that provides unique capabilities

Evaluating Site Response Analysis



Issues with surface array:

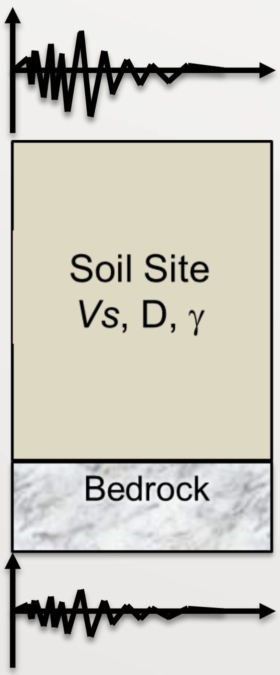
- Difficult to find rock outcrop near soil site
- Rock site has its own site response

Downhole array:

- Most direct observation of site response
- Kik-Net arrays in Japan, arrays in other parts of the world

Evaluating Site Response Analysis

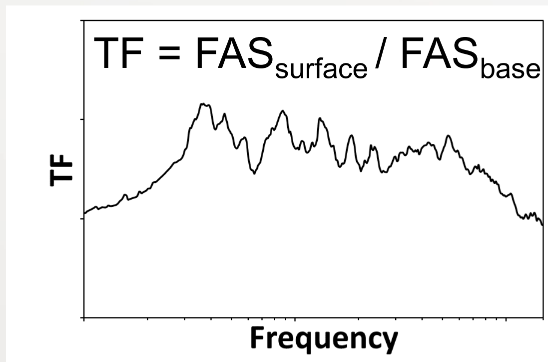
Surface recording or prediction



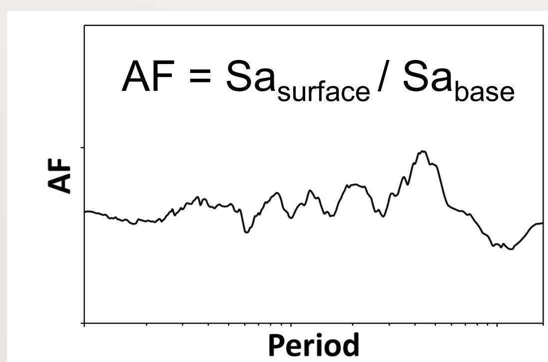
Base recording

Observed Response

Transfer Function

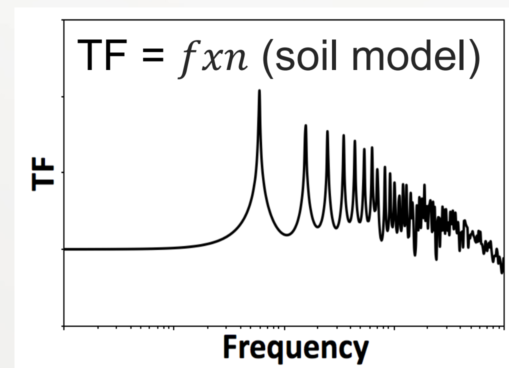


Amplification Factor

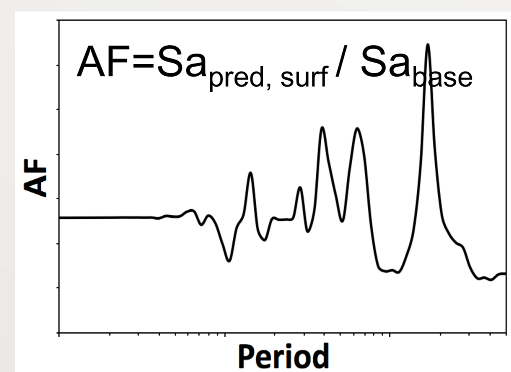


Predicted Response

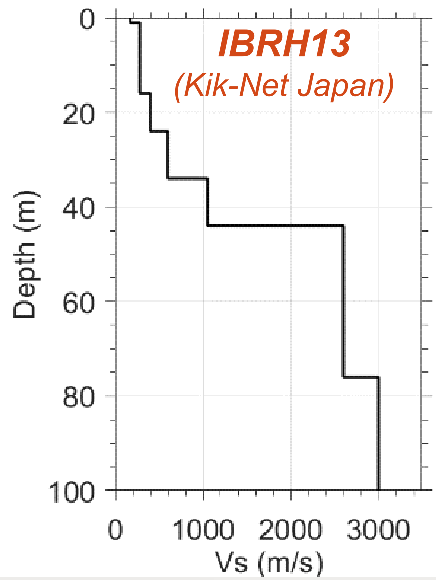
Transfer Function

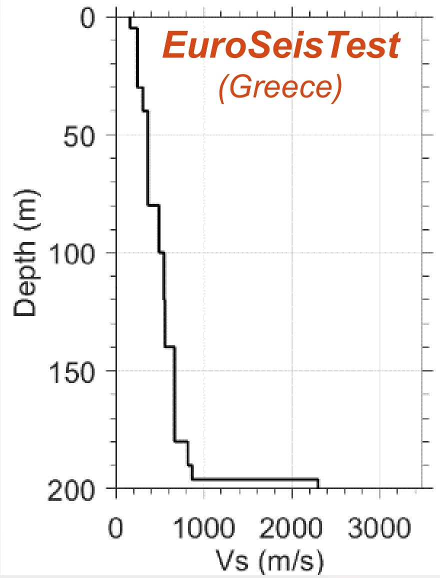


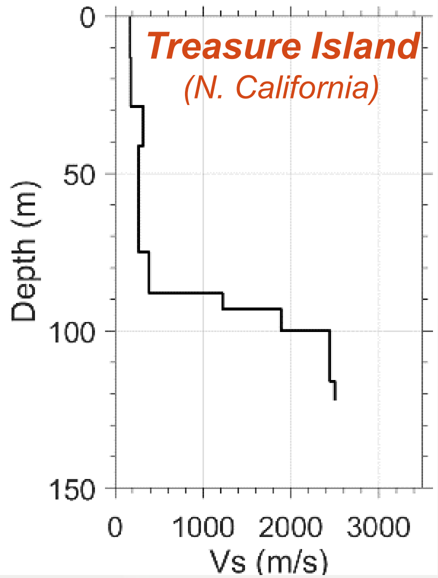
Amplification Factor

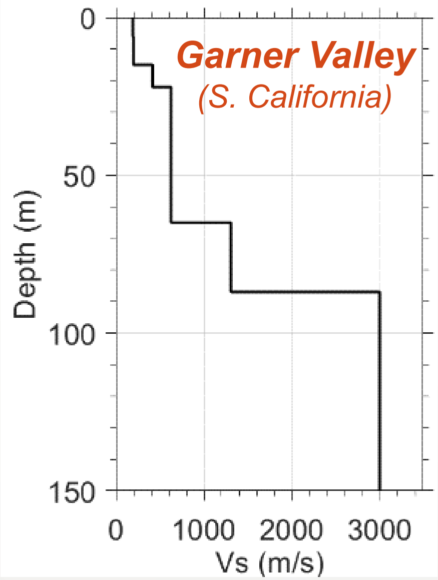


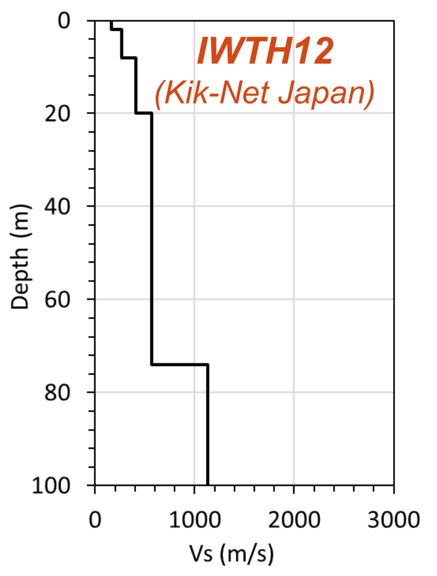
Downhole Array Sites

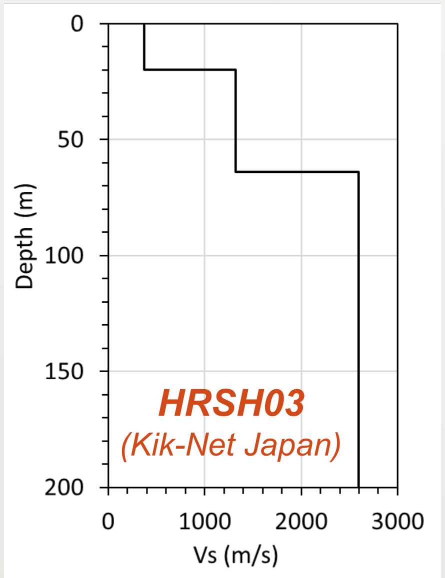






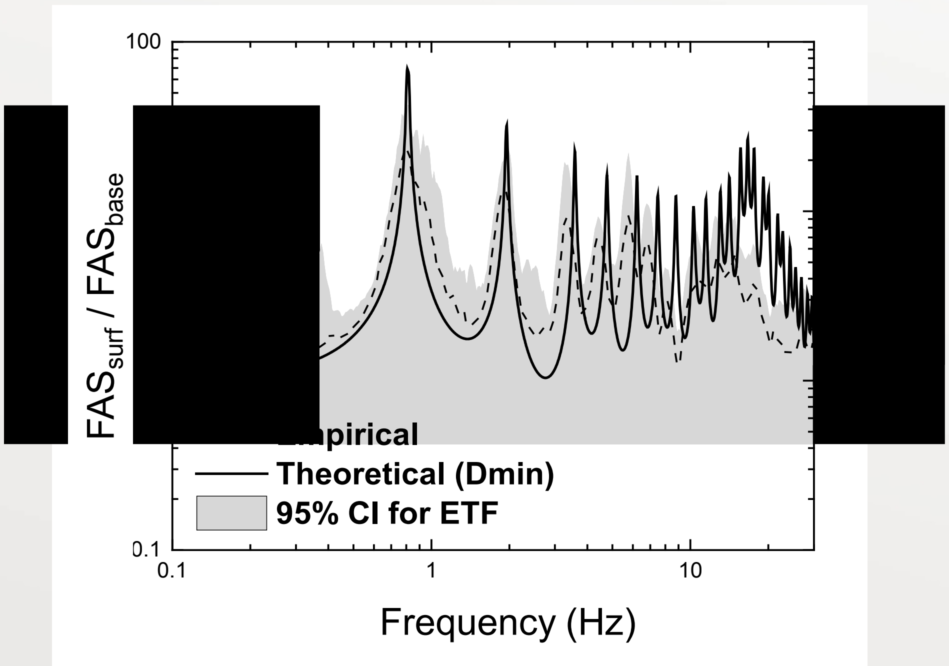




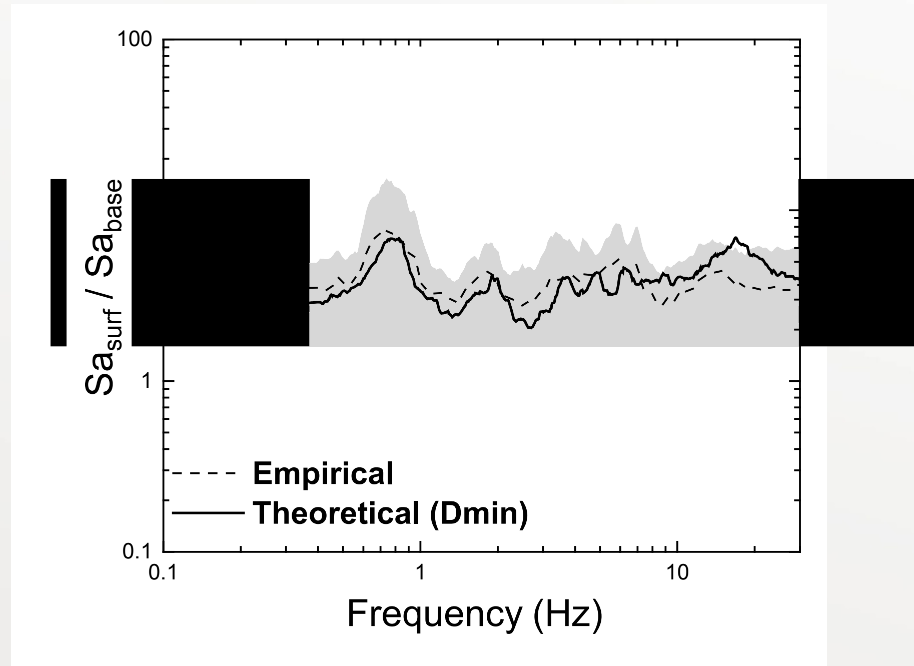


Treasure Island Response

Transfer Function

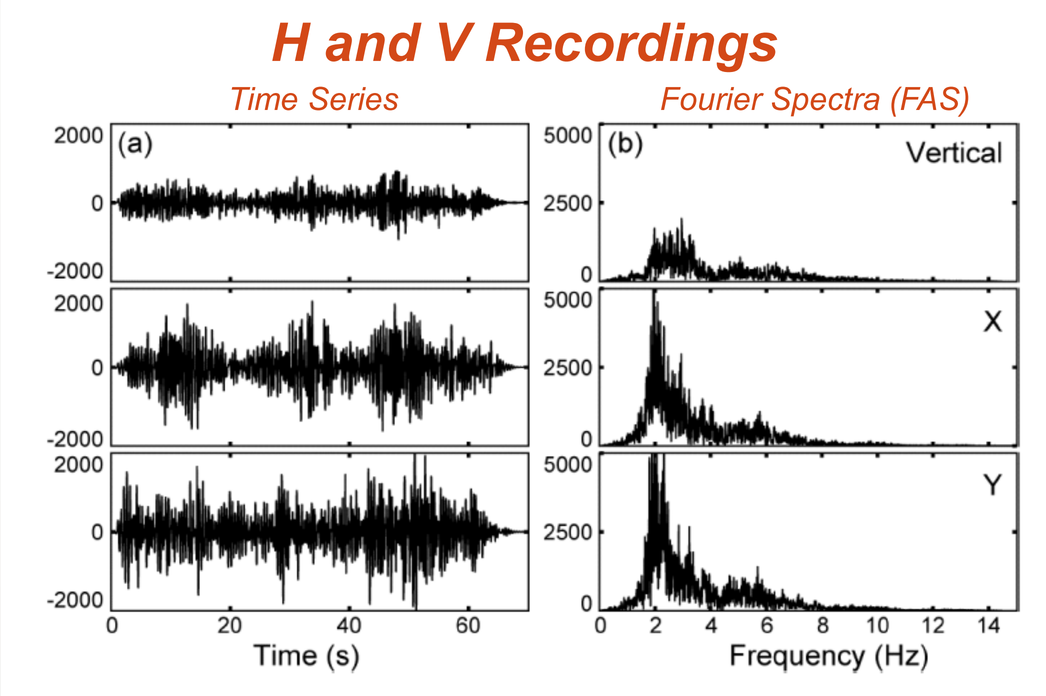


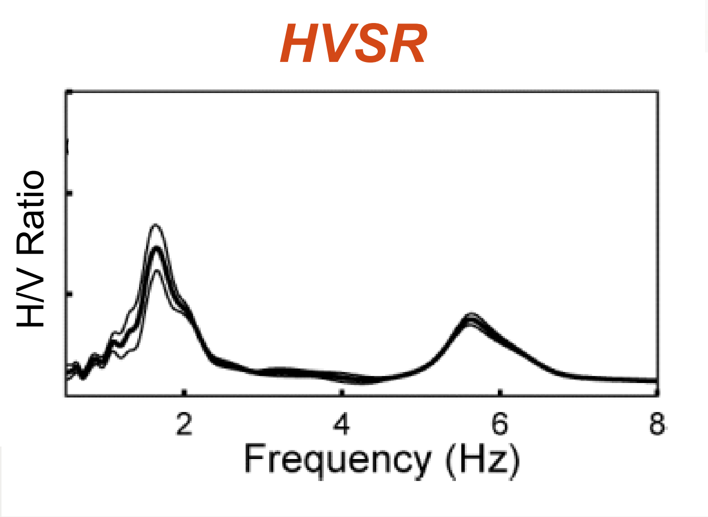
Amplification Factor



How can we confirm resonant frequencies at a site that is not a downhole array??

Horizontal to Vertical Spectral Ratio (HVSR)



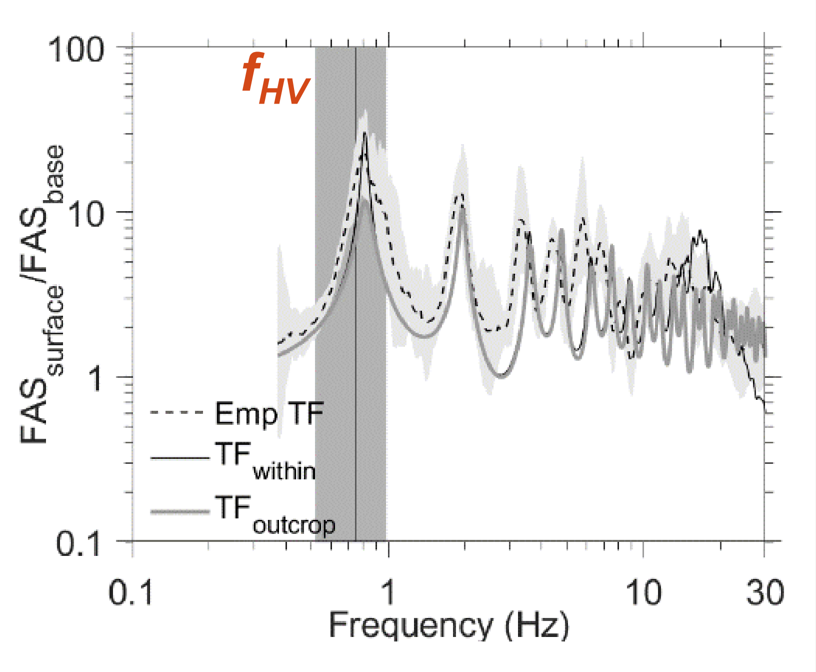


Bonnefoy-Claudet et al. (2006)

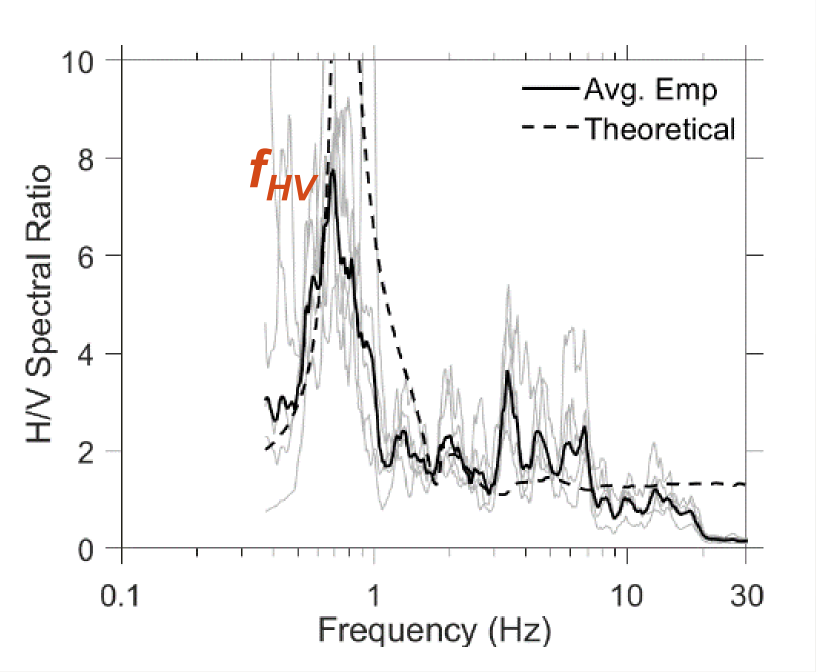
- Peak in HVSR coincides with first mode frequency of site
- HVSR can be measured from noise as part of site characterization with a single 3-component sensor

Treasure Island Response

Transfer Function



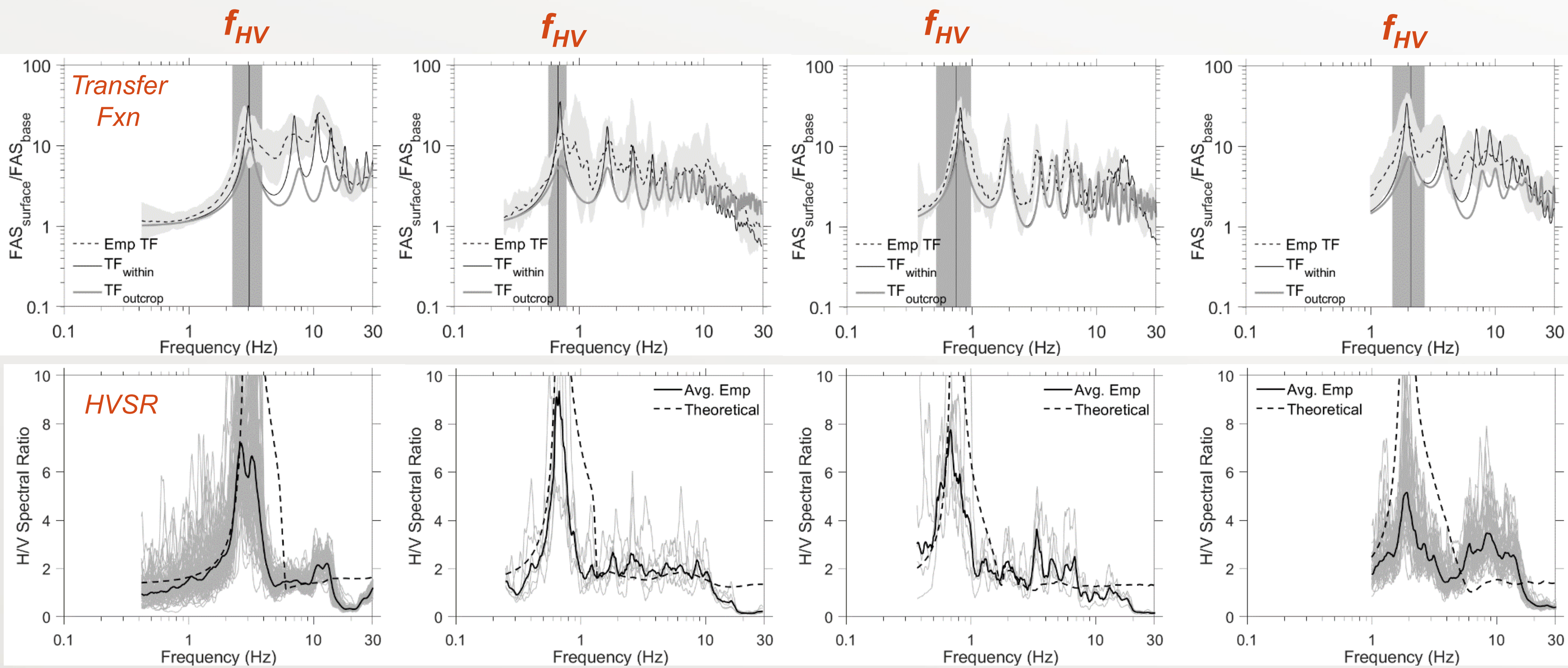
HVSR



Peak in HVSR spectrum (f_{HV}) is consistent with observed TF and predicted TF

Transfer Functions and HVSR

IBRH13	**EuroSeisTest**	**Treasure Island**	**Garner Valley**
(Kik-Net Japan)	*(Greece)*	*(N. California)*	*(S. California)*

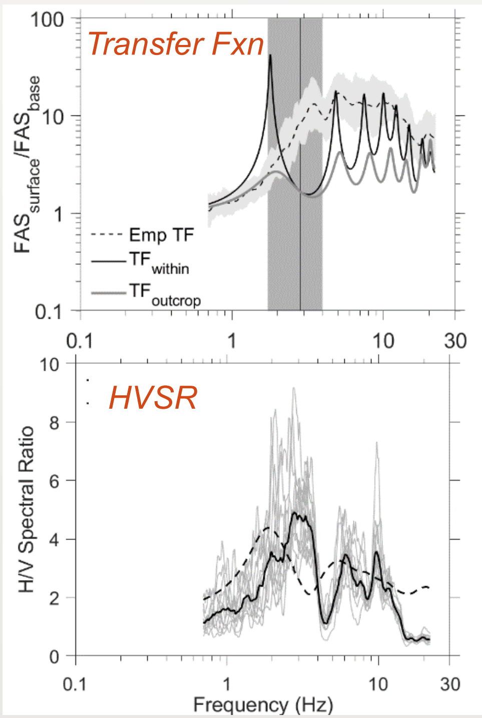


24 of 31 sites analyzed (77%) showed consistency between peaks in observed TF, predicted TF, and f_{HV}

Transfer Functions and HVSR

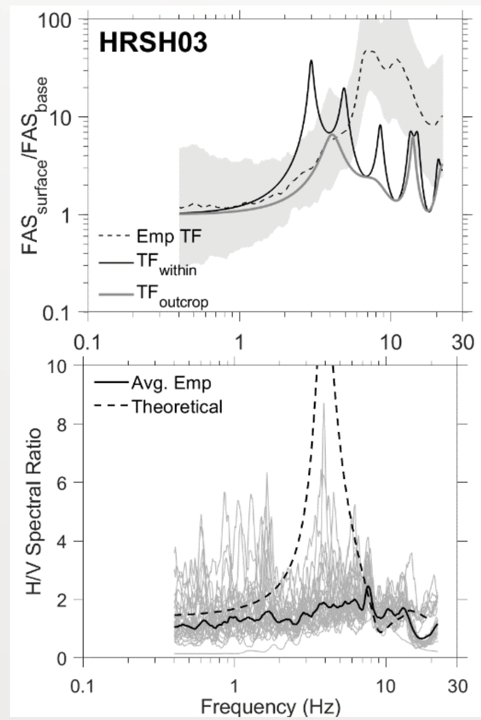
IWTH12 (Kik-Net Japan)

f_{HV}



HRSH03 (Kik-Net Japan)

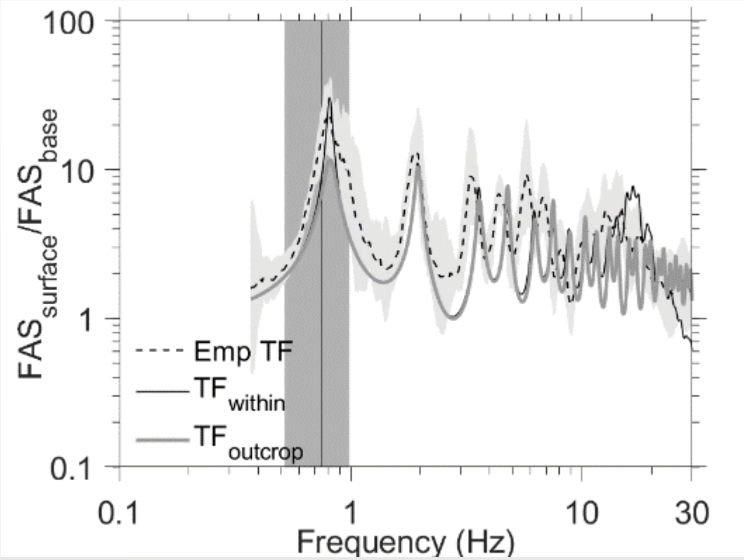
No f_{HV}

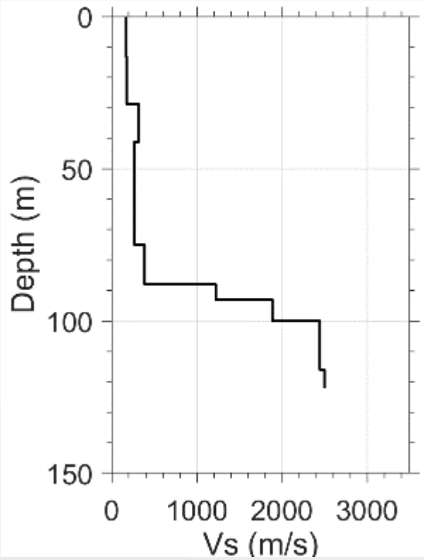


7 of 31 sites analyzed (23%) showed inconsistency between peaks in observed TF, predicted TF, and f_{HV}

Observations

- Characteristics of sites modeled well by 1D analysis
  - These sites have a clear HVSR peak that is consistent with the theoretical TF from the Vs profile
  - These sites tends to have a Vs contrast within the profile

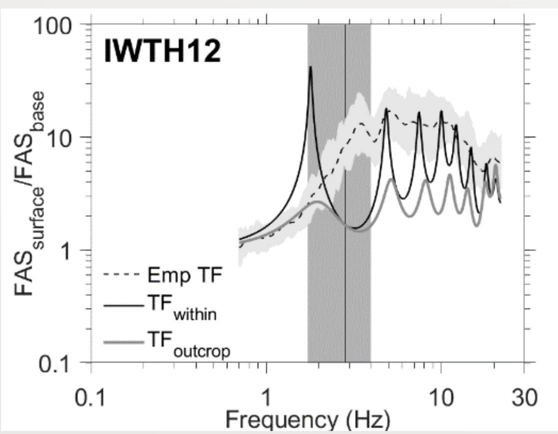


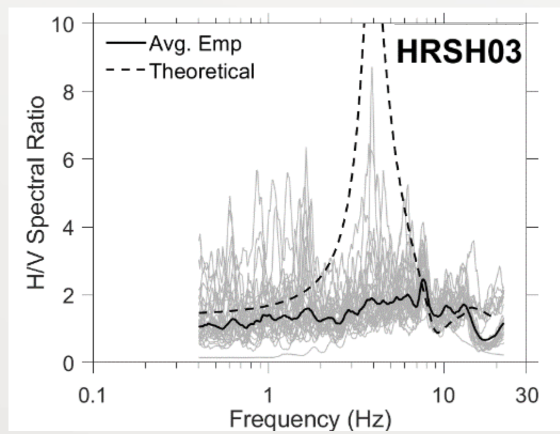


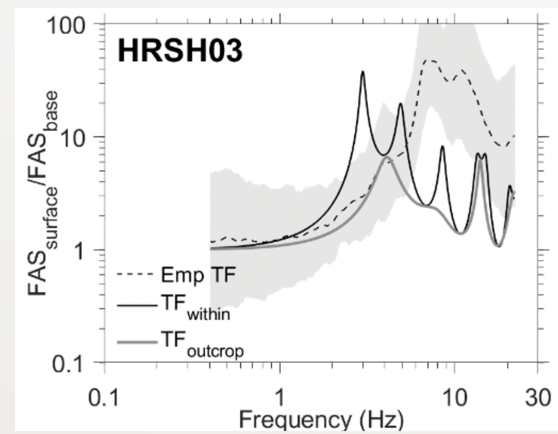
Tao and Rathje (2019) accepted *Soil Dynamics and Earthquake Eng.*

Observations

- Sites not modeled well by 1D analysis have inconsistent HVSR peak or no peak
  - Inaccurate Vs profile? Basin effects? Topographic effects?







HVSR is an important component of a seismic site characterization

Outline

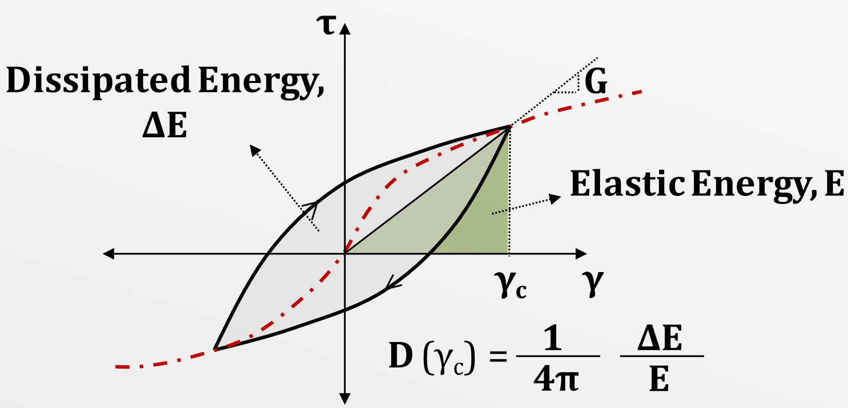
- ***Accuracy of 1D Site Response Analysis***
  - Use *small-strain* motions from downhole arrays to investigate validity of 1D analysis
- ***Large-Strain Site Response***
  - Use *large-strain* motions from downhole arrays to asses the accuracy of site response analysis for large-intensity, design level ground motions
- ***Strata Tool for Site Response Analysis***
  - Open-source code for site response analysis that provides unique capabilities

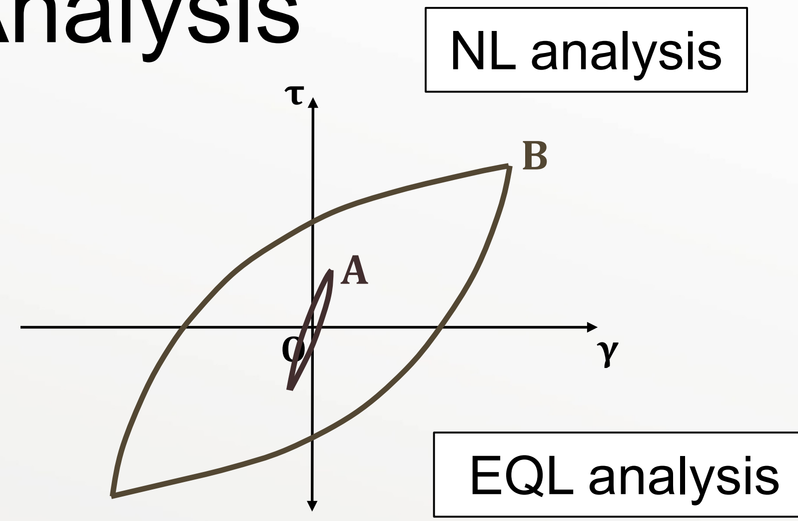
Large-Strain Site Response

- Analyze downhole arrays using:
  - Equivalent-linear (EQL) analysis
  - Nonlinear (NL) analysis
  - EQL analysis with frequency-dependent properties (EQL-FD)
  - EQL analysis with κ scaling
- Compare predicted and observed amplification of spectral acceleration (AF)
- Consider low-intensity and large-intensity motions

Strata and DeepSoil

EQL and NL Analysis





- Low strain hysteretic loops (**A**)

⬇

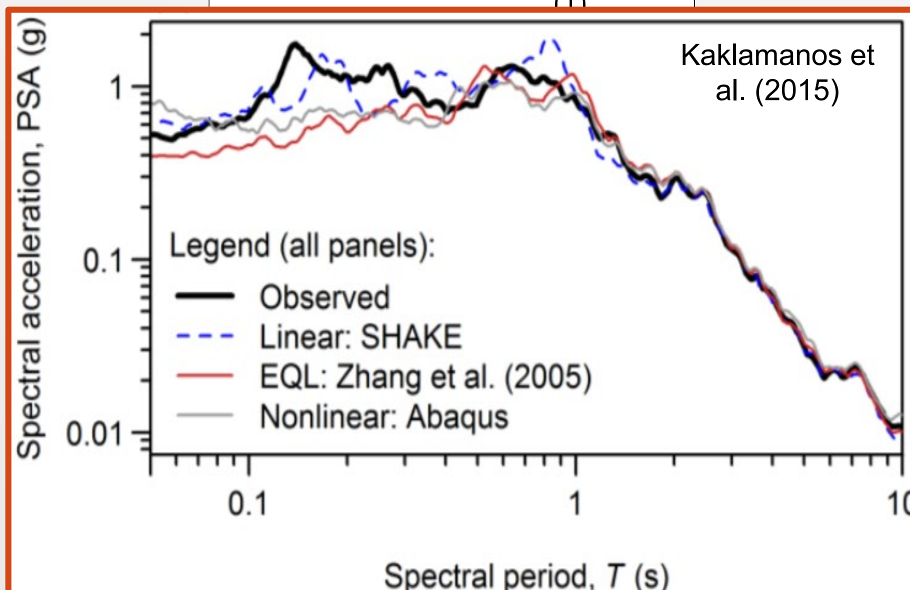
large G/G_{max} ; *small* Damping

- Large strain hysteretic loops (**B**)

⬇

small G/G_{max} ; *large* Damping

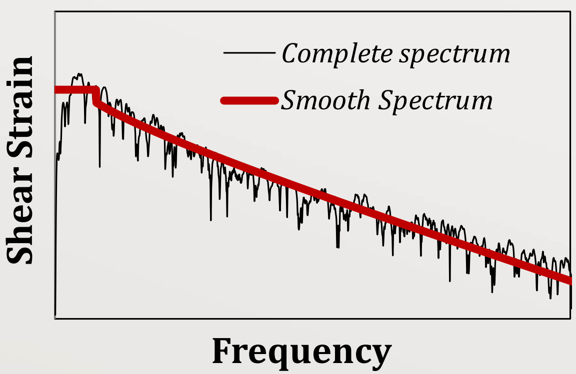
Issue: over-damping of high frequencies when large strains are induced



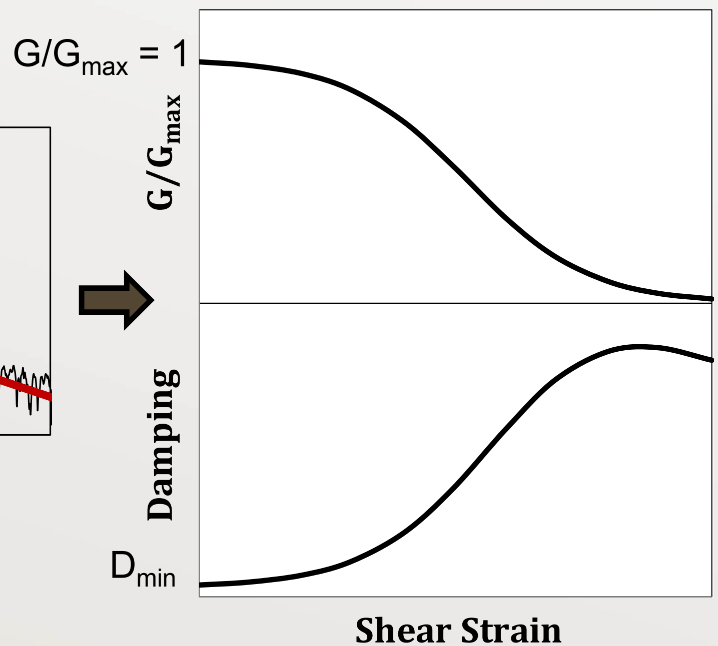
EQL with Frequency Dependent Properties (EQL-FD)

<u>Concept</u> → Convert *frequency-dependence* of **shear strains** to *frequency-dependence* of **G/G$_{max}$** and **Damping** via *nonlinear material curves*

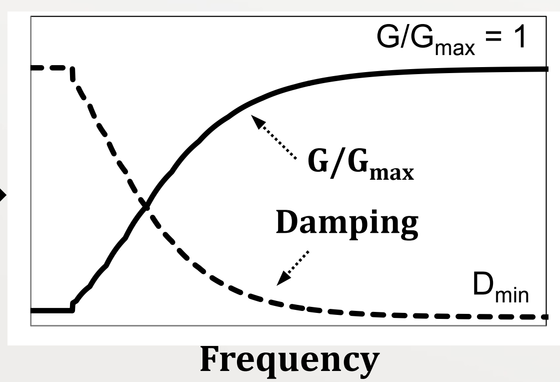
Frequency-Dependent Shear Strains



Nonlinear Material Curves

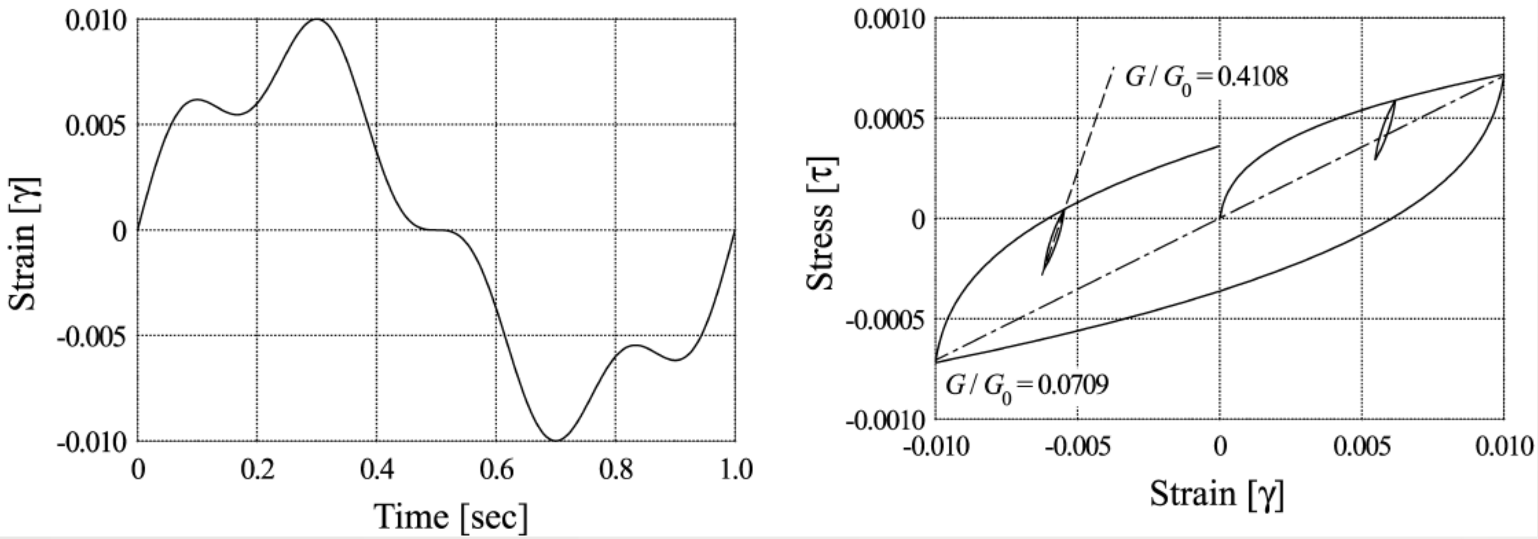


Frequency-Dependent G/G$_{max}$ and Damping



EQL-FD Physical Justification

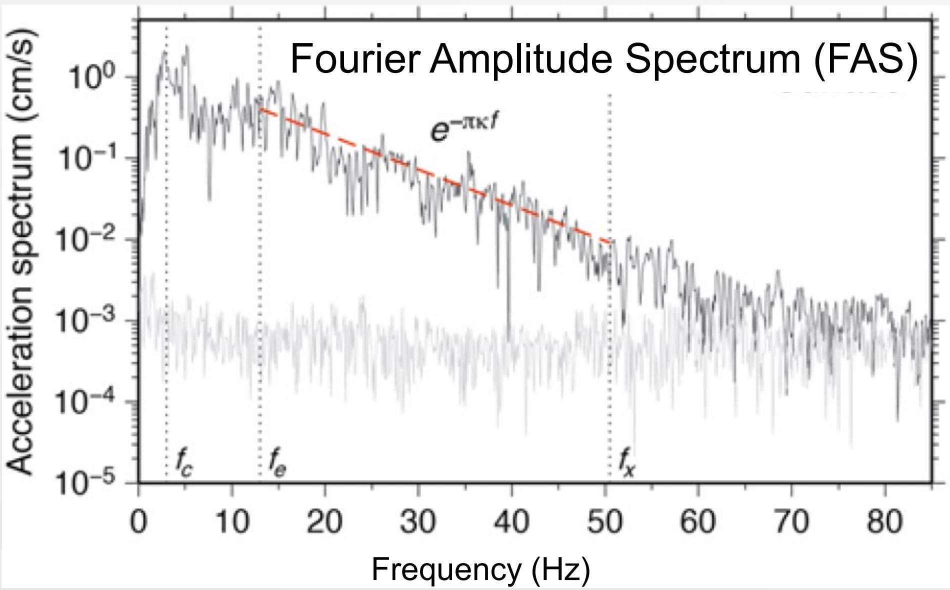
High frequencies represent shear stress reversals that are stiffer and have less damping



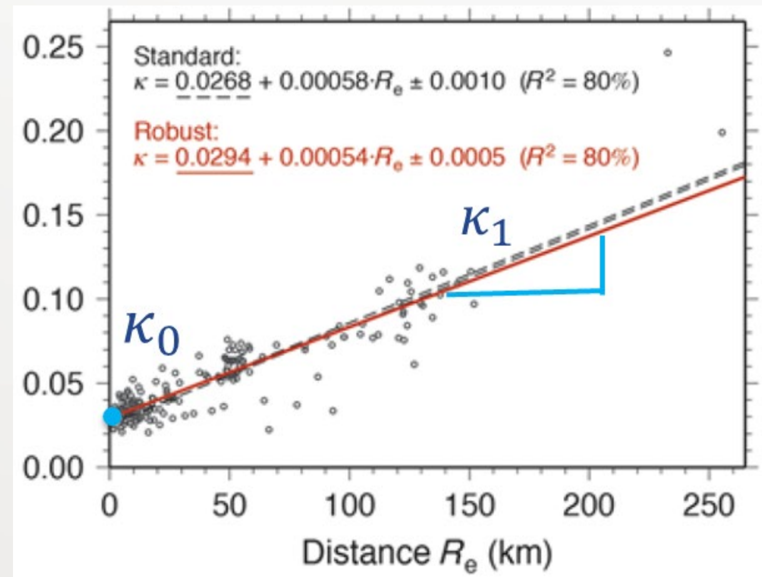
(Assimaki and Kausel 2002)

Kappa (κ)

High frequency spectral decay parameter (κ)



(Ktenidou. et. al 2013)



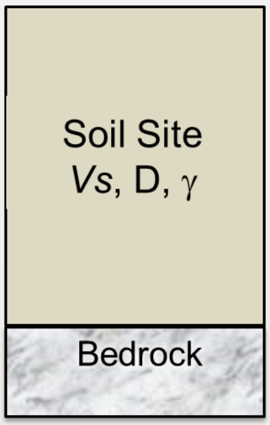
"Site κ"

FAS(f) $\propto \exp(-\pi \cdot \kappa \cdot f)$

$\boldsymbol{\kappa_0}$: κ at R = 0

Kappa (κ) Relationship with Damping

Surface



Base rock

$$\kappa_{o,surf} = \kappa_{o,base} + \Delta\kappa_{soil}$$

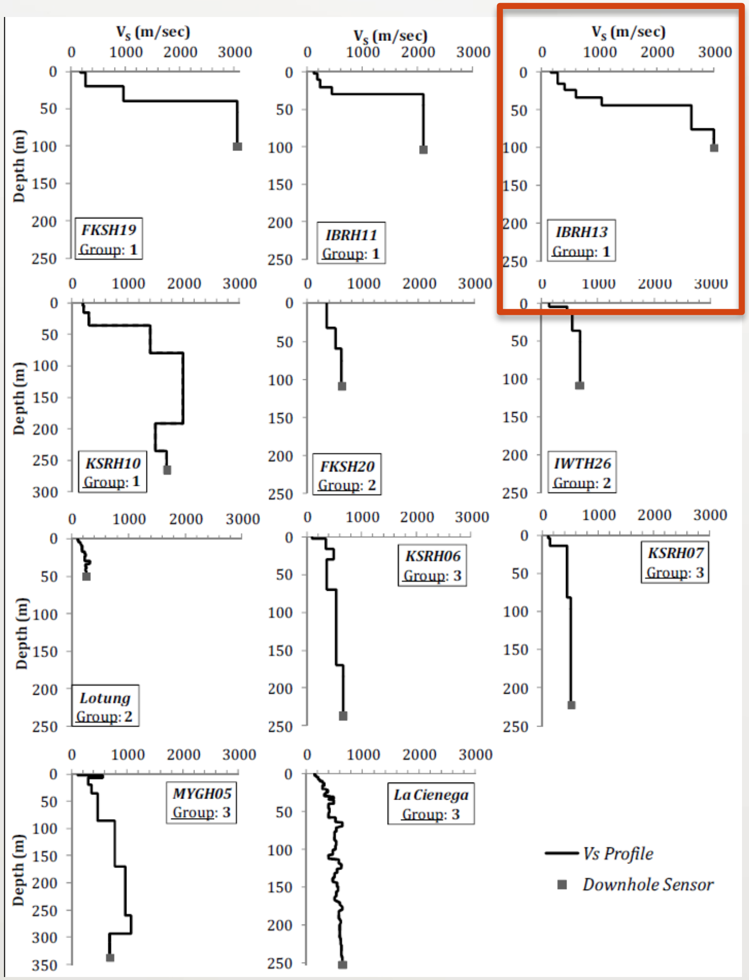
$$\kappa_{o,surf} = \kappa_{o,base} + \int \frac{2 \cdot D}{V_s} dz$$

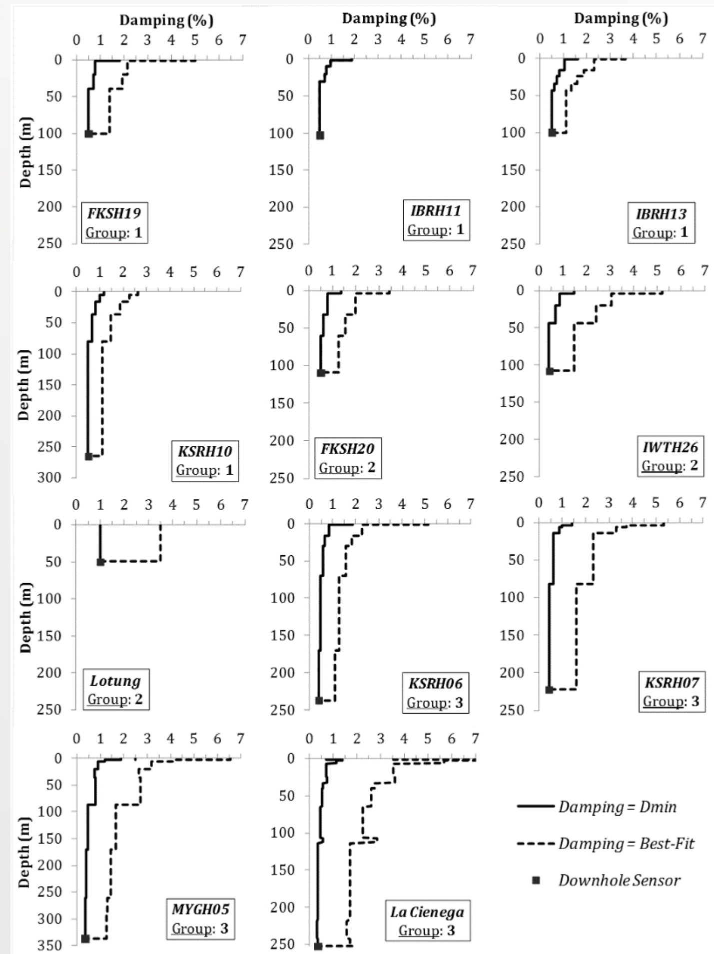
D = damping profile
V_s = shear wave velocity profile

- κ_o controls high frequency spectral shape of shaking
- κ_o is a measure of damping at a site
- κ_o can be measured directly from ground motion recordings

Downhole Array Sites

Stokoe & Darendeli (2001) G/G$_{max}$ and D curves

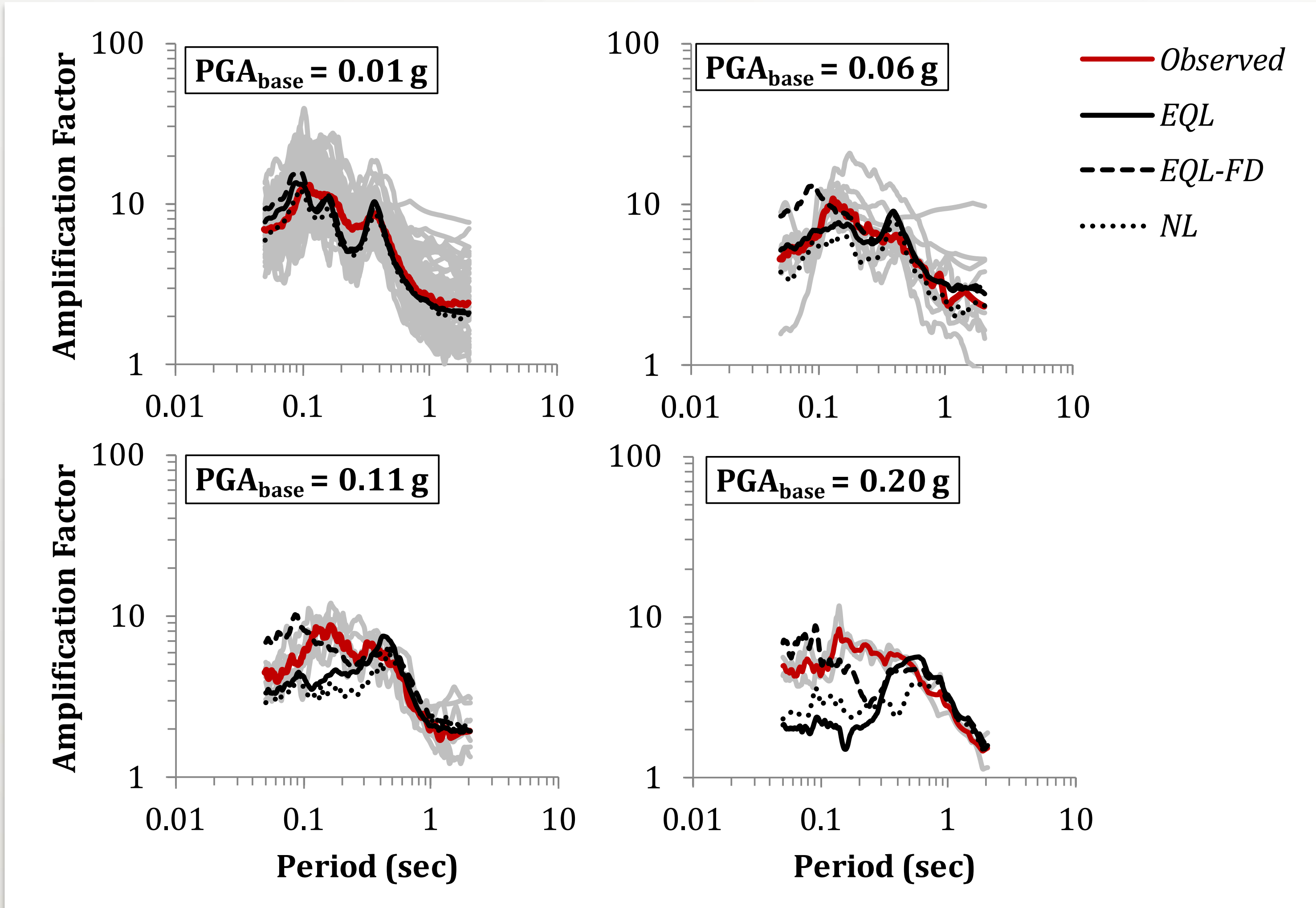




Zalachoris and Rathje (2015) *ASCE JGGE*

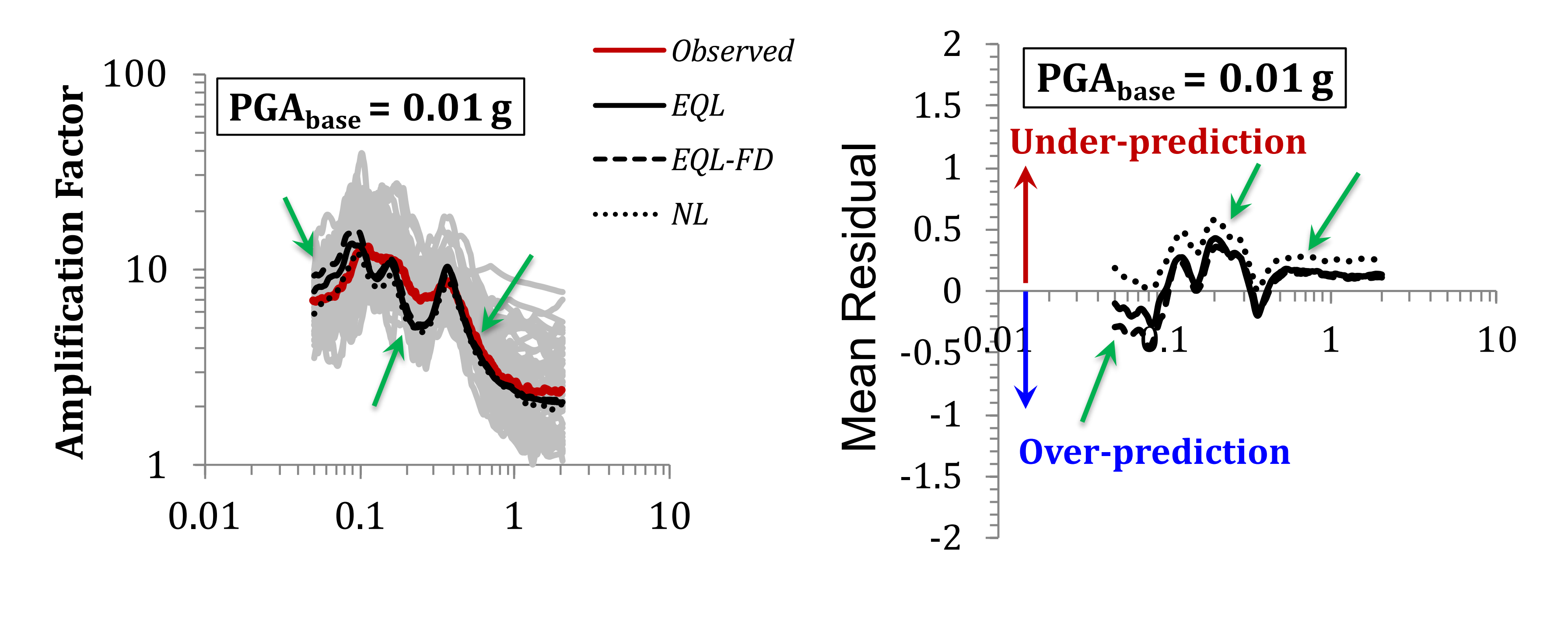
Response Spectrum Amplification

Site: IBRH13 Vs30 = 335 m/s



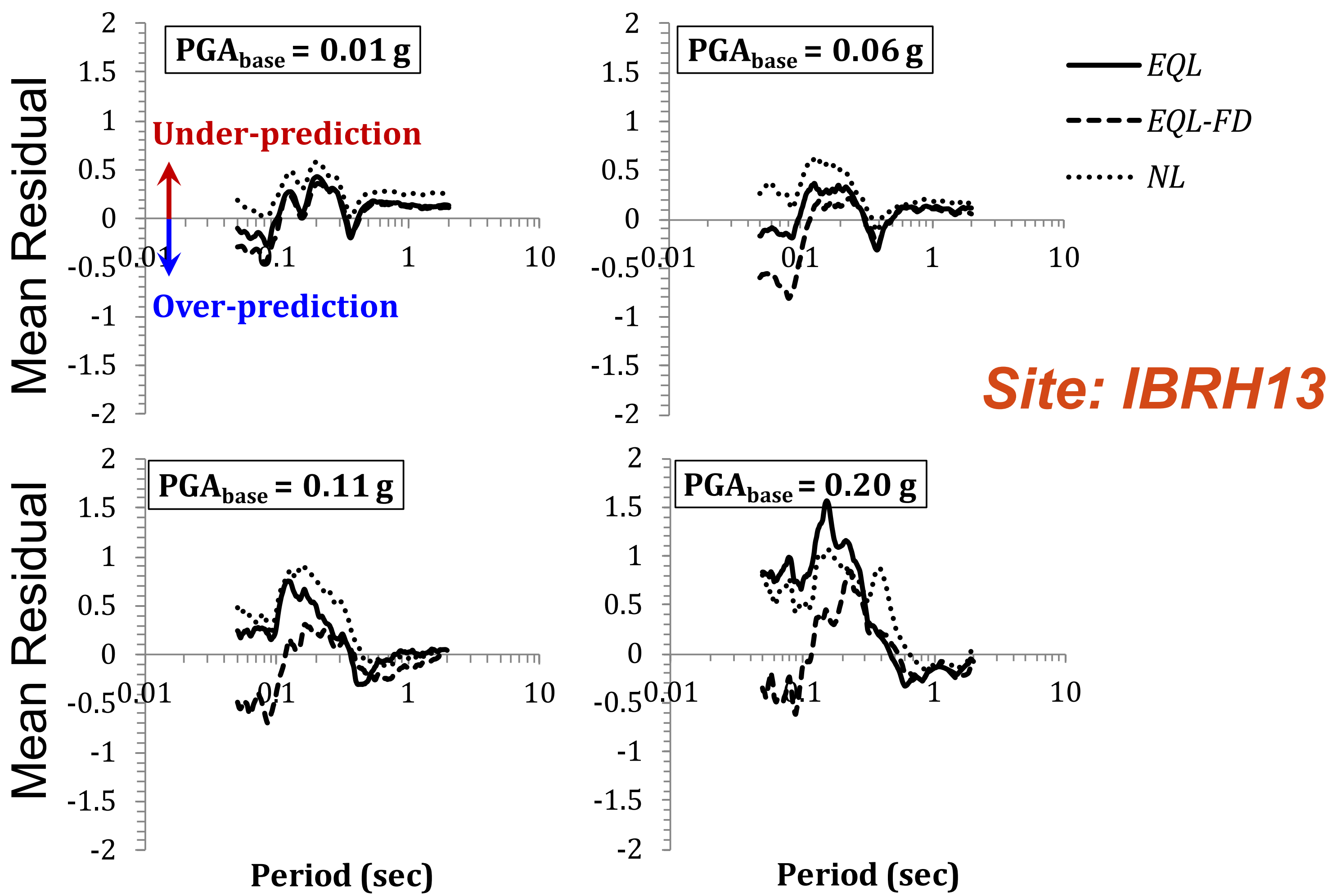
Amplification Residuals

$$\text{Residual} = \ln AF_{observed} - \ln AF_{calculated} = \ln(\text{Obs/Calc})$$



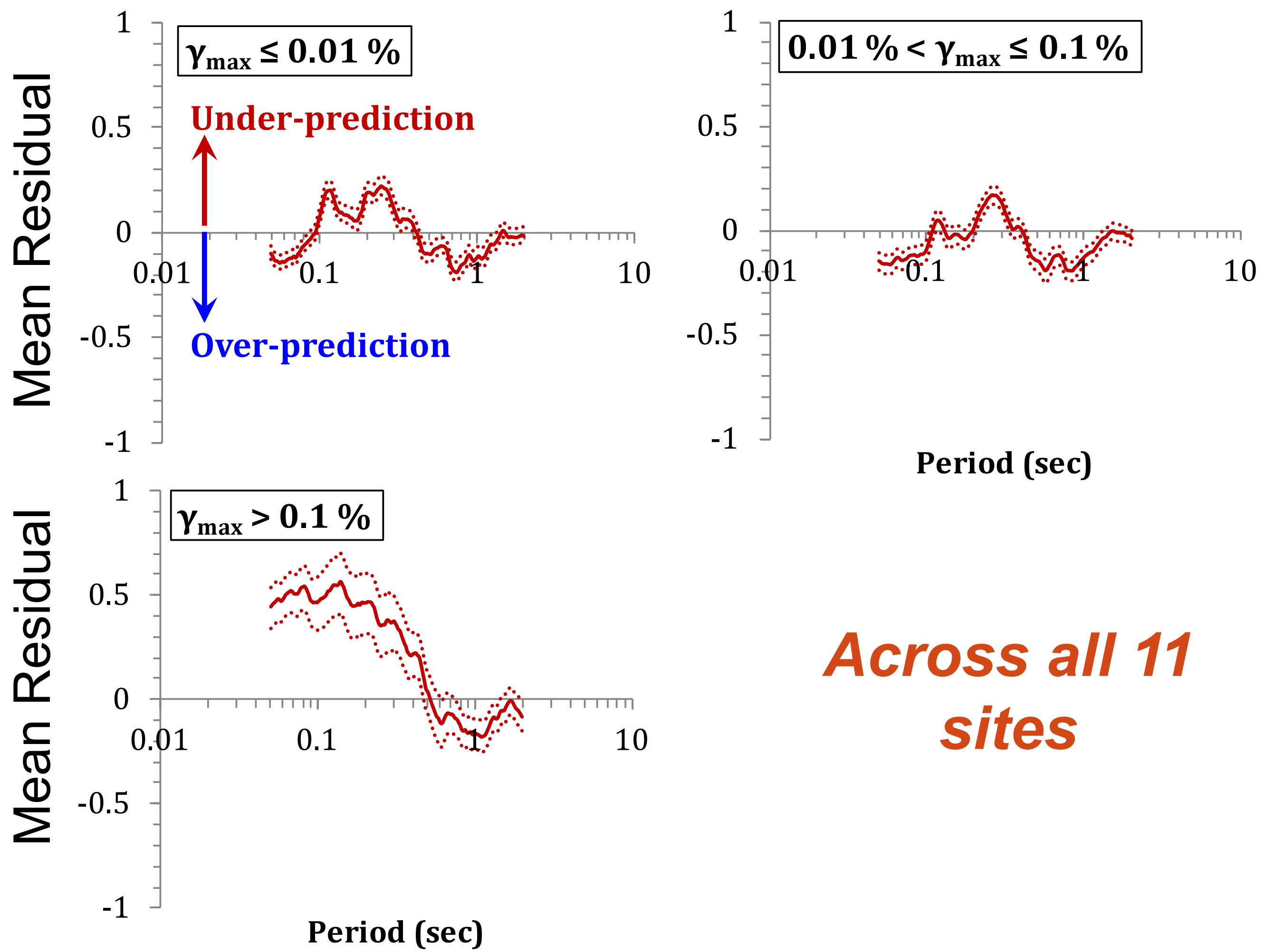
Mean Amplification Residuals

$$\text{Residual} = \ln AF_{observed} - \ln AF_{calculated}$$



Mean AF Residuals - EQL

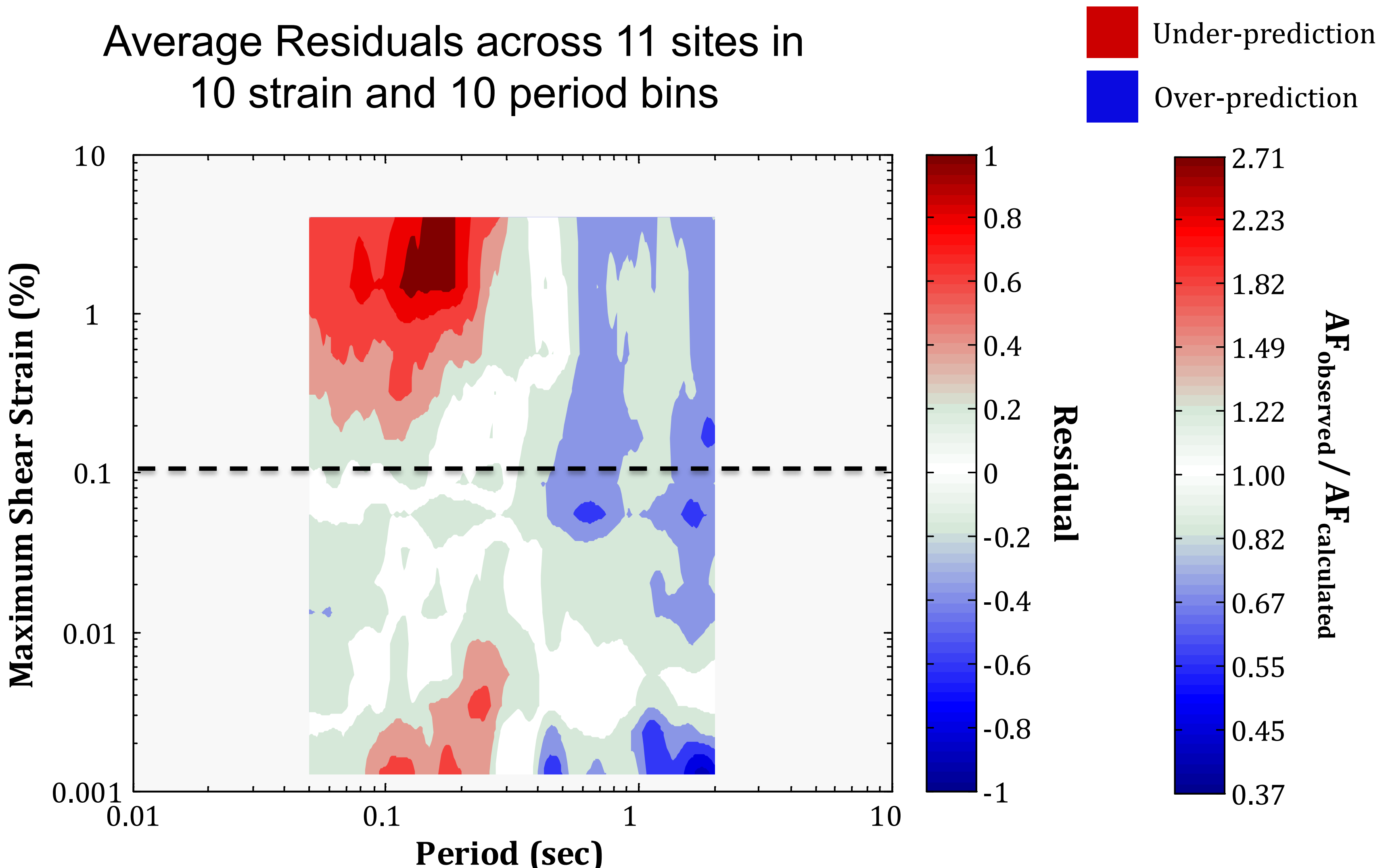
Computed max shear strain (γ_{max}) is a better indicator of residuals across sites

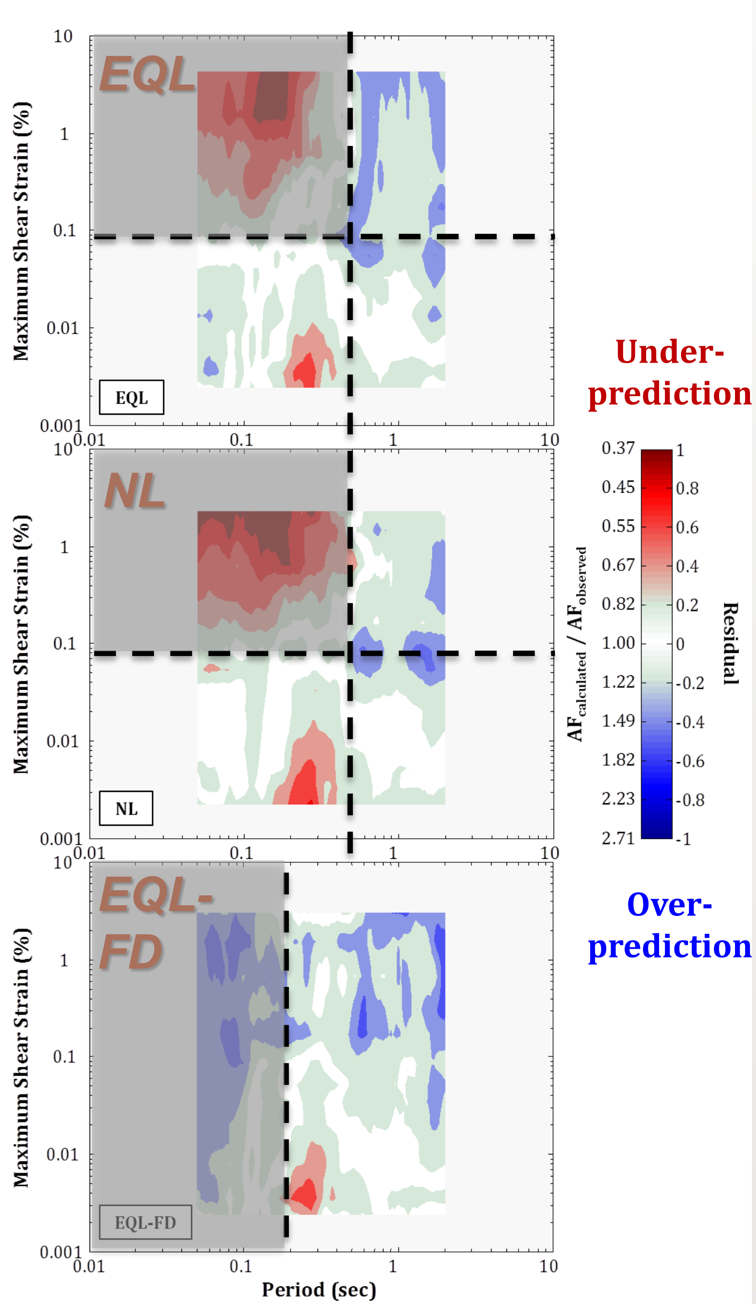


Across all 11 sites

Aggregated Residuals - EQL

Average Residuals across 11 sites in
10 strain and 10 period bins

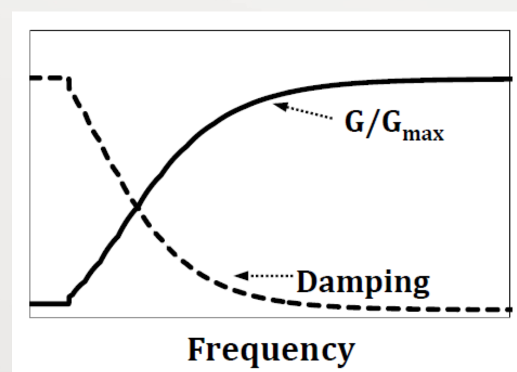




Mean AF Residuals

Residuals as a function of computed γ_{max} and period

- Under-prediction by EQL and NL for T < 0.5 s & γ_{max} > 0.1%
- Slight over-prediction by EQL-FD at T < 0.2 s due to use of small-strain damping (D_{min}) at high frequencies



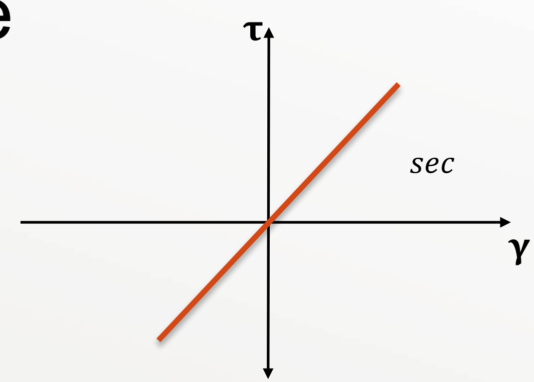
Zalachoris and Rathje (2015) *ASCE JGGE*

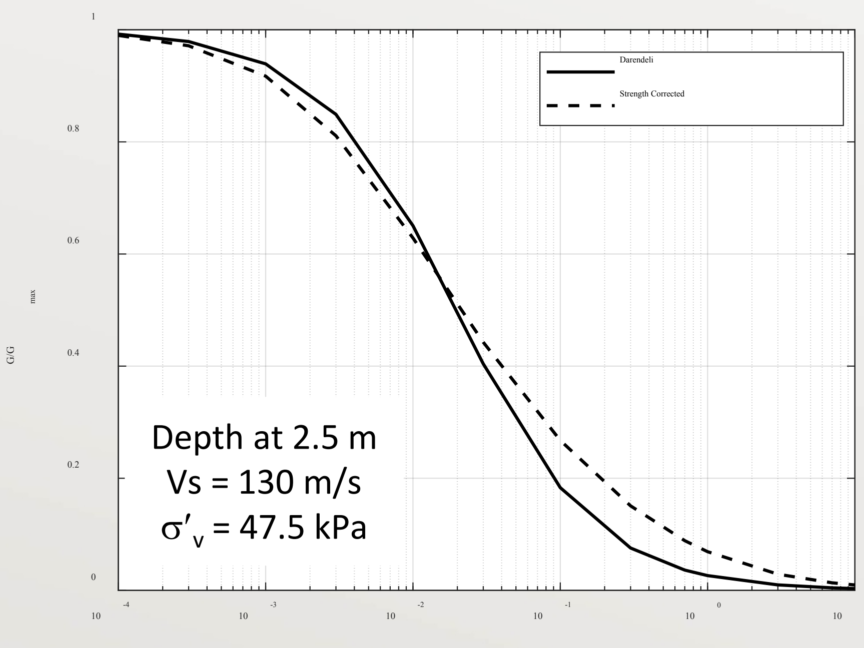
Consideration of Shear Strength (τ_{max})

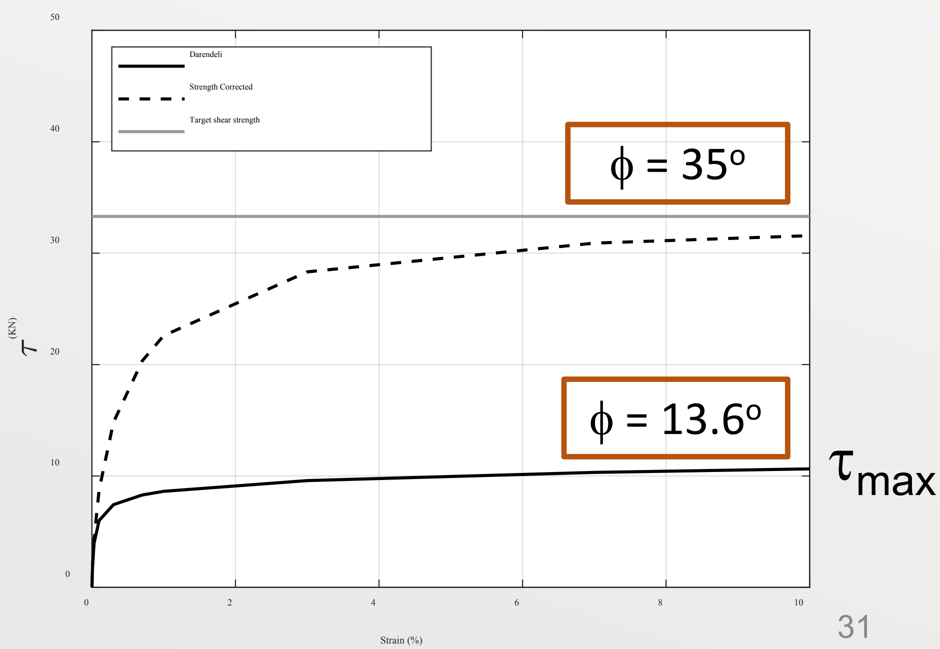
- Vs and G/G_{max} imply a τ vs. γ curve

$$\tau = {}_{sec} \cdot \gamma = G_{max} \cdot \left(\frac{G}{G_{max}}\right)_{@\gamma} \cdot \gamma$$

$$= \rho \cdot V_s^{\,2} \cdot \left(\frac{G}{G_{max}}\right)_{@\gamma} \cdot \gamma$$

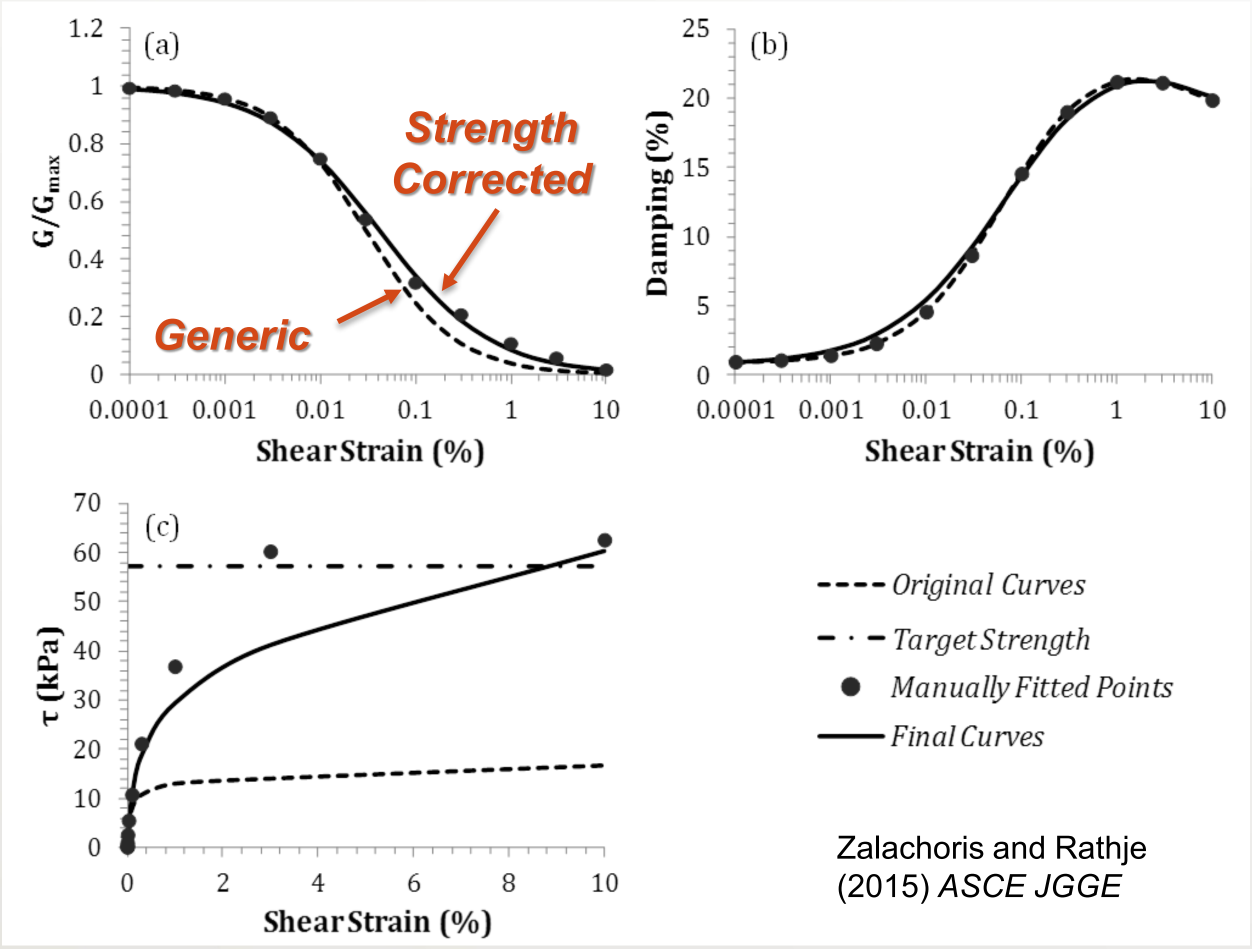






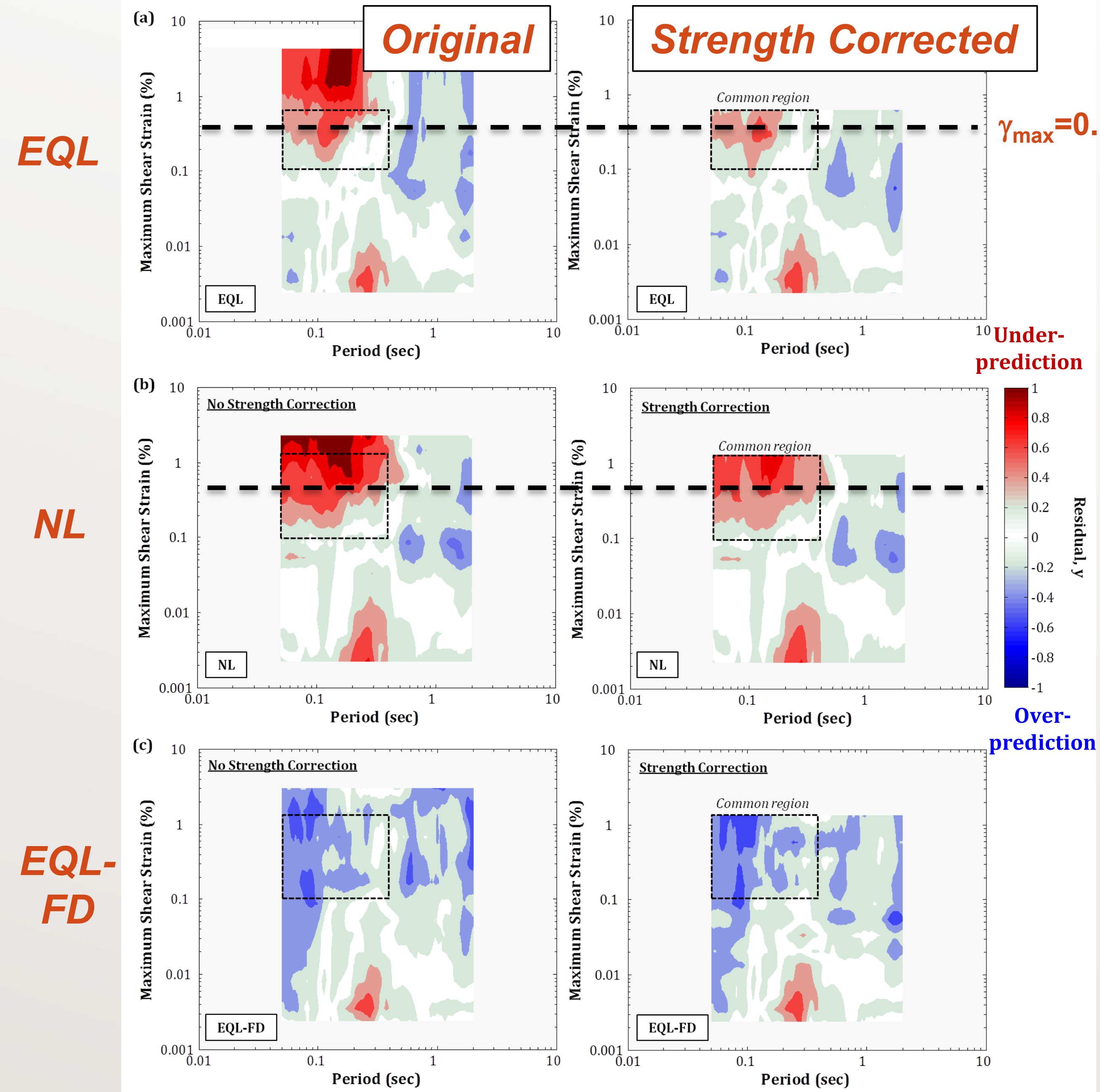
Shear Strength Correction

Modify G/G_{max} for all layers with induced γ_{max} greater than 0.1% to be consistent with $\phi \sim 30°$



Zalachoris and Rathje (2015) *ASCE JGGE*

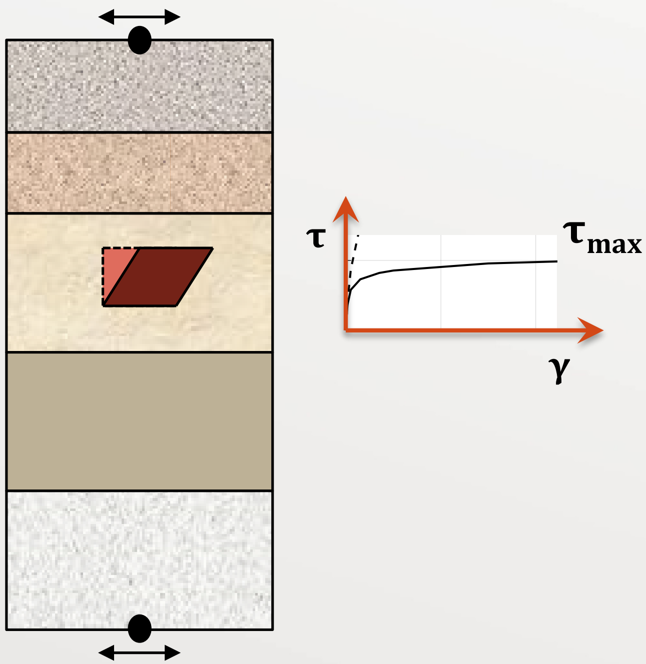
Mean AF Residuals



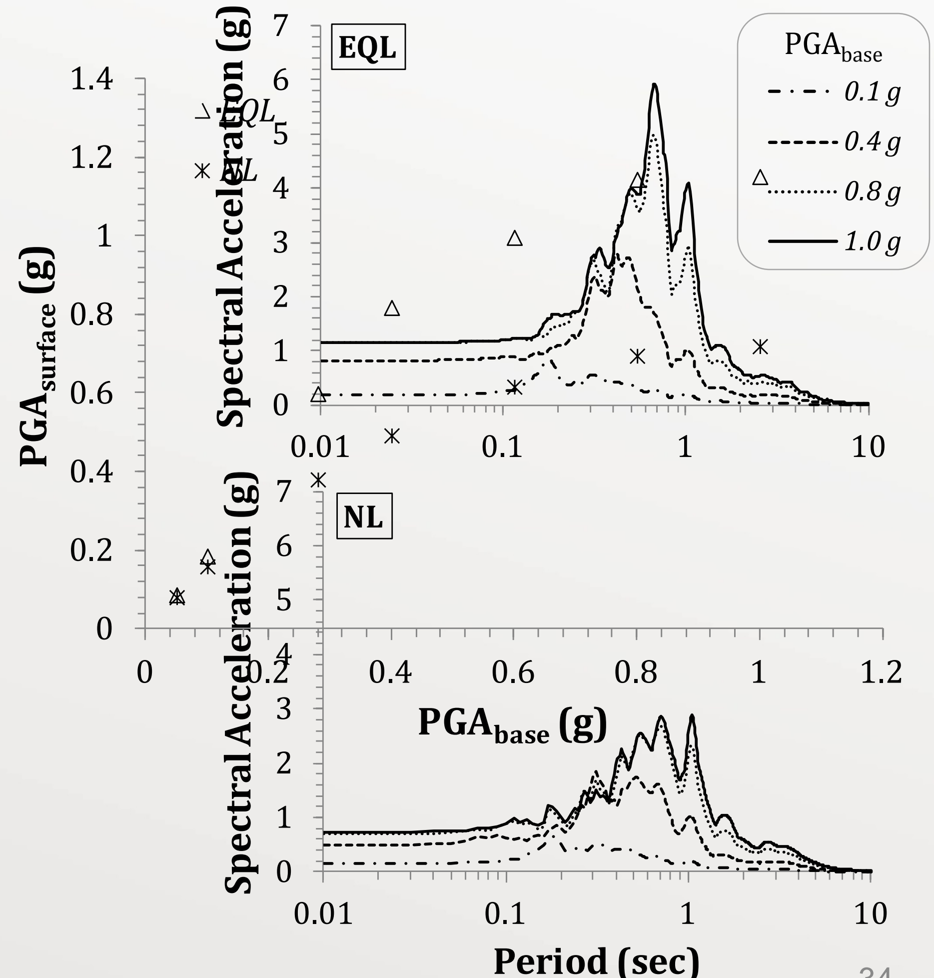
- Strains reduced by modified G/G_{max}
- Under-prediction still exists for EQL and NL
- EQL-FD relatively unchanged

Zalachoris and Rathje (2015) *ASCE JGGE*

Base Isolation Effect for 1D Analysis



Surface Spectra



Zalachoris (2014) *PhD Dissertation*

Observations

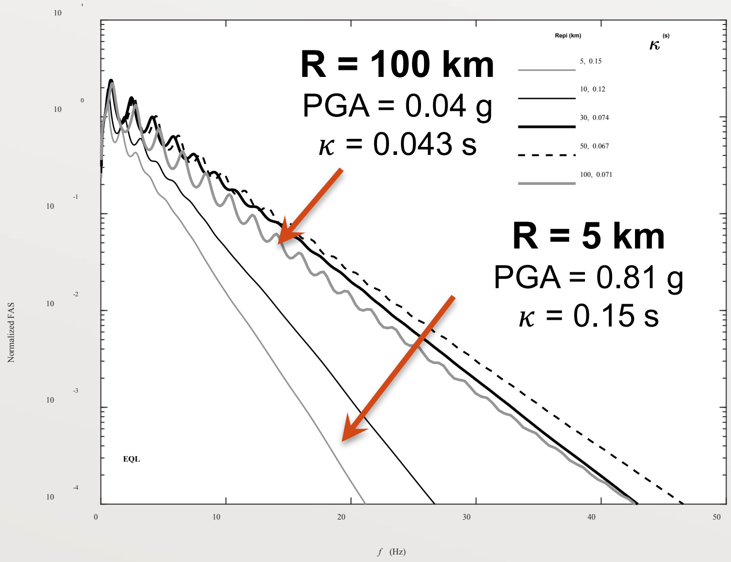
- EQL and NL analyses under-predict motions at γ_{max} > 0.1% and T < 0.4 to 0.5 s
  - Strength correction for G/G_{max} improves results somewhat but does not remove bias
  - Under-prediction may be as much as 50%
- EQL-FD over-predicts motions at T < 0.2 s
  - Over-prediction may be as much as 25%
- 1D EQL or NL analysis should not be used when γ_{max} > 0.5%
  - EQL-FD preferred…

…or perhaps kappa can help…

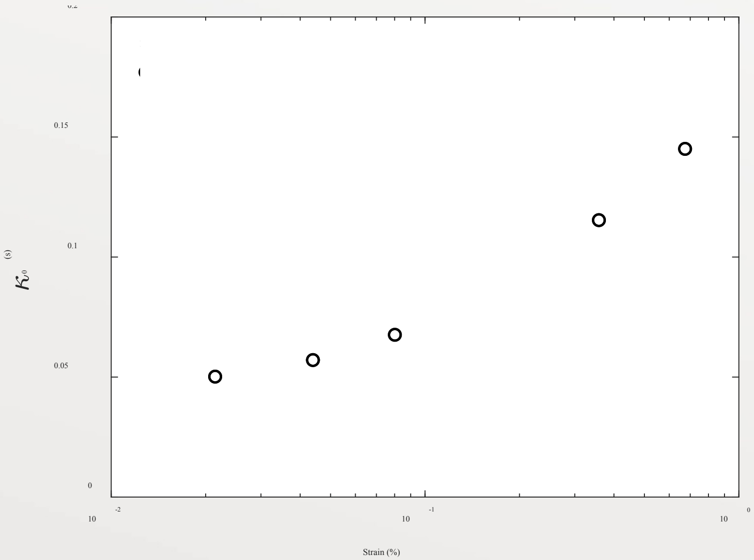
Theoretical Effect of Soil Nonlinearity on κ

- Hypothetical profile: 100 m; V_S 400 m/s
- Site response analysis for a range of input motions (R = 5 to 100 km)
- Compute **κ (slope)** for surface motion calculated by EQL analysis

Surface FAS



κ vs. Induced Strain



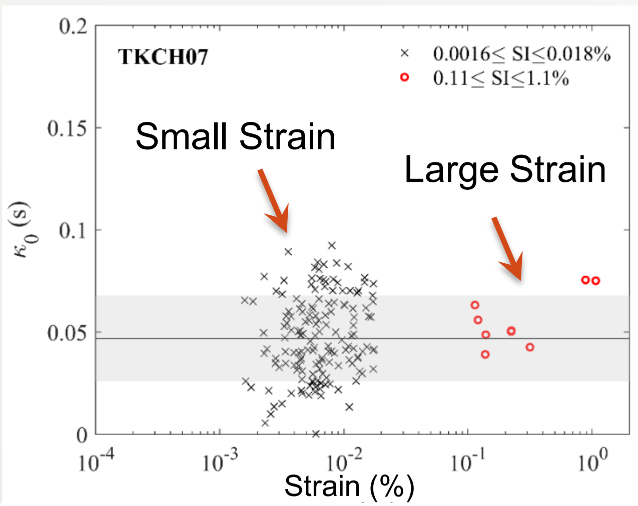
Do earthquake recordings confirm this relationship?

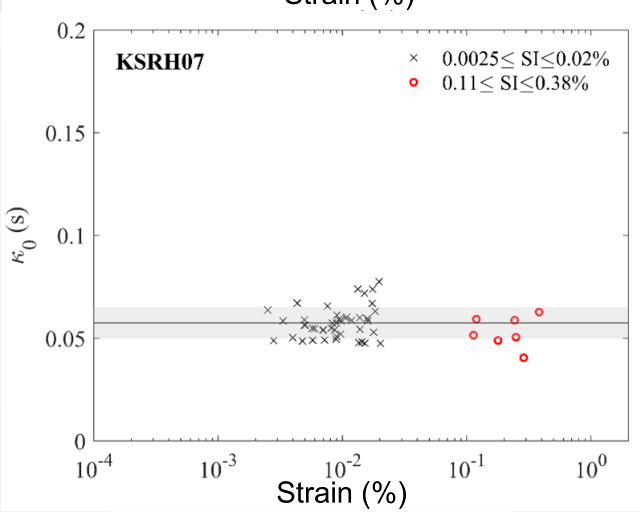
THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

κ Observations: Strain Dependence

Site-Specific Results

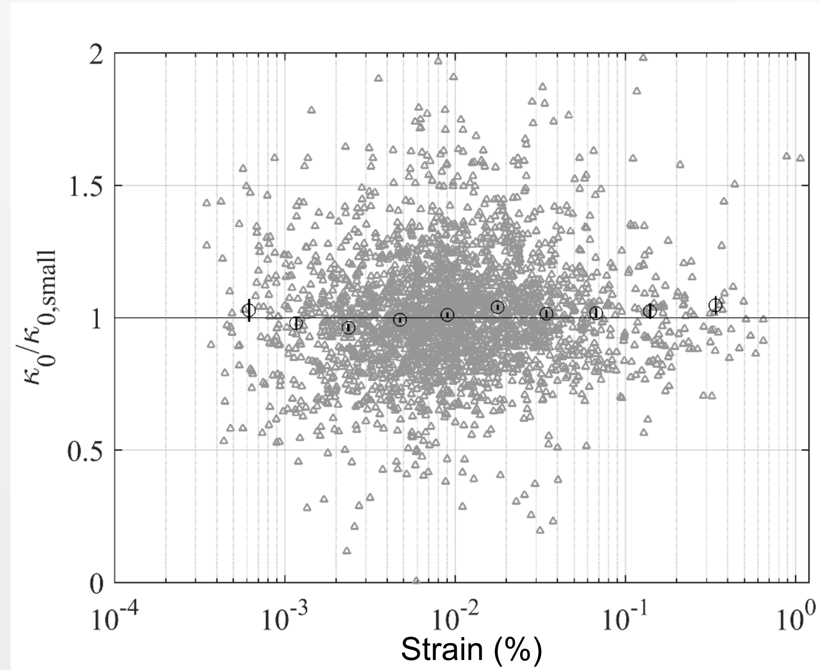




Xu (2019) *PhD Dissertation*

Aggregated Results

2,638 motions, 32 sites

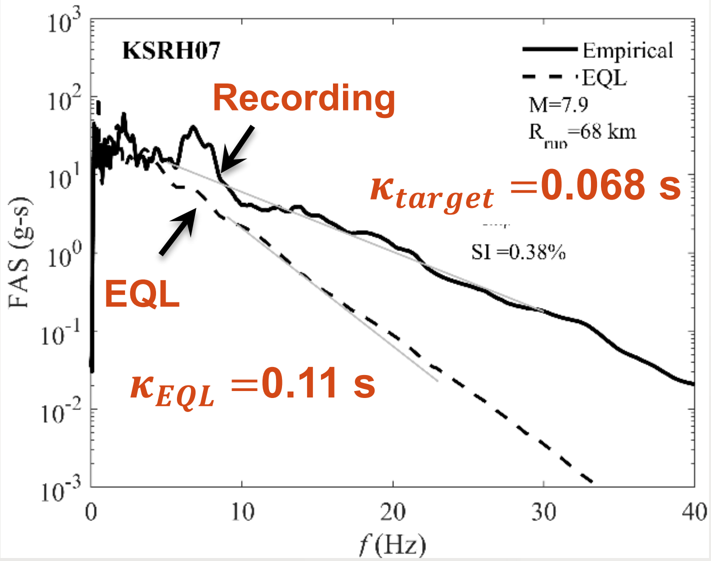


Agreement between small-strain and large-strain κ_0 indicates that damping should remain at D_{min} at high frequencies for large strain motions

EQL Analysis with κ Scaling

EQL Analysis

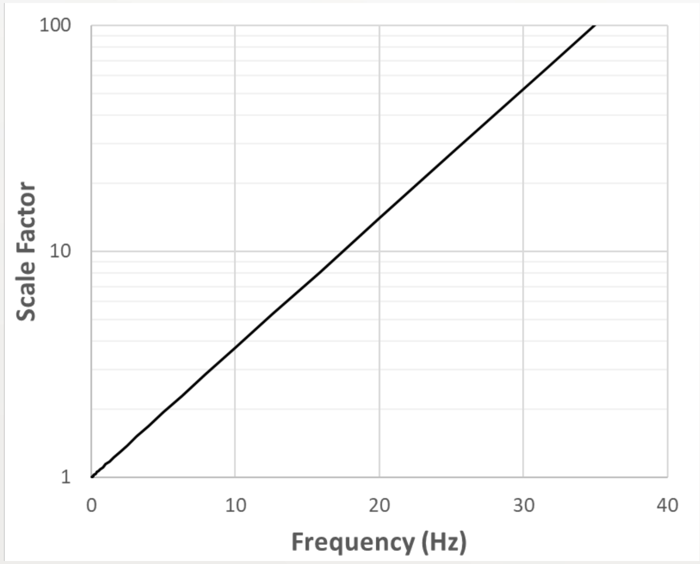
Surface FAS



$$\Delta\kappa = \kappa_{target} - \kappa_{EQL}$$

Define Scale Factor (S)

Frequency dependent



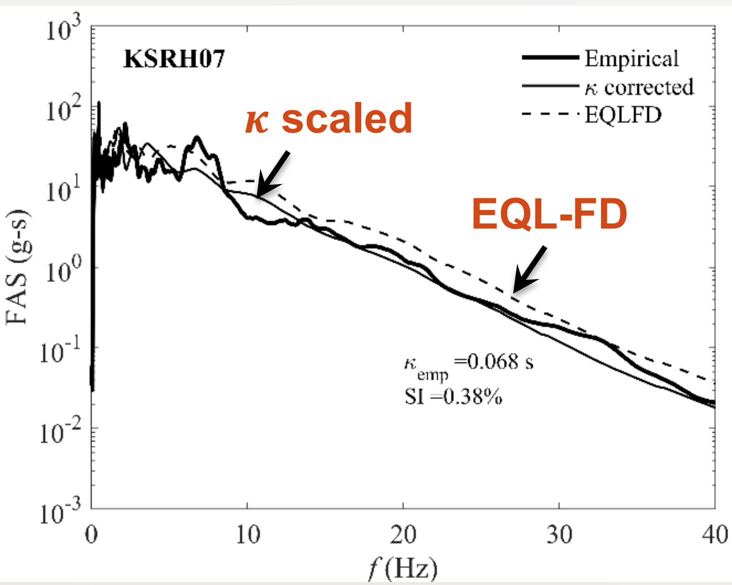
$$\mathbf{S}(\boldsymbol{f}) = \exp(-\pi \cdot \Delta\kappa \cdot f)$$

For non-downhole array sites, κ_{target} can be derived from small-strain recordings or from empirical relationships (Xu et al. 2019)

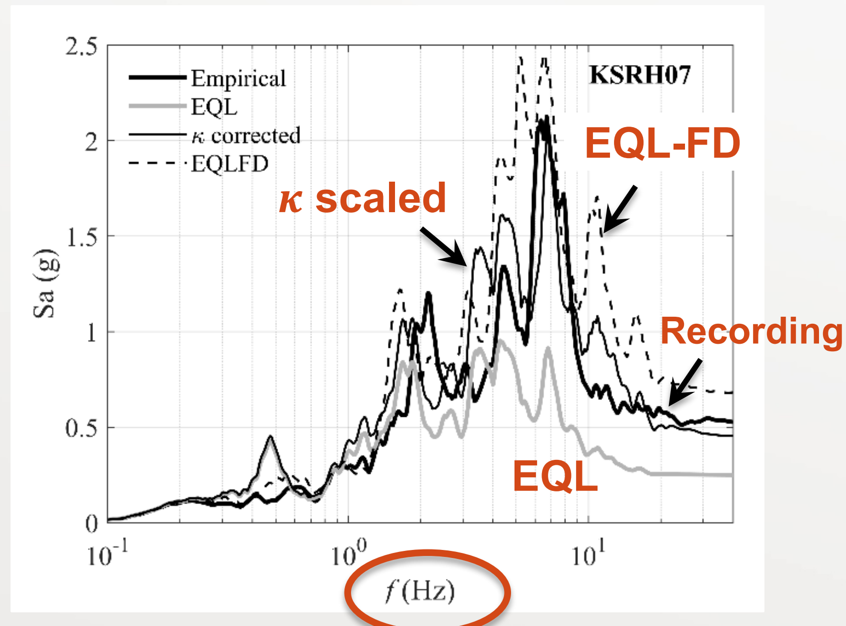
EQL Analysis with κ Scaling

Apply S(f)

$$\mathrm{FAS}(f) = FAS_{EQL}(f) \cdot \mathrm{S}(f)$$



Compute Response Spectrum

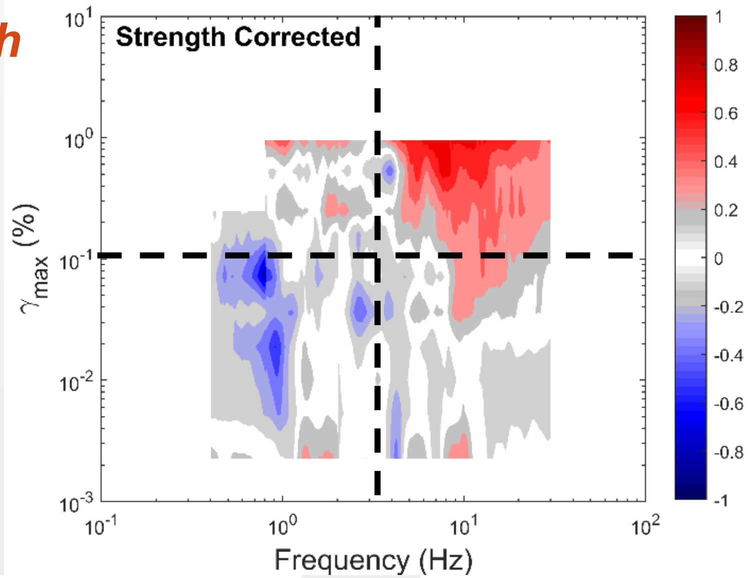


Compute residuals for surface response spectra (Sa) for over 400 motions from 6 downhole array sites

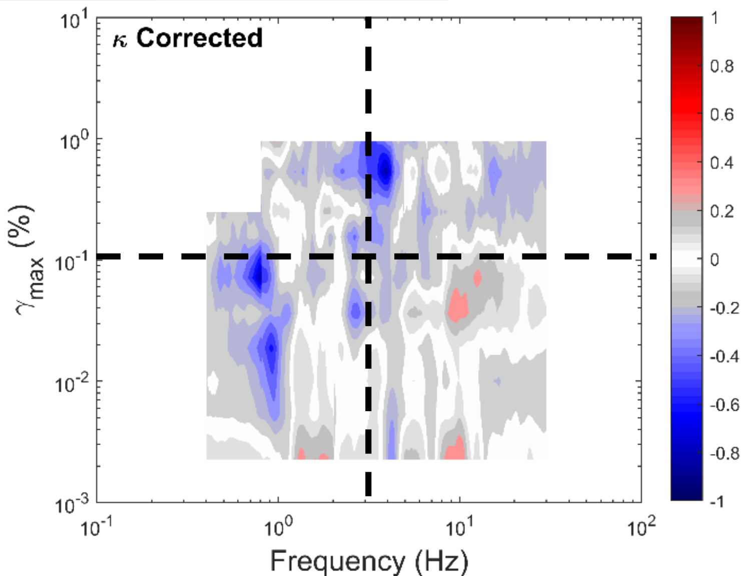
Sa residuals: Aggregated Results

Xu (2019) *PhD Dissertation*

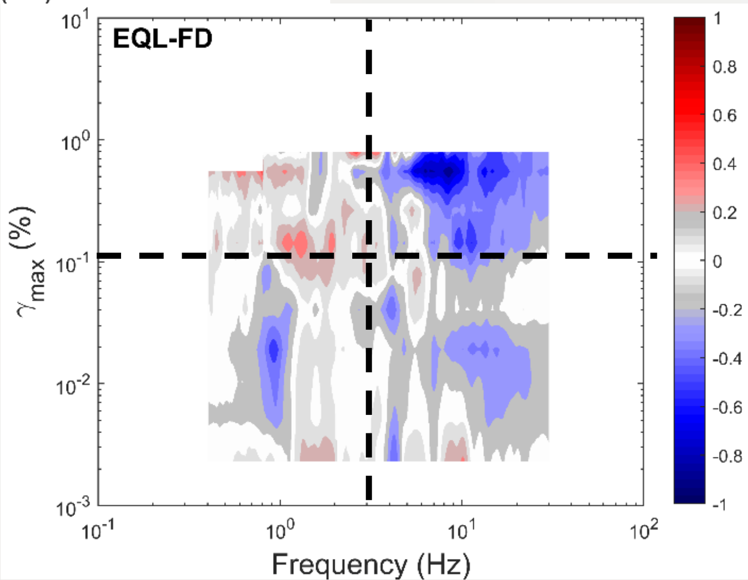
EQL: Strength Corrected



κ Scaling



EQL-FD



Observations

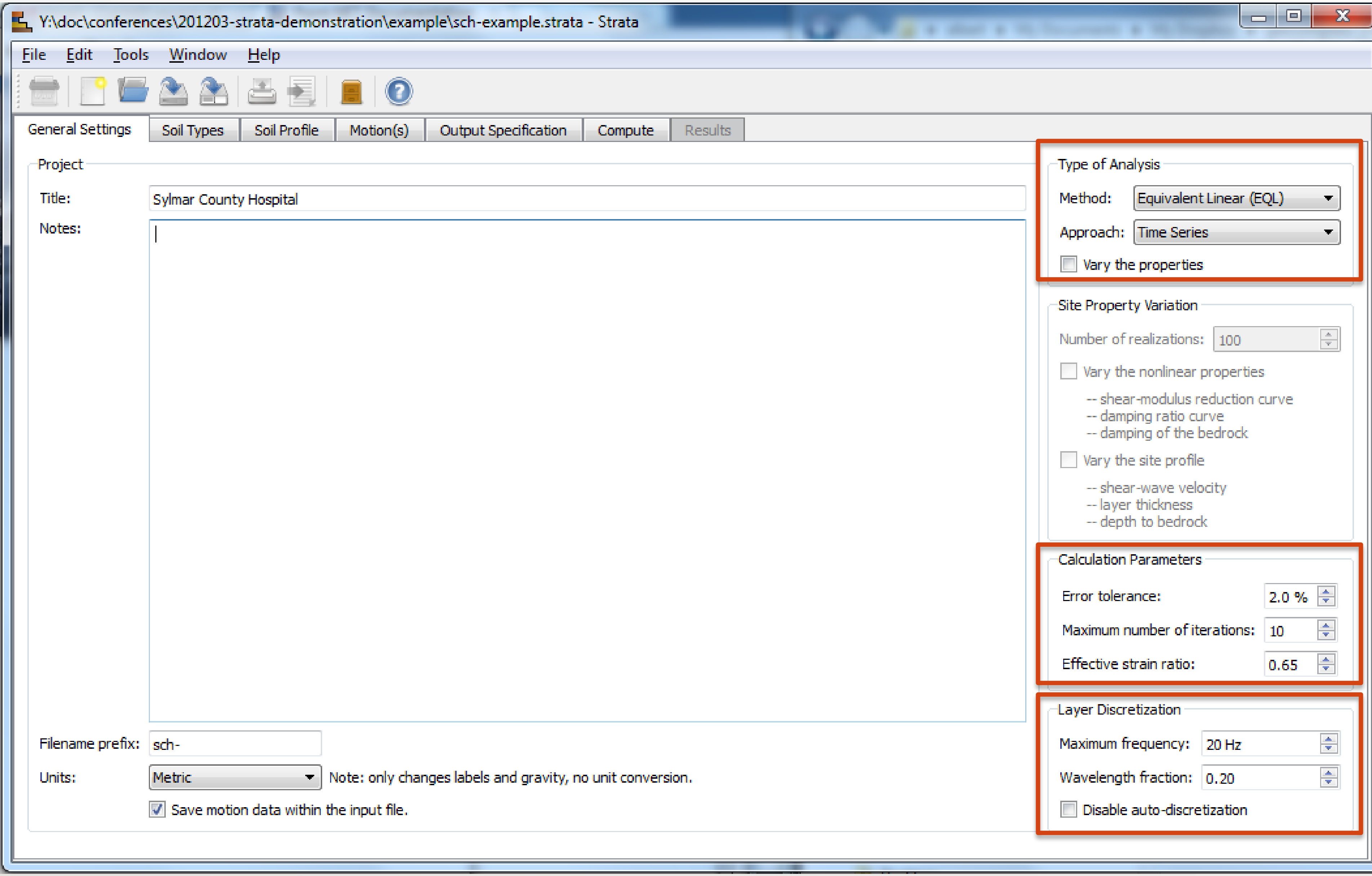
- Consistent with previous study, EQL analyses under-predict motions at γ_{max} > 0.1% and T < 0.4 to 0.5 s (f > 3 Hz)
- EQL-FD over-predicts motions at T < 0.2 s (> 5 Hz)
- κ scaling provides the most unbiased results over a broad frequency / strain range
- EQL or NL analysis should not be used when γ_{max} > 0.5%
  - EQL-FD or κ correction required, κ scaling preferred

Outline

- ***Accuracy of 1D Site Response Analysis***
  - Use *small-strain* motions from downhole arrays to investigate validity of the 1D analysis
- ***Large-Strain Site Response***
  - Develop approaches that improve predictions of site response at large strains
- ***Strata Tool for Site Response Analysis***
  - Time series and RVT input motions
  - Performs EQL, EQL-FD analyses
  - Incorporates variability in the material properties through Monte Carlo simulations

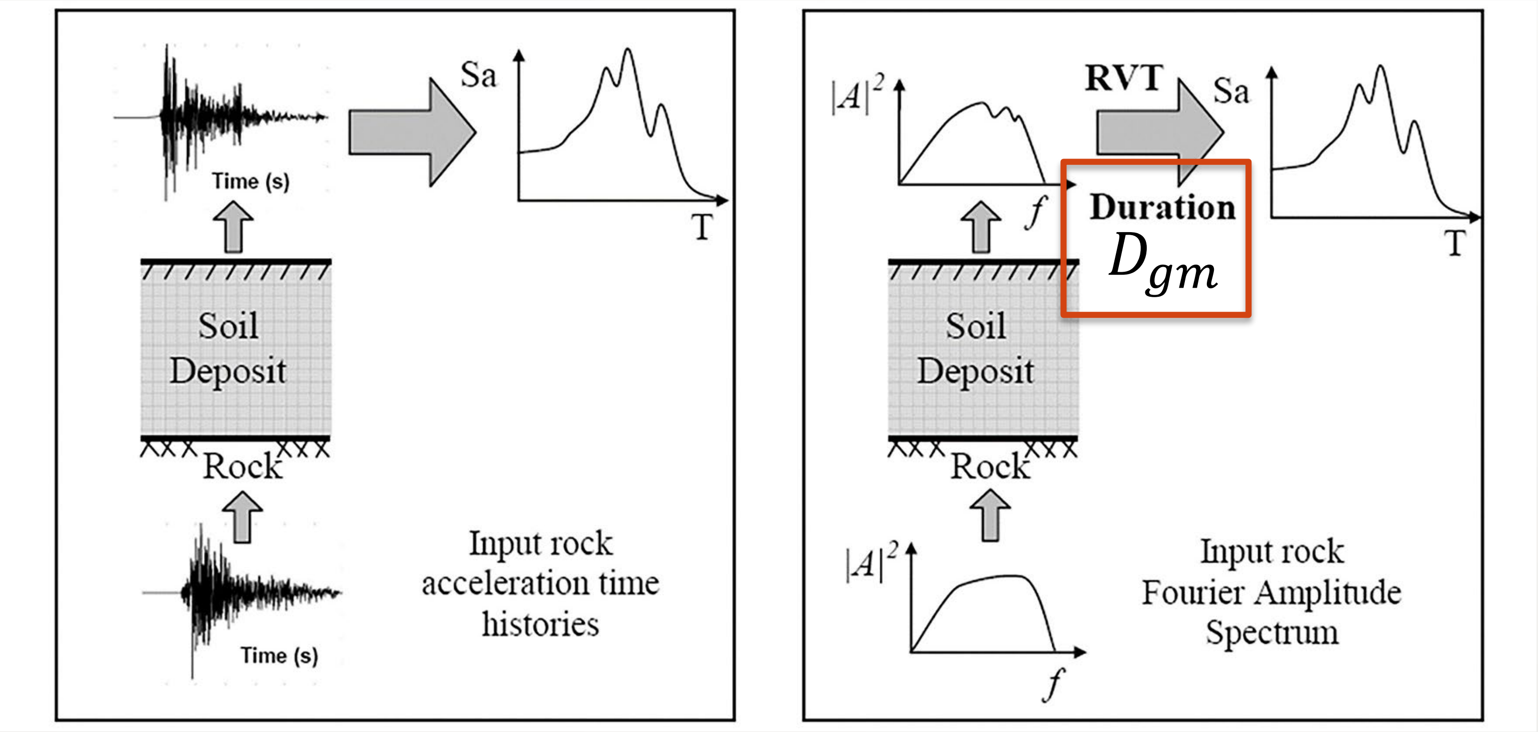
Site Response Software: Strata

- Open-source (i.e., free), user-friendly site response program
  - Kottke and Rathje (2008) PEER 2008/10 Report
  - https://github.com/arkottke/strata
- Frequency domain wave propagation
  - EQL and EQL-FD analysis
- Input motions characterized by
  - Time series
  - Random vibration theory (RVT)
- Statistical variation of site properties
  - Layering, Vs, nonlinear properties, etc.


Y:\doc\conferences\201203-strata-demonstration\example\sch-example.strata - Strata
File Edit Tools Window Help
General Settings
Soil Types
Soil Profile
Motion(s)
Output Specification
Compute
Results
Project
Title: Sylmar County Hospital
Notes:
Filename prefix: sch-
Units: Metric
Note: only changes labels and gravity, no unit conversion.
Save motion data within the input file.
Type of Analysis
Method: Equivalent Linear (EQL)
Approach: Time Series
Vary the properties
Site Property Variation
Number of realizations: 100
Vary the nonlinear properties
-- shear-modulus reduction curve
-- damping ratio curve
-- damping of the bedrock
Vary the site profile
-- shear-wave velocity
-- layer thickness
-- depth to bedrock
Calculation Parameters
Error tolerance: 2.0 %
Maximum number of iterations: 10
Effective strain ratio: 0.65
Layer Discretization
Maximum frequency: 20 Hz
Wavelength fraction: 0.20
Disable auto-discretization

RVT Site Response Analysis

Time Series Analysis ***RVT Analysis***



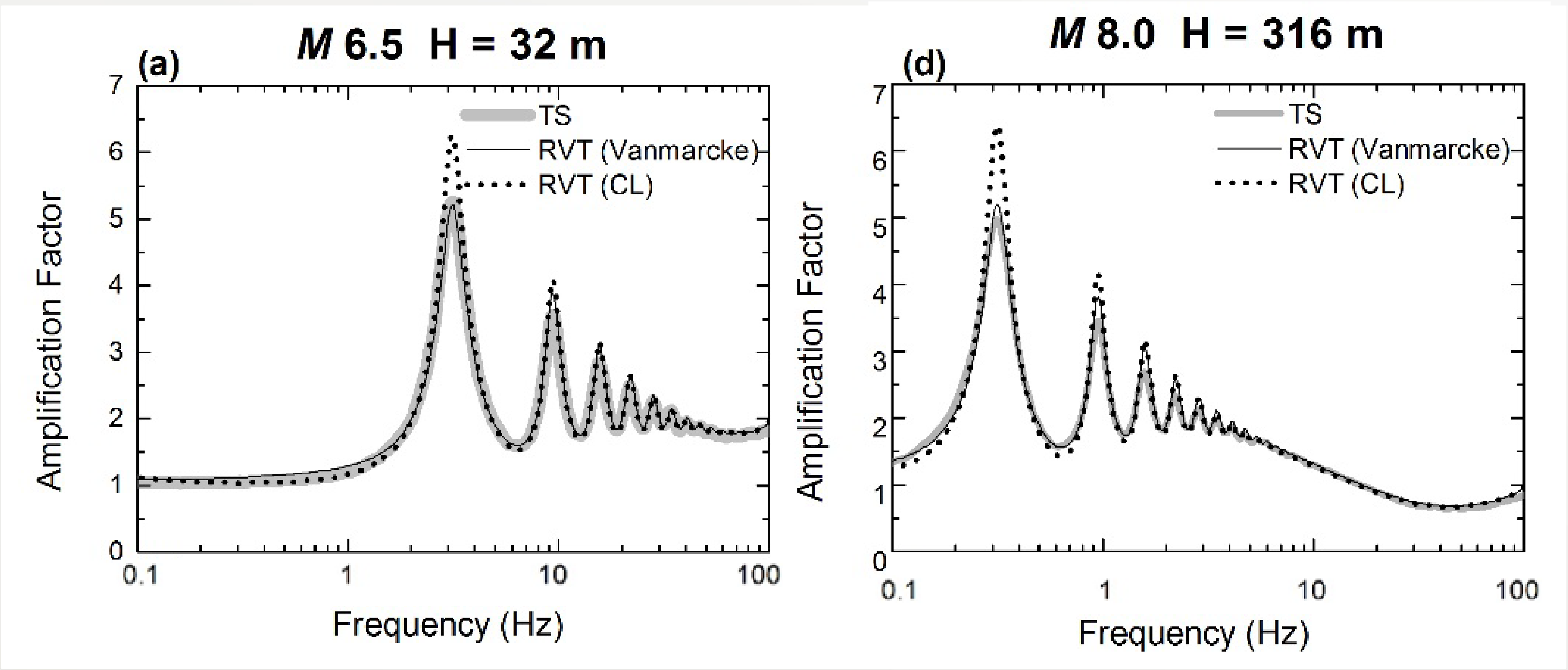
$$a_{max} = a_{rms} \times peak\ factor$$

$$a_{rms} = \sqrt{\frac{1}{D_{gm}} \int_0^\infty a^2(t)dt} = \sqrt{\frac{2}{D_{gm}} \int_0^\infty |A(f)|^2 df}$$

From statistical model of distribution of peaks

Comparison with Time Series (TS) Analysis

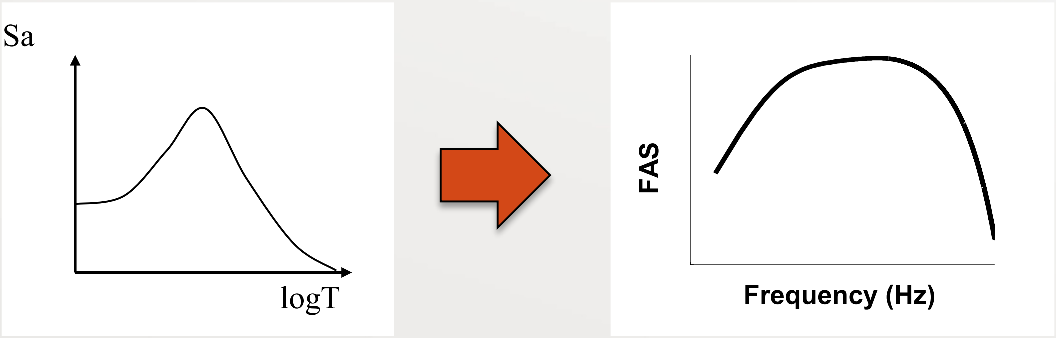
Site Vs = 400 m/s, Variable height (H) and EQ Magnitude
TS represents average of 100 input motions



Wang and Rathje (2016, 2018) *BSSA*

Input Motion Specification for RVT

- Requires Fourier Amplitude Spectrum (FAS) and duration (D_{gm})
- Input FAS defined via:
  - Response spectrum compatible FAS from GMPE using inverse RVT



  - Seismological parameters (e.g., M, R, stress drop $\Delta\sigma$)
  - User-defined FAS

Conclusions

- HVSR is an important component of a seismic site characterization and should always be included
  - The frequency of HVSR peak should be consistent with the theoretical Transfer Function from the Vs profile
- One-dimensional site response analysis can under-predict ground motions at T < 0.5 s for γ_{max} larger than about 0.1%
  - True for both equivalent-linear and nonlinear analyses
  - Strength correction for G/G_{max} improves results somewhat by reducing strains but does not remove bias
  - EQL and NL <u>should not</u> be used for γ_{max} > 0.5%

Conclusions

- Equivalent-linear analysis with frequency dependent properties (EQL-FD) does not under-predict motions
  - Can over-predict motions at $T < 0.2$ s
- κ scaling of the surface motion from EQL analysis provides the most unbiased site response results for large-strain analysis ($\gamma_{max} > 0.5\%$)
- Open-source Strata software provides unique capabilities for site response analysis
  - https://github.com/arkottke/strata