Proposed Approach to CENA Site Amplification

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with acknowledgement to many co-authors, especially Ghofrani, Hassani, Assatourians, and Braganza.

The model is a team effort reflecting their hard work over the last 7 years, involving hundreds of thousands of seismograph records and nearly as many hours

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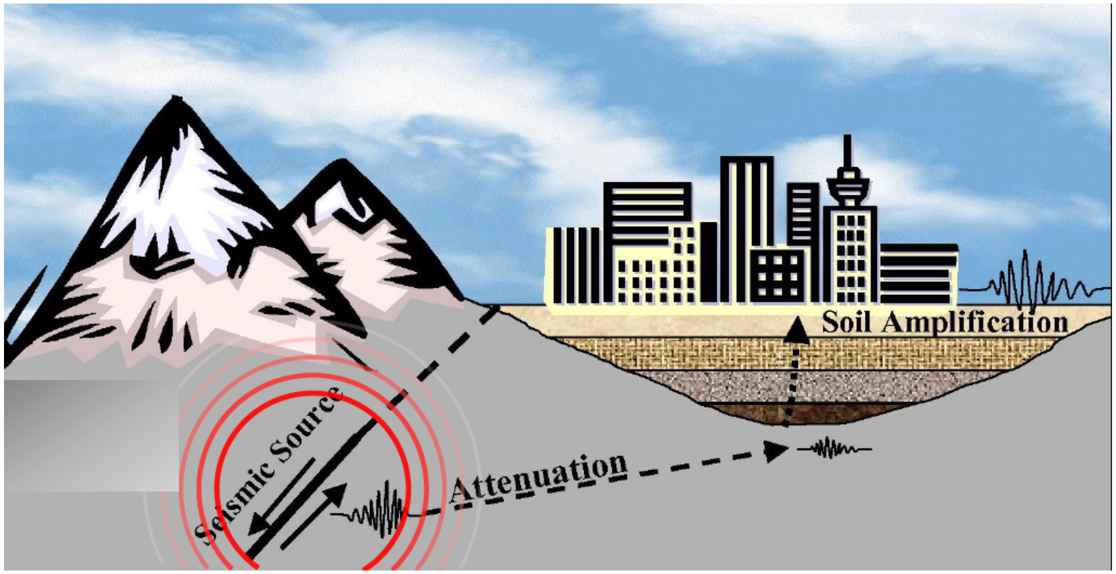
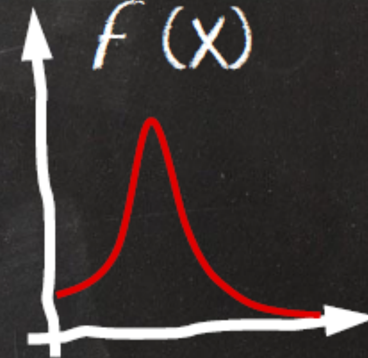


SITE VARIABLES



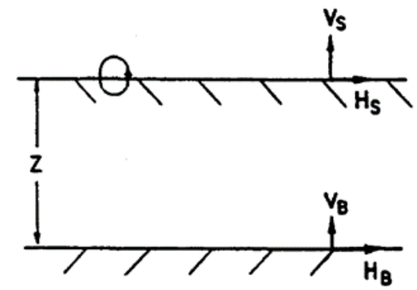
DESCRIBING THE **DEPTH** AND **STIFFNESS** OF THE DEPOSIT

- The average shear-wave velocity in the uppermost 30 m (**V_{S30}**):

$$V_{S30} = 30/\mathrm{sum}(d_i/V_i),\ i = 1{:}n$$

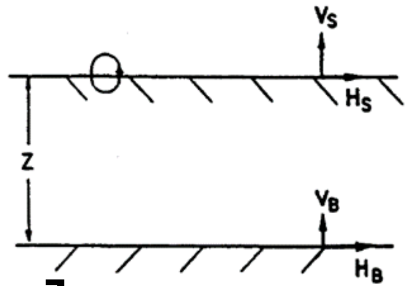
- The **fundamental frequency** depends on both layer depth and its stiffness; may carry information on deeper part of the soil column, in comparison to V_{S30}

Conclusions



- Fundamental frequency (f_{peak}) is the most diagnostic descriptive variable for site response in central and eastern North America (CENA)
- V_{s30} provides useful information on stiffness (if available) – it can also be a model parameter (but cannot replace fpeak)
- If V_{s30} not available, stiffness based on surficial geology can be used

Why peak frequency?



- In CENA, as in other regions such as Japan, we often have a soft layer over a much stiffer substratum (e.g. soil over glaciated bedrock), resulting in a predominant amplification peak at a fundamental frequency (fpeak)
  - This differs from California; California gradational velocity profiles result in broader, more subdued amplification curves, in which stiffness is diagnostic
- Peak frequency can be readily obtained from site H/V ratio - from earthquakes or microtremors (easier to get than V_{s30})
  - Can also be obtained by proxy (depth to bedrock)

Concluding Suggestions

- Develop CENA site response model using both f_{peak} and V_{s30}
- Develop empirical/theoretical relationships to obtain f_{peak} from V_{s30} and vice versa on a regional basis; these can be default relationships to get one if only the other is known
- Include both f_{peak} and V_{s30} in future GMPEs
- Inclusion of both f_{peak} and V_{s30} will reduce sigma in CENA and also in other regions (e.g. NGA-subduction)

Presentation Overview:

1 - How we reached this conclusion: background

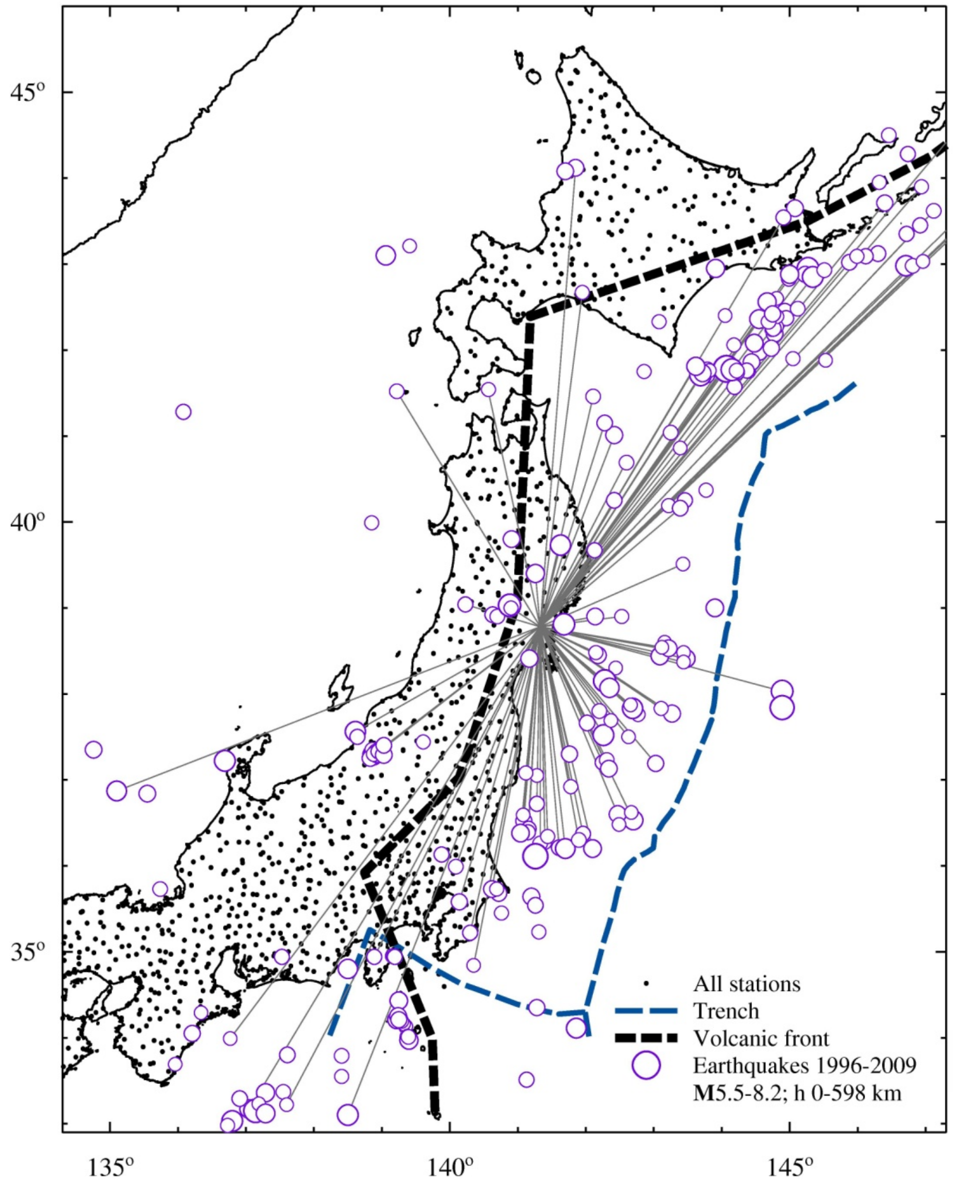
- Studies of amplification from borehole and surface records in Japan (Ghofrani et al.)
  - H/V is a proxy for site response and can provide fpeak
  - Development of generic amplification model in fpeak
- Studies of H/V in CENA (Hassani et al., Braganza et al.)
  - fpeak is a better measure of site response than Vs30 for NGA-East database
  - use of fpeak in GMPEs in CENA can reduce sigma

Presentation Overview:

2 – Key points in the proposed CENA site amplification model

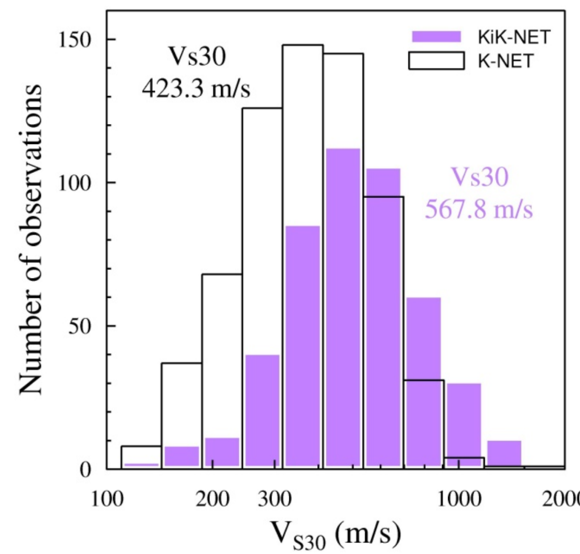
- f_{peak} is the primary descriptive variable
  - fpeak can be determined from H/V from earthquake records (seismograph stations), microtremor data (site surveys) or estimated from depth to bedrock (with greater uncertainty)
- V_{s30} (or surficial geology) is a good supplementary parameter to reflect the effects of stiffness on peak amplitude
- If we know f_{peak} and V_{s30} we can define the site response curve vs. frequency very well (for linear response)
- Suggest future GMPE developments and site response models in CENA include both f_{peak} and V_{s30} as predictive variables

Background: amplification in Japan based on surface and borehole records (Ghofrani et al., 2013)



K-NET & KiK-NET Data (1996-2009) + Tohoku

Magnitude range:	5.5-8.2 + 9.0
Depth range:	0-598 km
# events:	258
# events per station:	1-149
# stations :	1724 (K-NET & KiK-NET)



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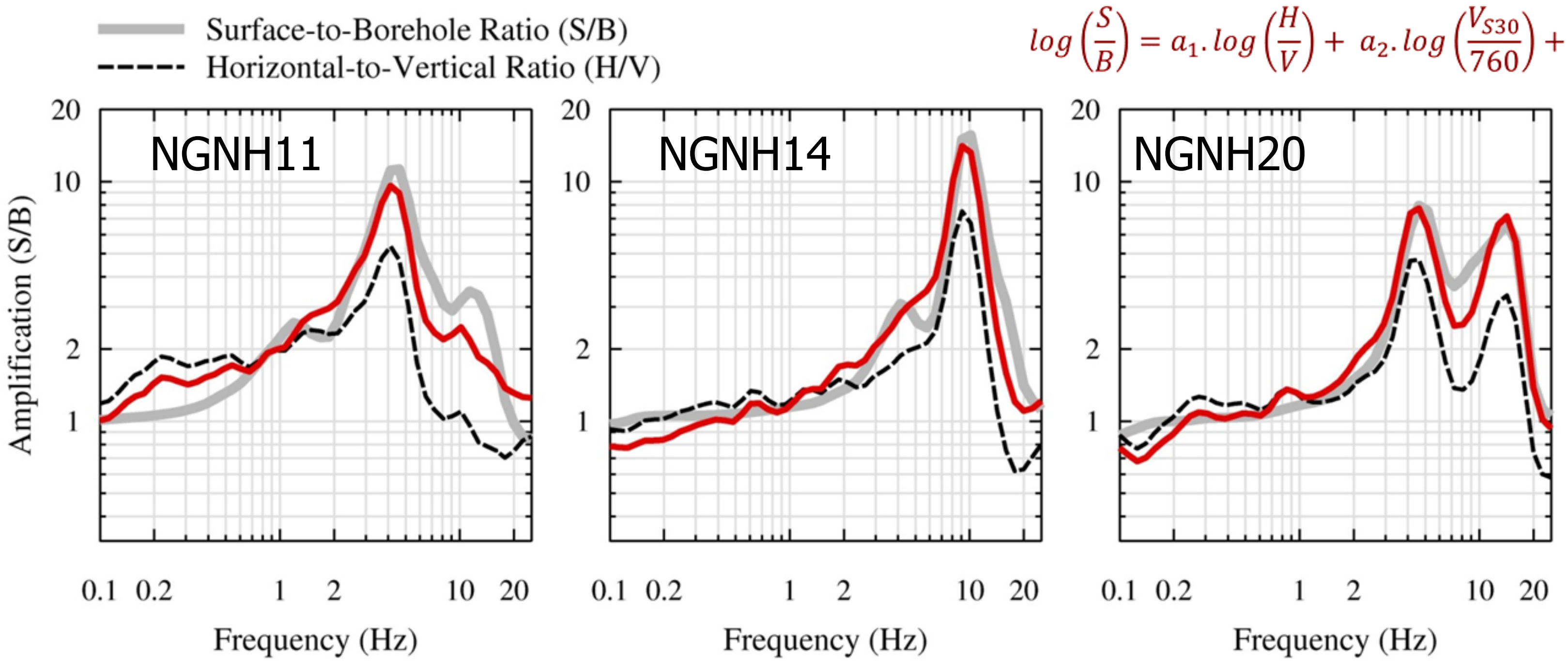
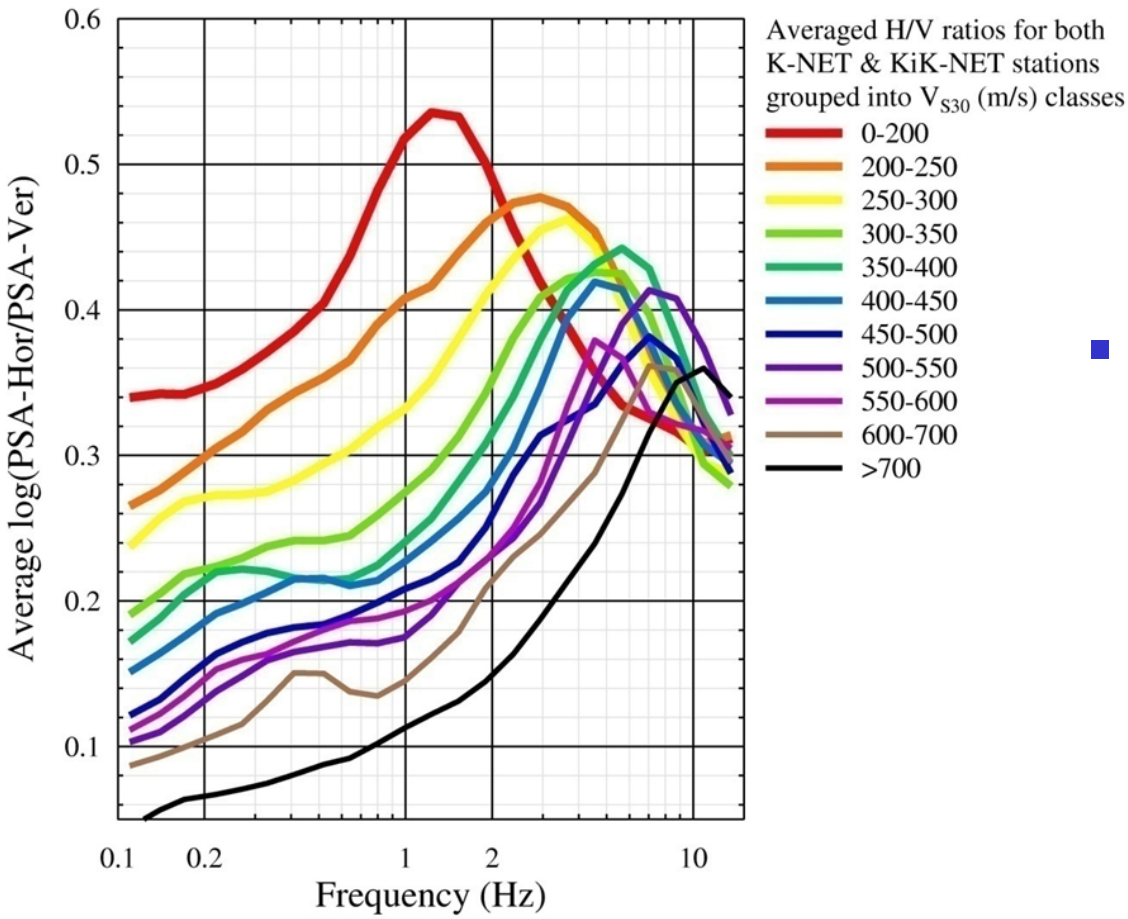
H/V as a measure of site response

- Actual amplification can be calculated as S/B: the ratio of motion on surface to that input at borehole (corrected for depth effects)
- H/V (horizontal to vertical component ratio) matches S/B well in peak frequency, but tends to underpredict amplitude of peak response
  - We can predict S/B (site response) accurately if we use H/V and Vs30 (red line)
- We obtain stable averages for both S/B and H/V because each site has recorded many earthquakes

$$log\left(\frac{S}{B}\right) = a_1.log\left(\frac{H}{V}\right) + a_2.log\left(\frac{V_{S30}}{760}\right) + a_3$$

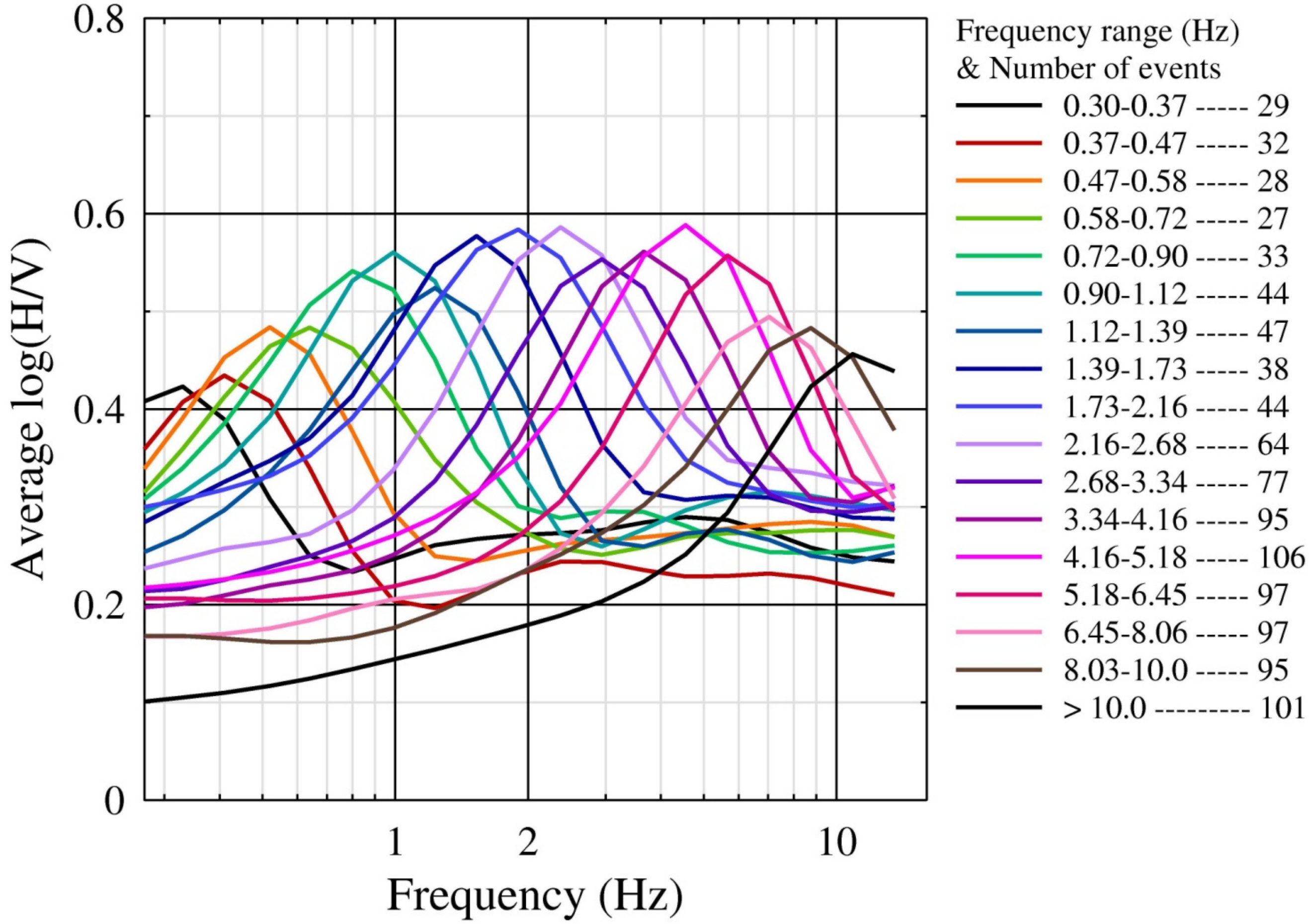


H/V (proxy for site response) -grouped by Vs30 for sites in Japan



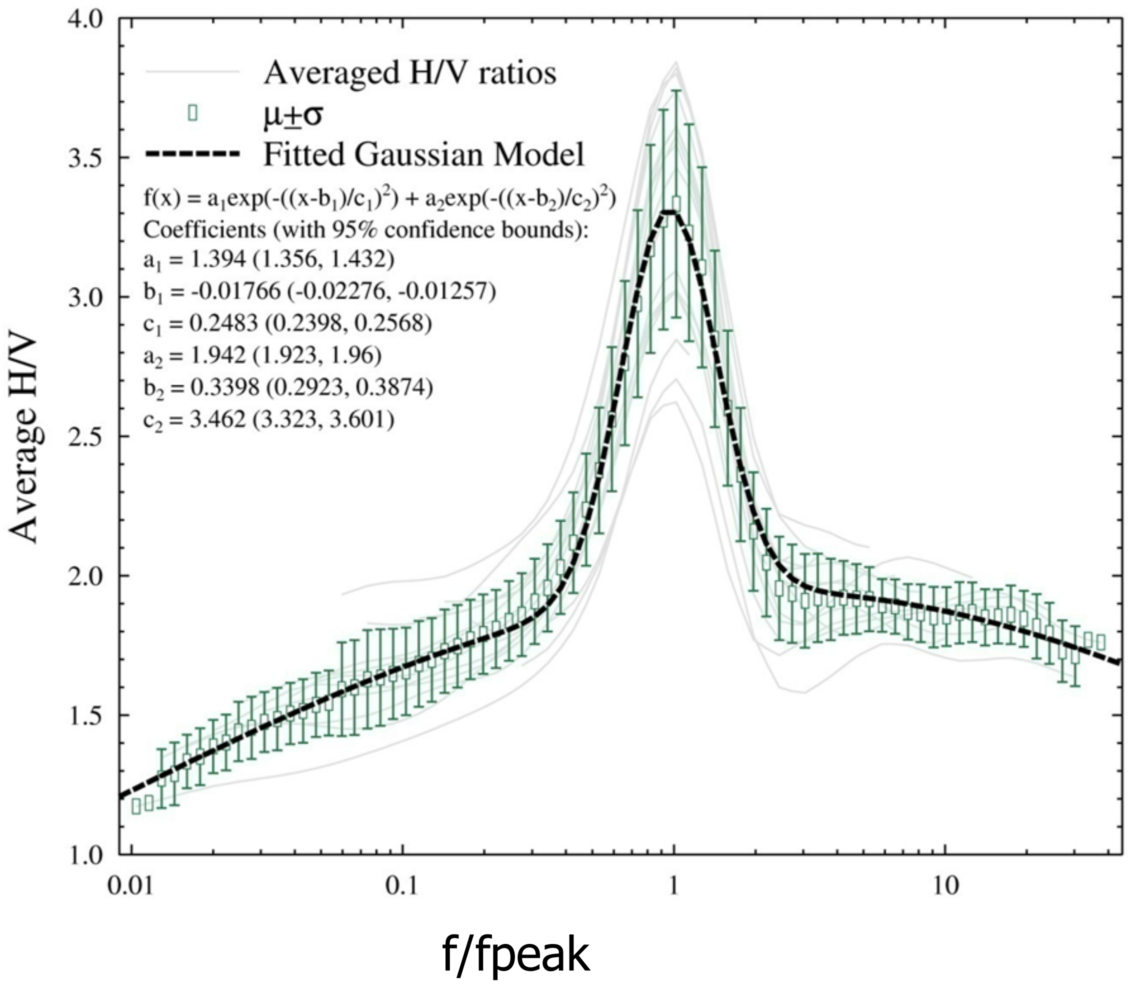
- In Japan, sites with high Vs30 are typically shallow soil (<30 m) over rock; Vs30 is increasing as the relative proportion of stiff underlying material increases
- Vs30 is diagnostic of site response curve and its peak amplitude only if it is low (<250 m/s)

H/V for sites in Japan
- grouped by peak frequency



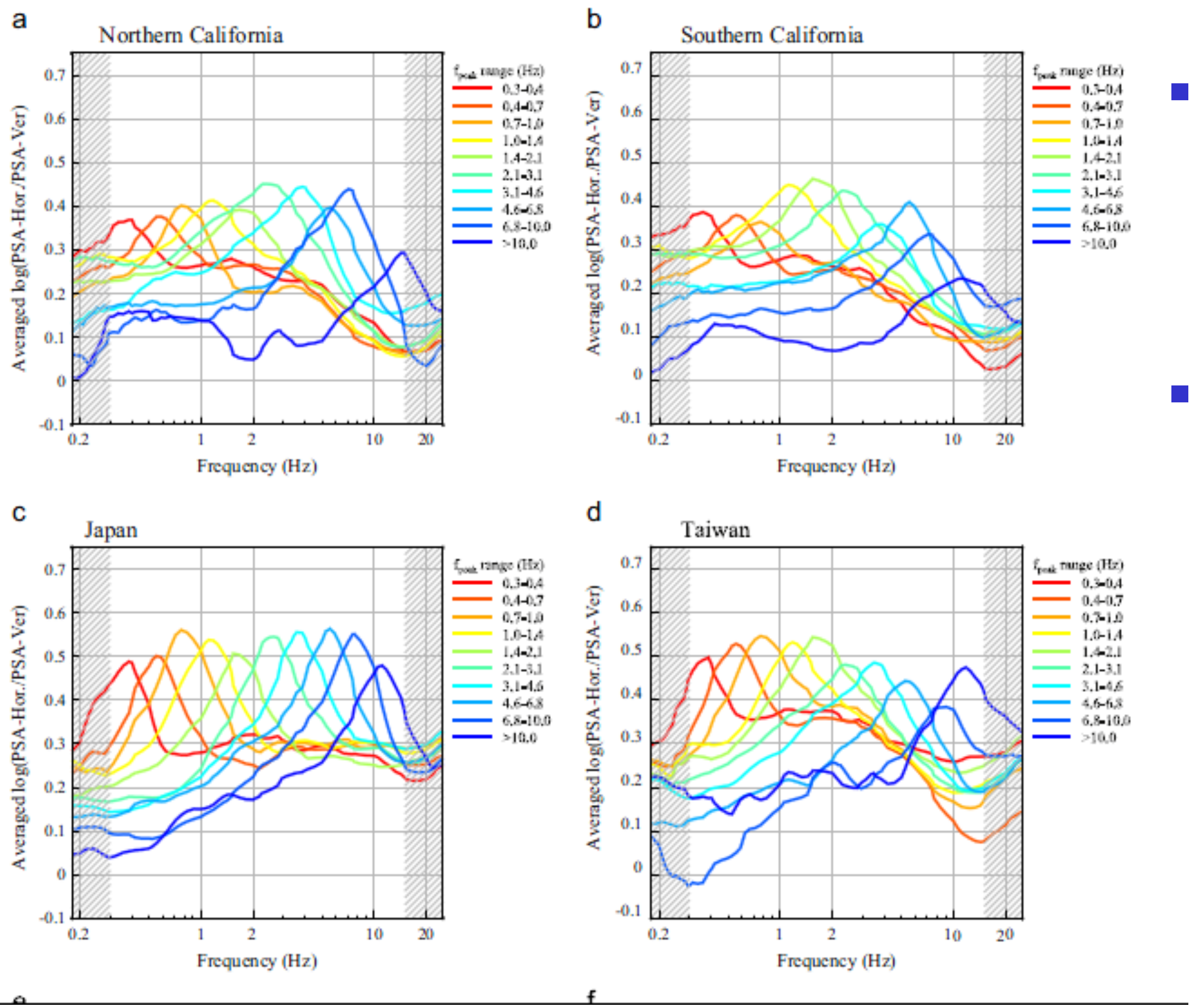
- Site response curves clearly distinguishable by peak frequency
- The peak amplitude varies between ~0.42 to 0.59 log units (factor 2.6 to 3.9)

Define a generic amplification curve, normalized by peak frequency



- Considering the small variation of peak amplitudes for the averaged-H/V spectra, we shifted all curves to be centered at f/fpeak = 1, and defined a single generic curve
- The green squares are the average values and bars are ±1 standard deviation around mean.
- This is a standard H/V curve, indicative of site response

We can also group sites by f_{peak} for other regions: NGA-West2 database



- H/V curves grouped by f_{peak} for regions in NGA-W2 database
- These can also be normalized, and compared to standard H/V curve

Standard H/V curve for NGA-W2

- 2 types of regions
- Japan, Taiwan, China have H/V curve as given by the standard response curve developed for Japan
- California sites have similar shape curve but a bit broader, and peak amplitude is shifted down by 0.12 log units on average; southern California has enhanced frequency content to left of fpeak

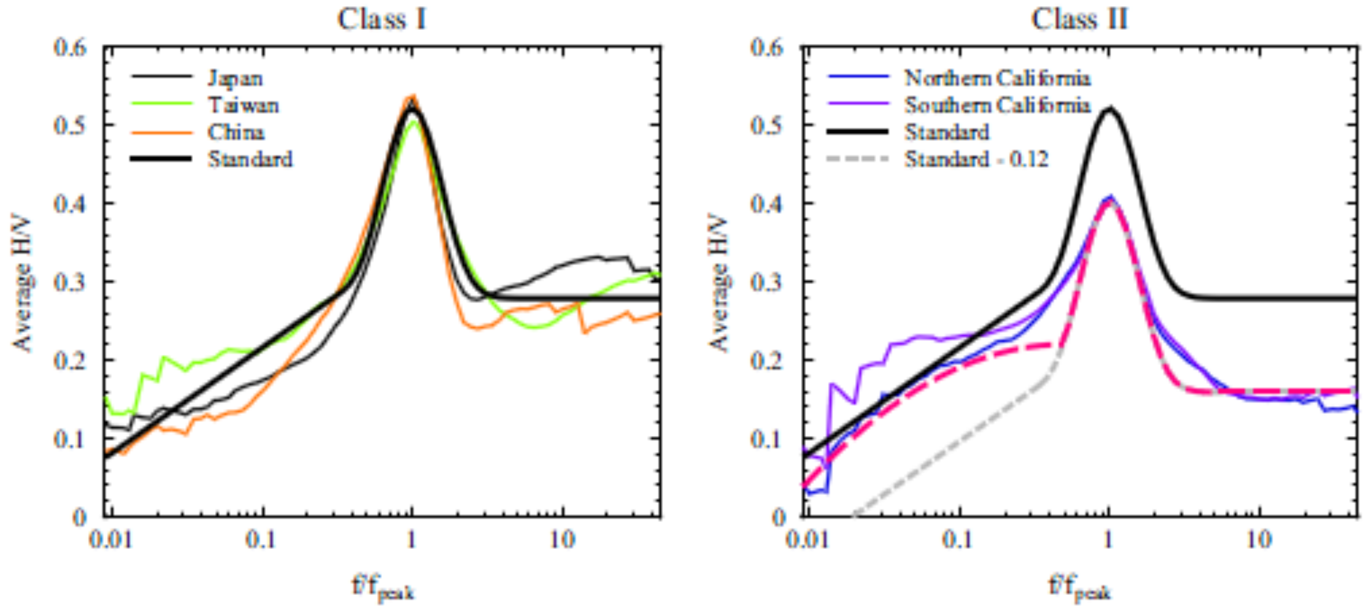
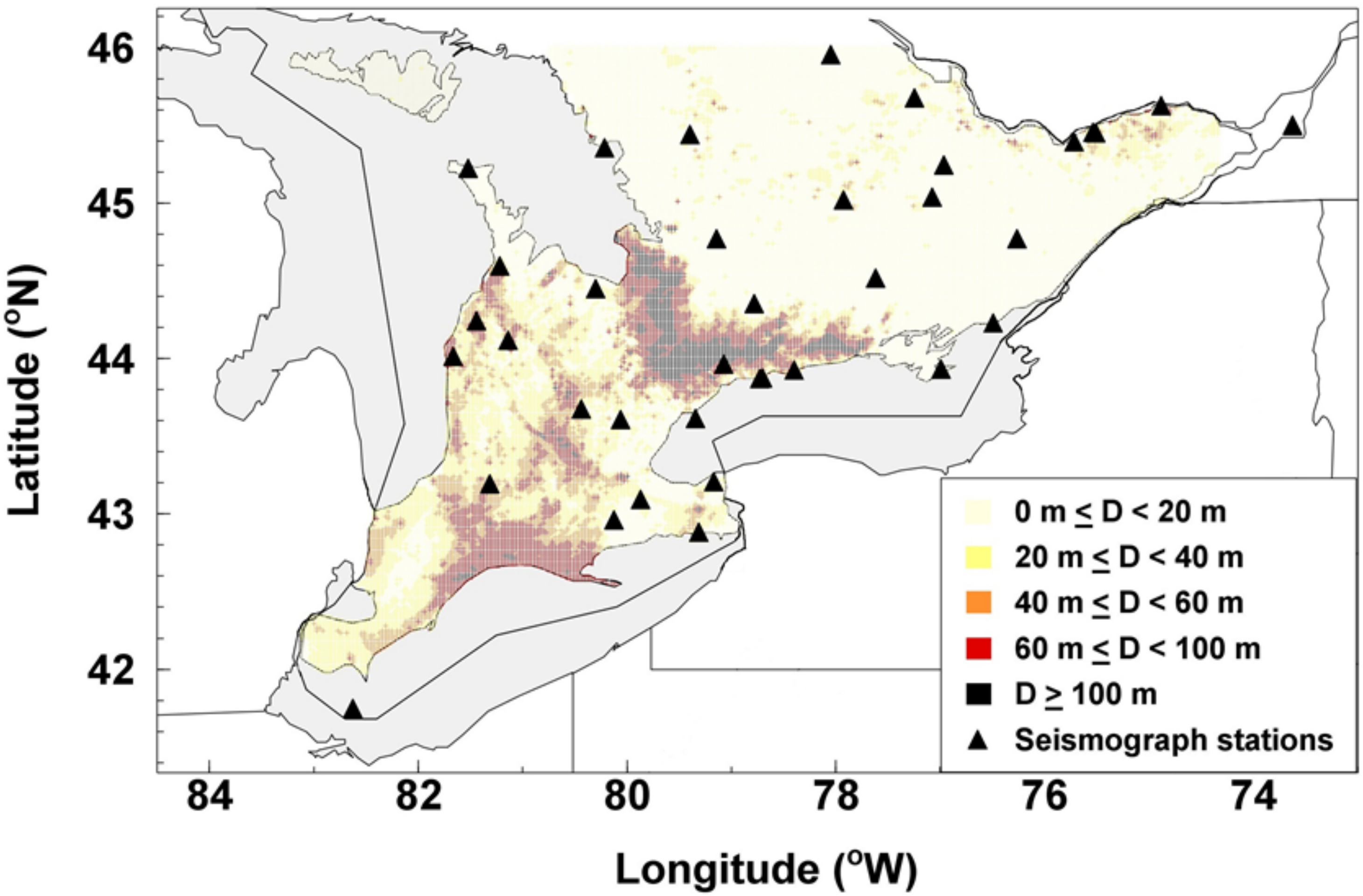


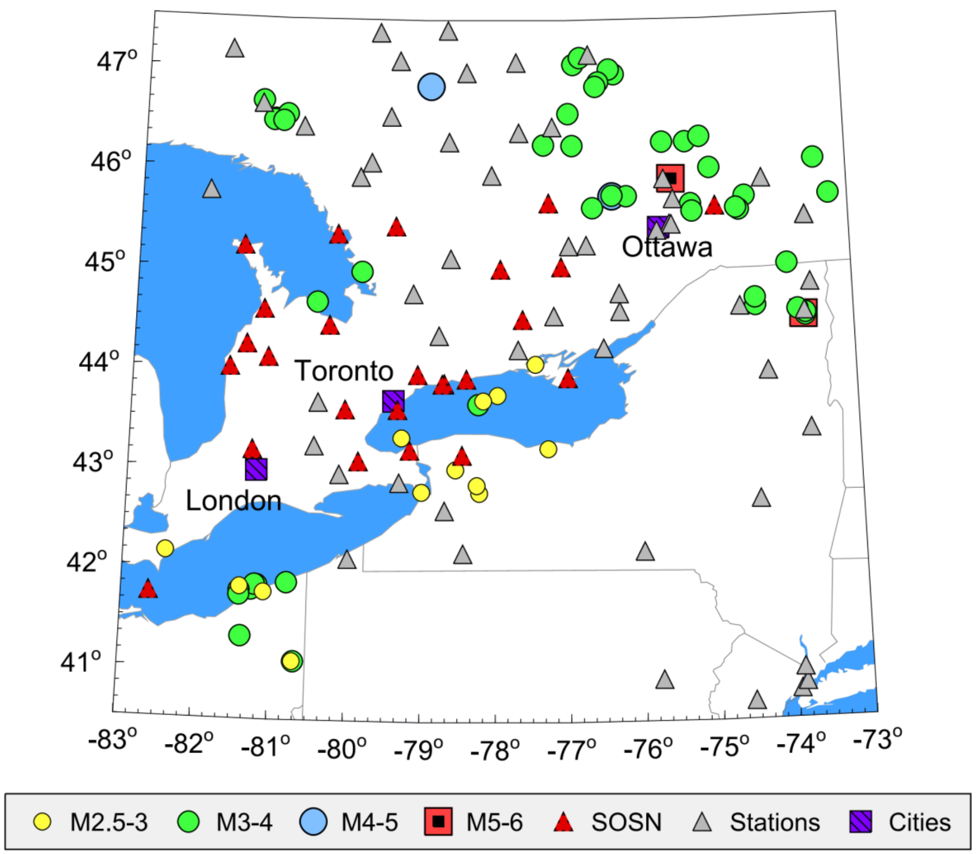
Fig. 14. H/V standard curves in the selected regions, grouped into two classes: Class I: Japan, China, and Taiwan; and Class 2: Northern and Southern California. The smooth black curve in both panels is the standard curve defined based on data in Japan (Fig. 7). For California, an adjustment of −0.12 (log units) is needed to bring the standard curve down to match the peak and the high-frequency end (dashed grey line). To mimic the bump at low frequencies relative to this shape in California, a further adjustment is needed (magenta line in Fig. 14).

More on H/V and site response: Studies in southern Ontario (Braganza et al.)

- varying sediment thicknesses from shallow (<20m) to deep (>100m) lead to a range of fpeak values (eastern Ontario has many bedrock sites)



Southern Ontario Database - overview

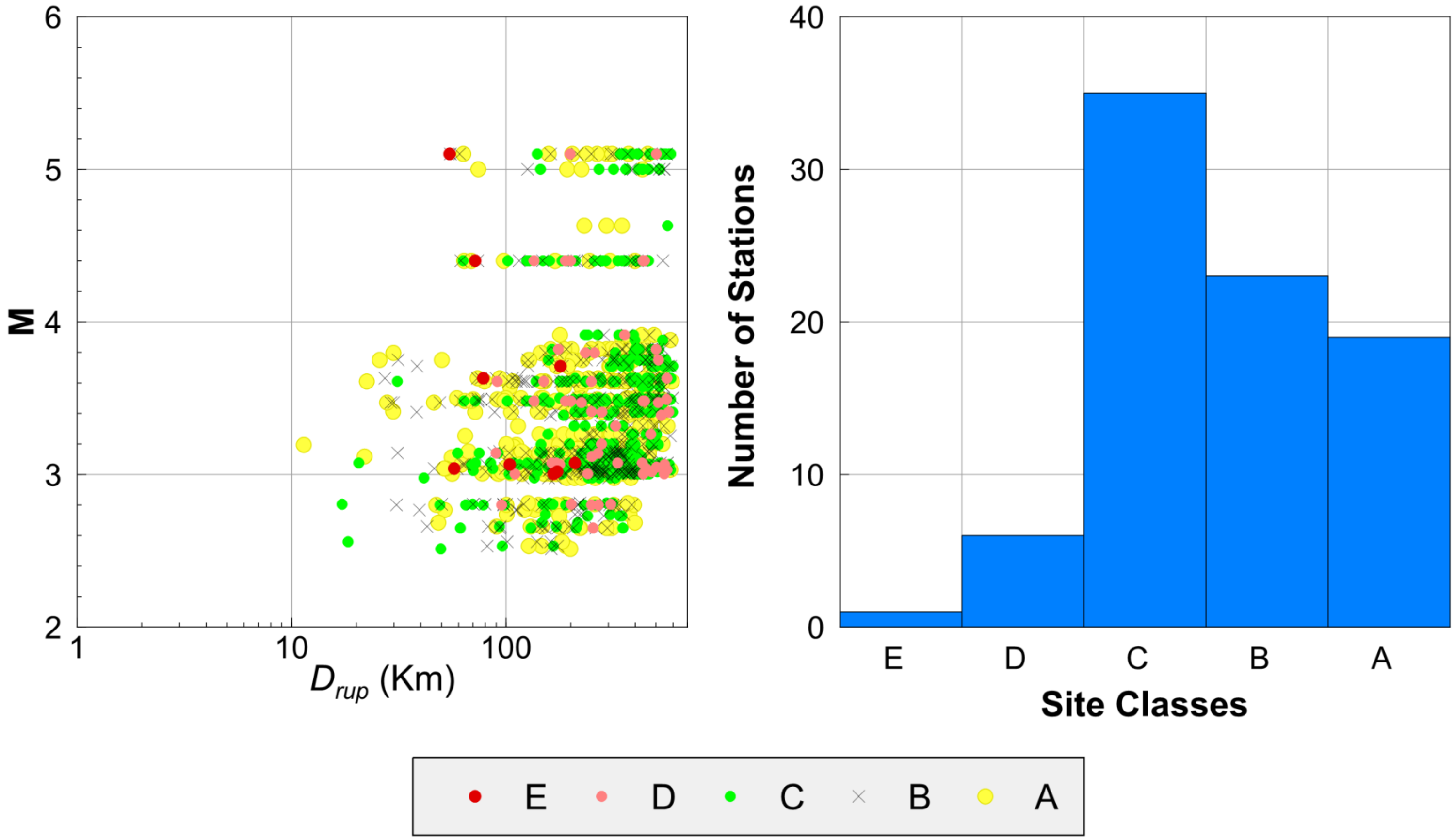


- Geomean horizontal components
- 5% damped **PSA** [0.1-20 Hz], **PGA, PGV**)
- 1205 Records
- 62 events (Minimum 3 records)
- 84 stations (Minimum 3 records)

Data: (Atkinson et al.)

- Southern Ontario database (75%)
- Seismotoolbox.ca (6%)
- NGA-East database (19%)

Southern Ontario Database – Data distribution



Data:

- Southern Ontario database (75%)
- Seismotoolbox.ca (6%)
- NGA-East database (19%)

Develop regional ground-motion prediction equation, based on generic GMPE model of Yenier and Atkinson (2015) (references a standard stochastic point-source model)

$$\ln Y = F_E + F_Z + F_\gamma + F_S + C$$

- **Source (F_E)**

  $F_E = F_M + F_{\Delta\sigma}$

- Anelastic attenuation (F_γ)

  γD_{rup}

- **Calibration factor (*C*)**

- **Geometrical spreading (F_Z)**

  bilinear $b_1, b_2, R_t =$

- **Site effects (F_S**

Generic GMPE – use to determine site terms for stations in southern Ontario, relative to bedrock

$$\ln Y = F_E + F_Z + F_\gamma + F_S + C$$

Simulation-based ($F_E + F_Z$) Empirical ($F_\gamma + F_S + C$)

- Assume the same F_M and F_Z Functions used for California and for CENA (NGA-W2 and NGA-east)

Define a functional form to describe the observed residual trends (e.g. $\log Residuals = F(f, r)$)

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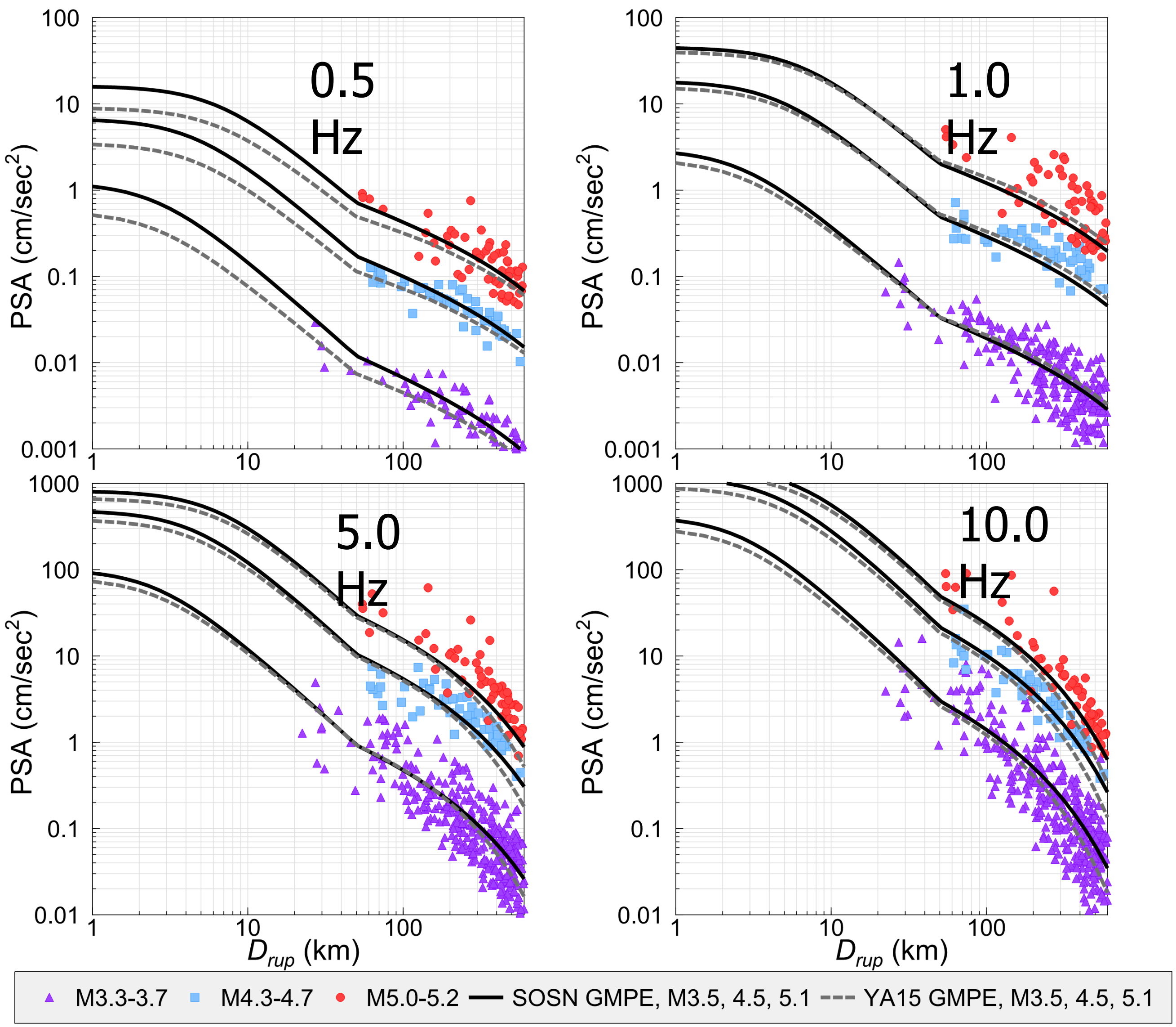
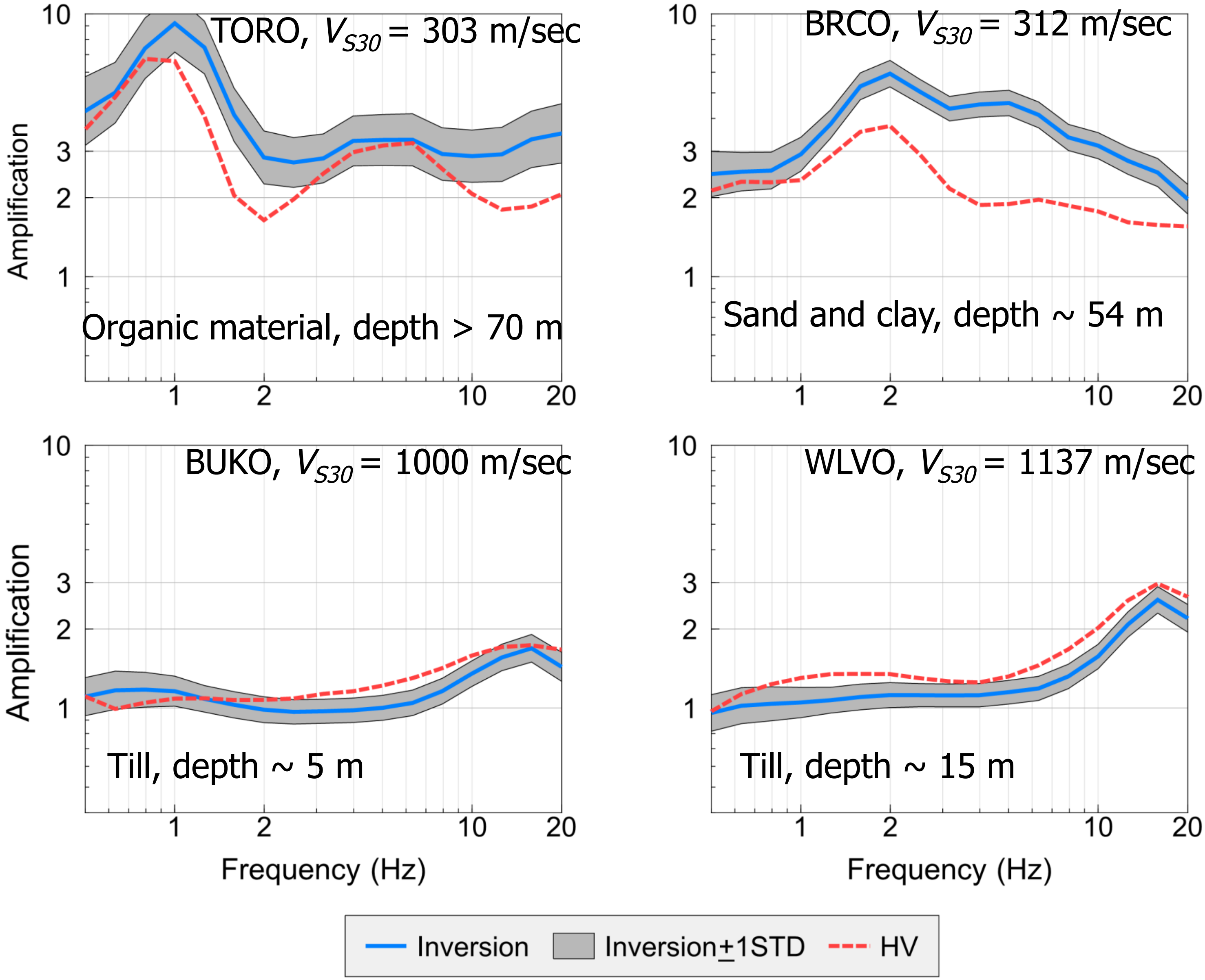
- Generalized inversion (Andrews, 1986)
- Determine source term for each event, region-specific anelastic attenuation (function of frequency), and site term for each station relative to reference
- Reference site condition V_{S30} ~ 2000 m/sec; constrain such that the average site term over all hard rock sites = 0.

Southern Ontario GMPE

$$\ln(Y) = F_M + F_Z + F_{\Delta\sigma,SOSN} + \gamma_{SOSN} D_{rup} + F_S + C_{SOSN}$$



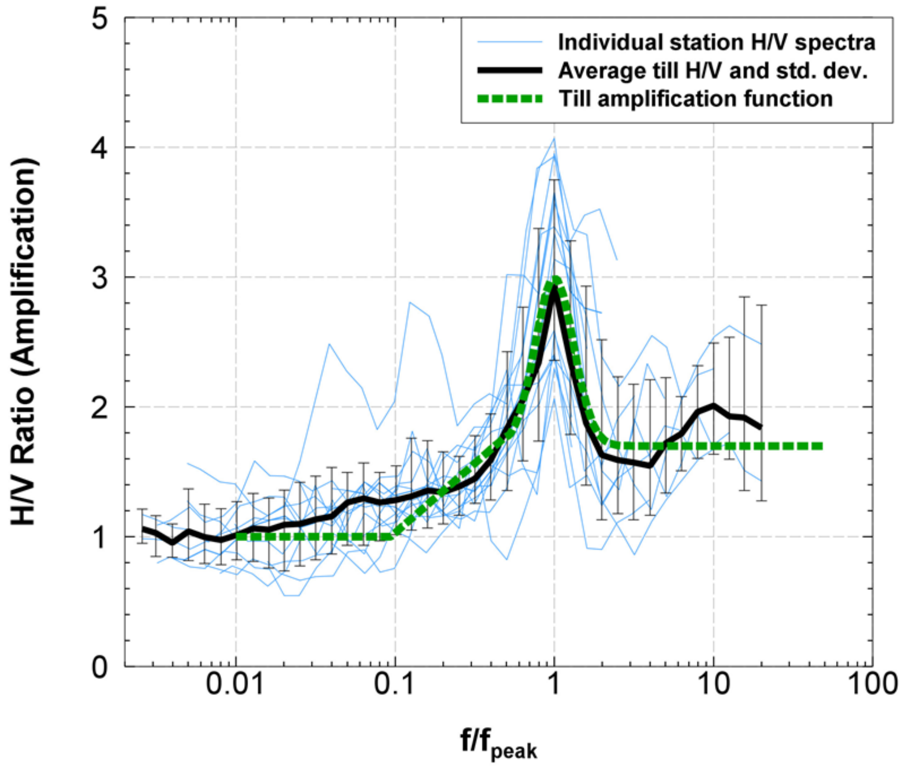
Site Amplification (F_S) relative to hard rock (Vs30~2000 m/s) (linear); matches H/V



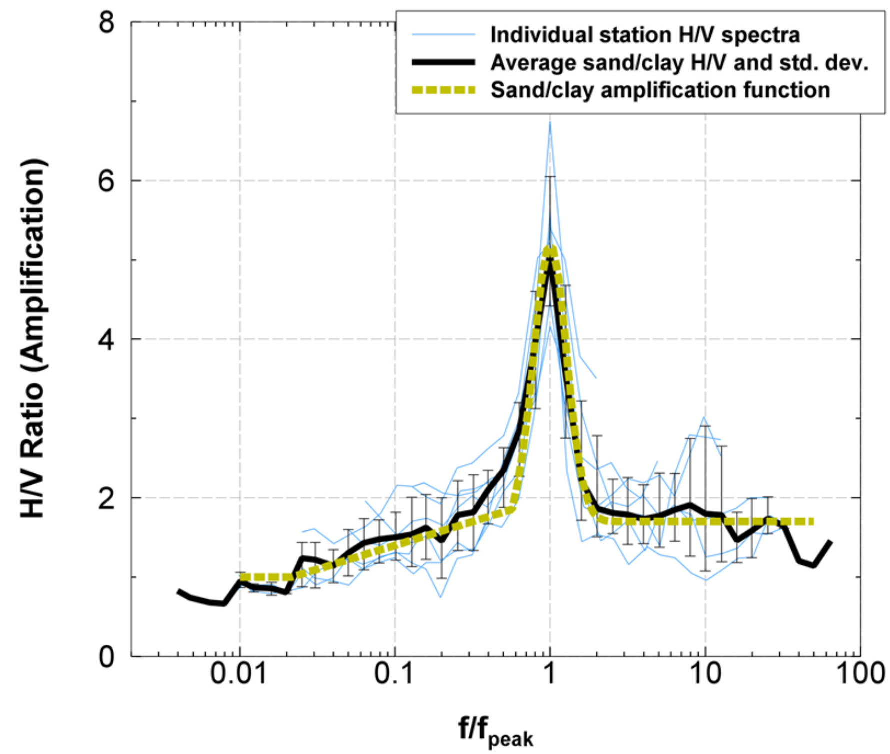
H/V shapes in eastern Canada

- Similar in shape to standard curves for Japan

Till sites

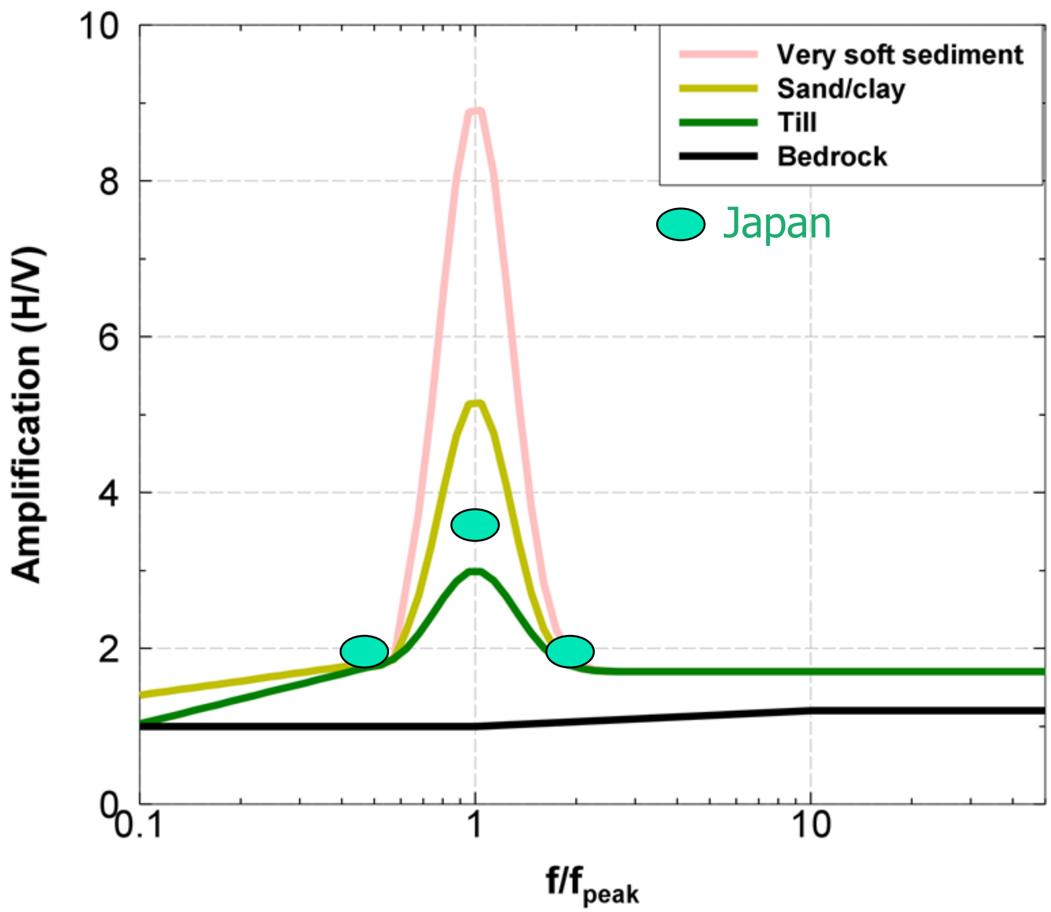


Sand/clay sites



H/V shapes in eastern Canada by site type

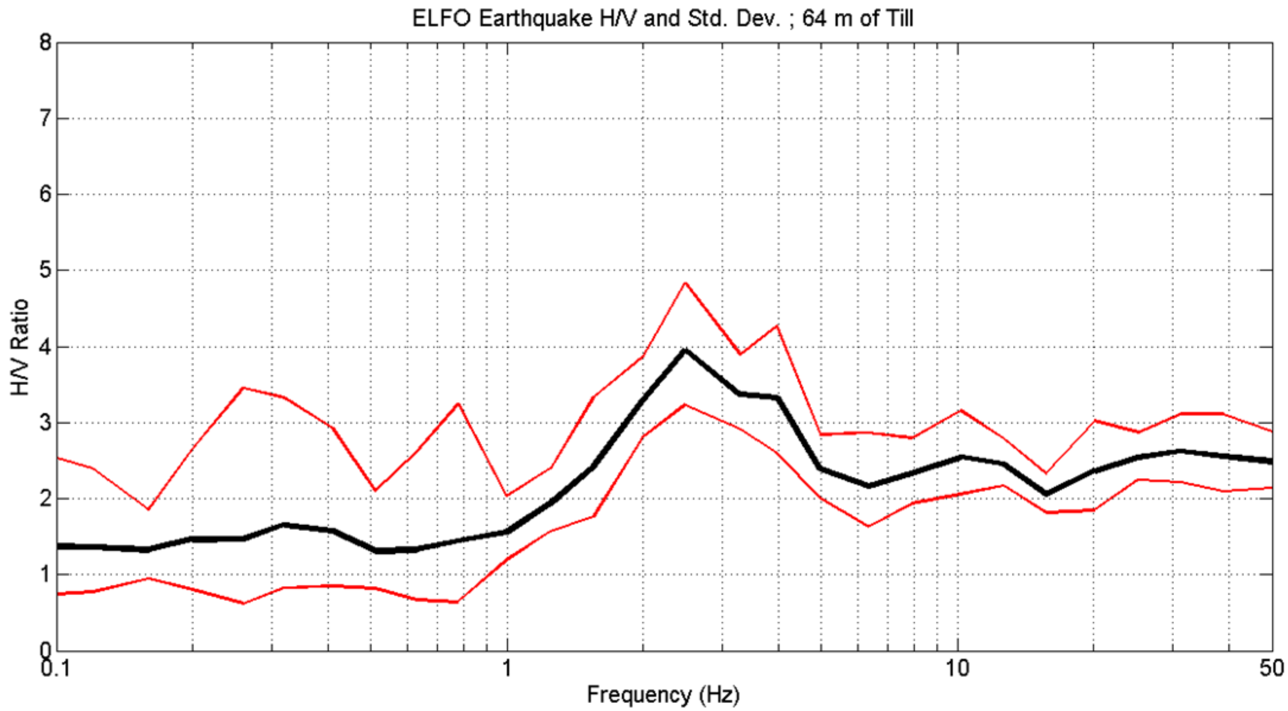
- Amplitude varies with stiffness of surficial soil deposit
- Note these are linear amplification factors relative to rock (Vs~2000m/s)



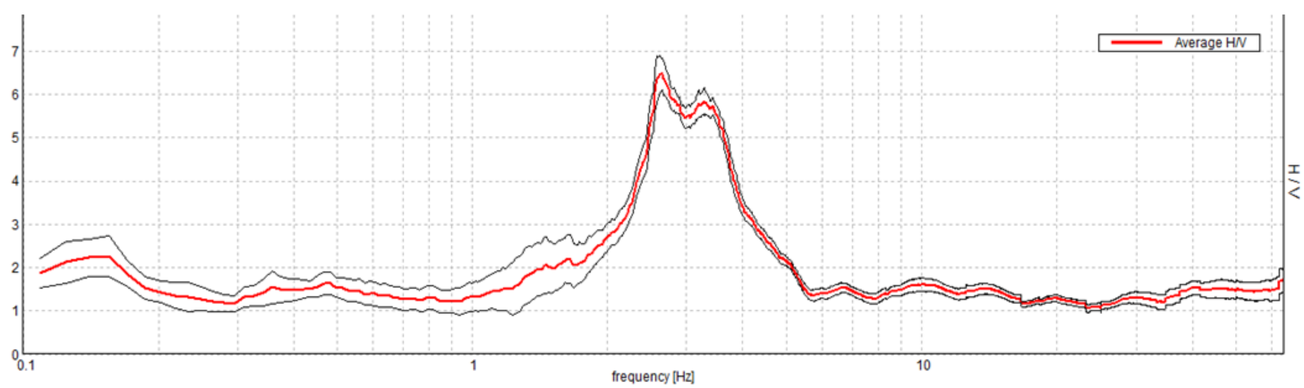
H/V shapes in eastern Canada similar whether obtained from earthquake recordings or microtremor (1 hour Tromino survey)

- Top figure is H/V from earthquake records at ELFO (64m of till)
- Lower figure is H/V from Tromino survey (same f_{peak} but higher A_{peak})

4 →



6 →



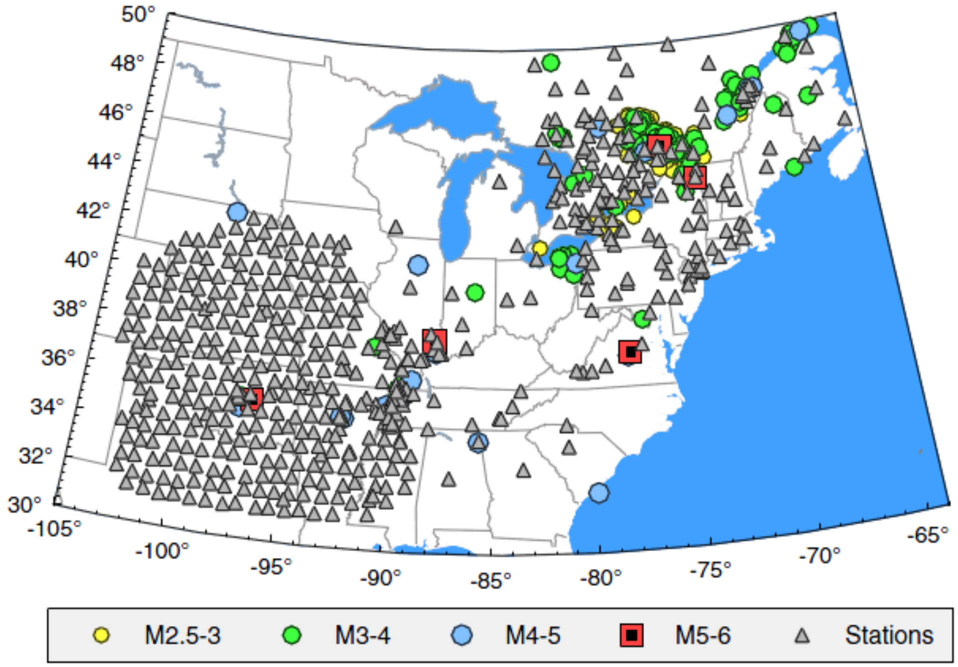


Figure 1. Geographic distribution of study events and stations. The color version of this figure is available only in the electronic edition.

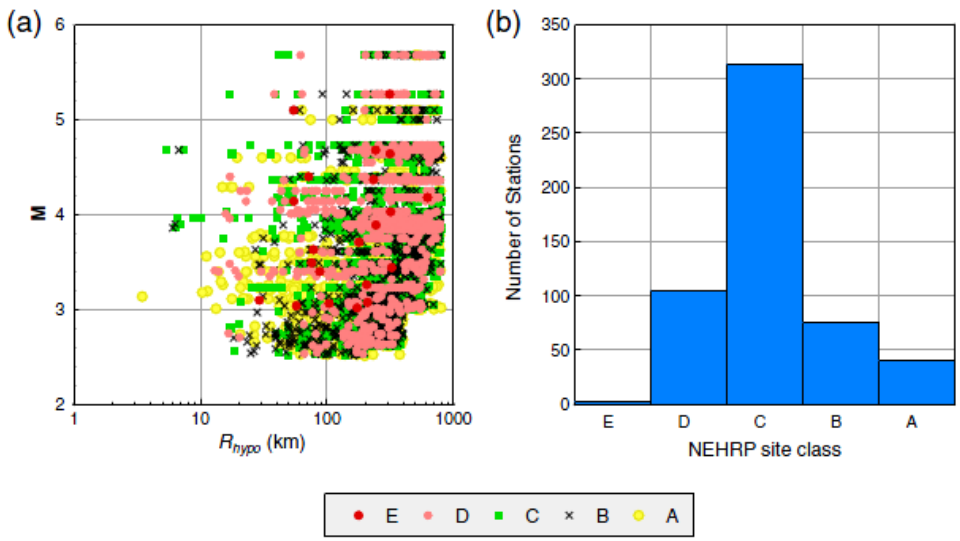


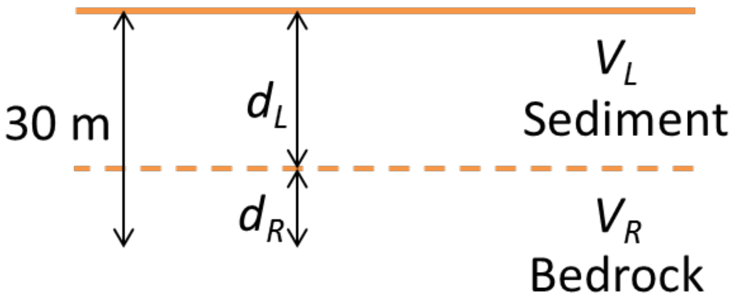
Figure 2. (a) Magnitude–distance distribution of the database, by National Earthquake Hazards Reduction Program (NEHRP) site classes and (b) histogram of number of stations in each site class. The color version of this figure is available only in the electronic edition.

Studies of site response variables in CENA (NGA-East database):

Note that Vs30 is measured for only about 6% of sites, for the rest it is estimated using proxies

Hassani et al.

Single layer model:



Expected relationship between f_{peak} and V_{s30} can be calculated for a given site profile.

Assume crustal velocity profile of Frankel et al., 1997 for rock profile, with a single softer layer sitting on top

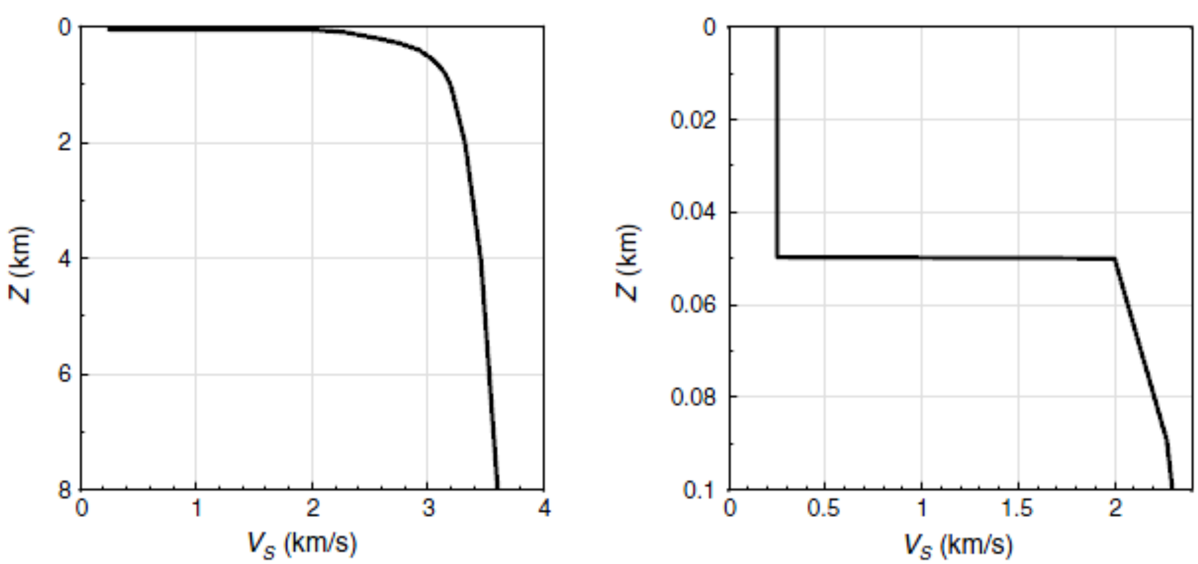
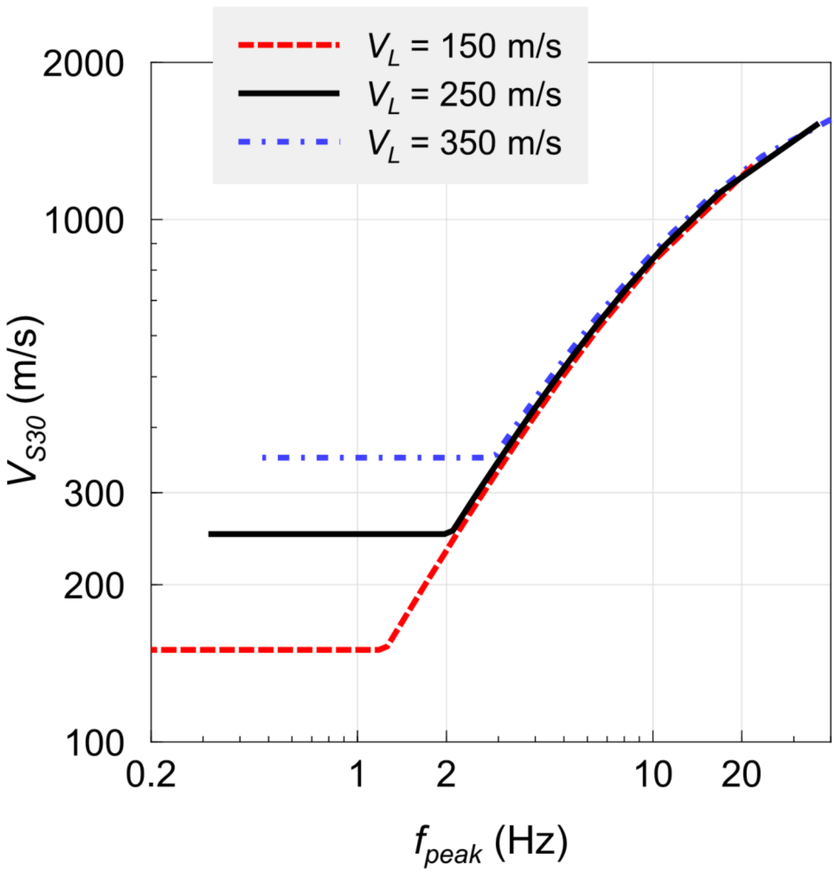


Figure 4. Adopted shear-wave velocity (V_S) profile as a function of depth (Z) for a single-layer model with constant velocity of $V_L = 250$ m/s, thickness of $d_L = 50$ m, and $V_R = 2000$ m/s.

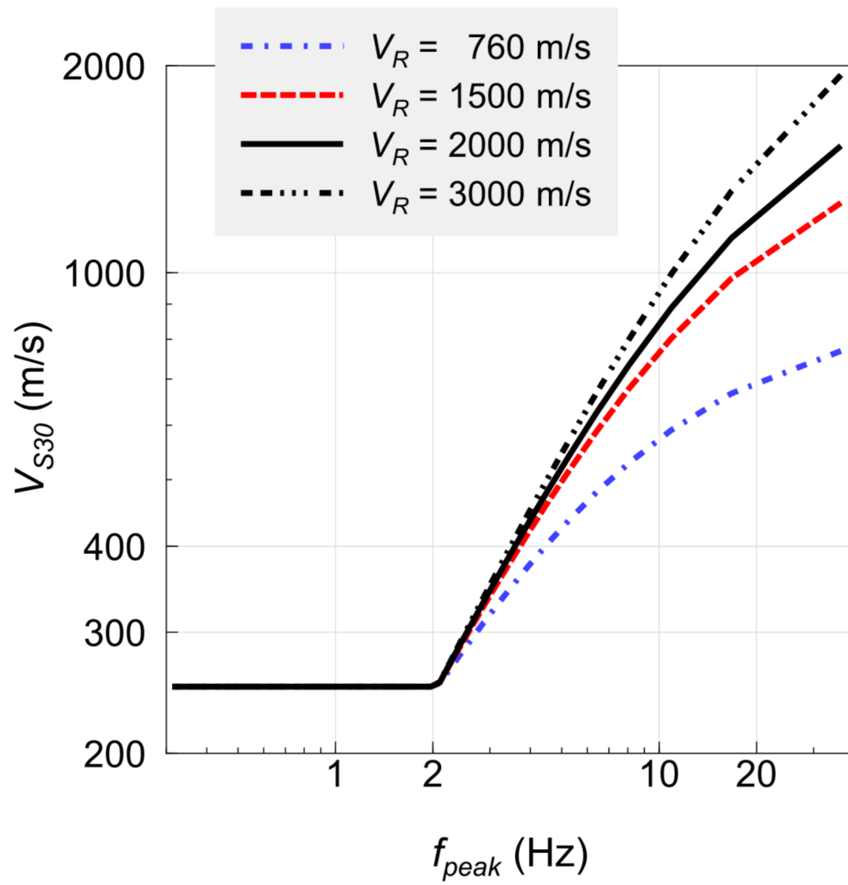
Predicted Relationship between f_{peak} vs. V_{S30}

Relationship between V_{s30} and f_{peak} for different layer velocities (V_L) and rock velocities (V_R), as calculated from square root impedance ratio method (SRI) (Joyner et al., 1981) Layer thickness 2m to 200m. Q=15

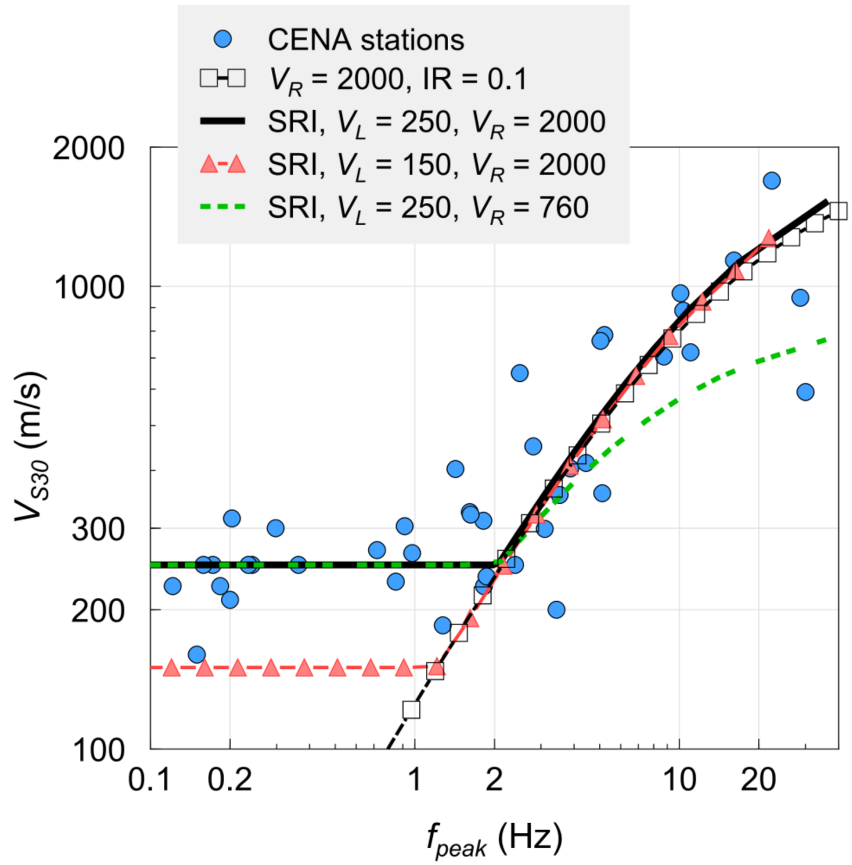
Constant V_R (2000 m/s)

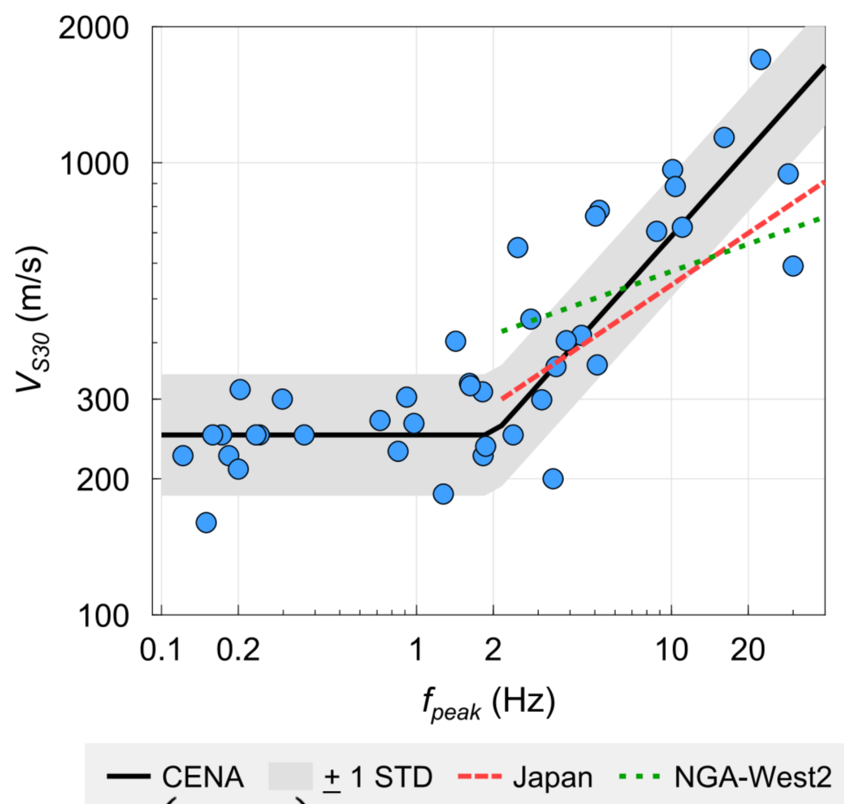


Constant V_L (250 m/s)



Observed CENA f_{peak} vs. V_{S30} : We can predict V_{s30} from f_{peak} (better than other proxies)





$$log\,10(V_{S30}) = \begin{cases} 2.2(\pm 0.04) + 0.63(0.06)log10\left(f_{peak}\right) & f > 2\,Hz \\ log10(250) & f \le 2\,Hz \end{cases}$$

Standard deviation is equal to 0.14 in log10 units, significantly smaller than for other proxies used in NGA-East database

Relationship between V_{s30} and f_{peak}

- We can use f_{peak} (measured from H/V) as a proxy to estimate V_{s30} for stations in the NGA-East database having no measured V_{s30}
- f_{peak} works better than other proxies to estimate V_{s30} (if we have measureable f_{peak})
- But is V_{s30} the most appropriate site response measure?
- Can we use generic models from the west to estimate site response if we know V_{s30} ?

Applicability of the NGA-West2 site effects model to sites in CENA (Hassani et al)

- No V_{S30}-based regional site amplification model for sites in CENA.
- GMPE modelers either used western-based site effects models or developed their own V_{S30}-based model (few measured V_{S30}).
- In CENA, V_{S30} may not be the best choice of site variable.
- Explore the applicability of the NGA-West2 site effects model for sites in CENA.

Site terms vs. f_{peak}

Residual Analysis of site terms (by station) relative to a GMPE

- Selected CENA Ground-motion prediction equation model (GMPE) (Yenier and Atkinson, 2015; **YA15**)
- NGA-West2 site amplification model (Seyhan and Stewart, 2014; **SS14**) (V_{S30}-based model)

$$\boldsymbol{log(re_{ij,B/C}) = log(obs_{ij,B/C}) - log(pre_{ij,B/C})}$$

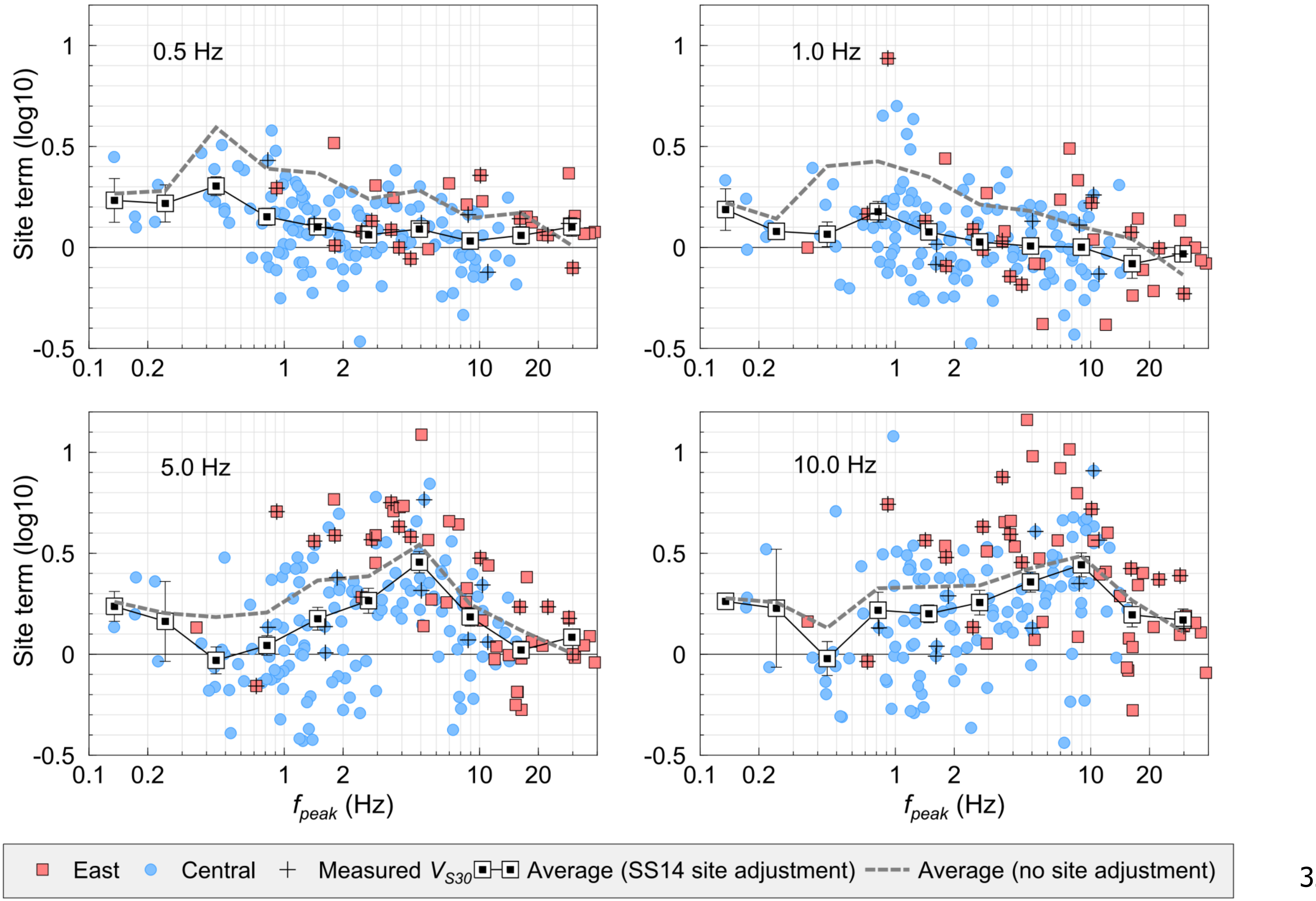
Residual | Observed adj to B/C (SS14) | Predicted for B/C (YA15)

$$\log(re_{ij,B/C}) = S_j + \eta_i + \varepsilon_{ij}$$

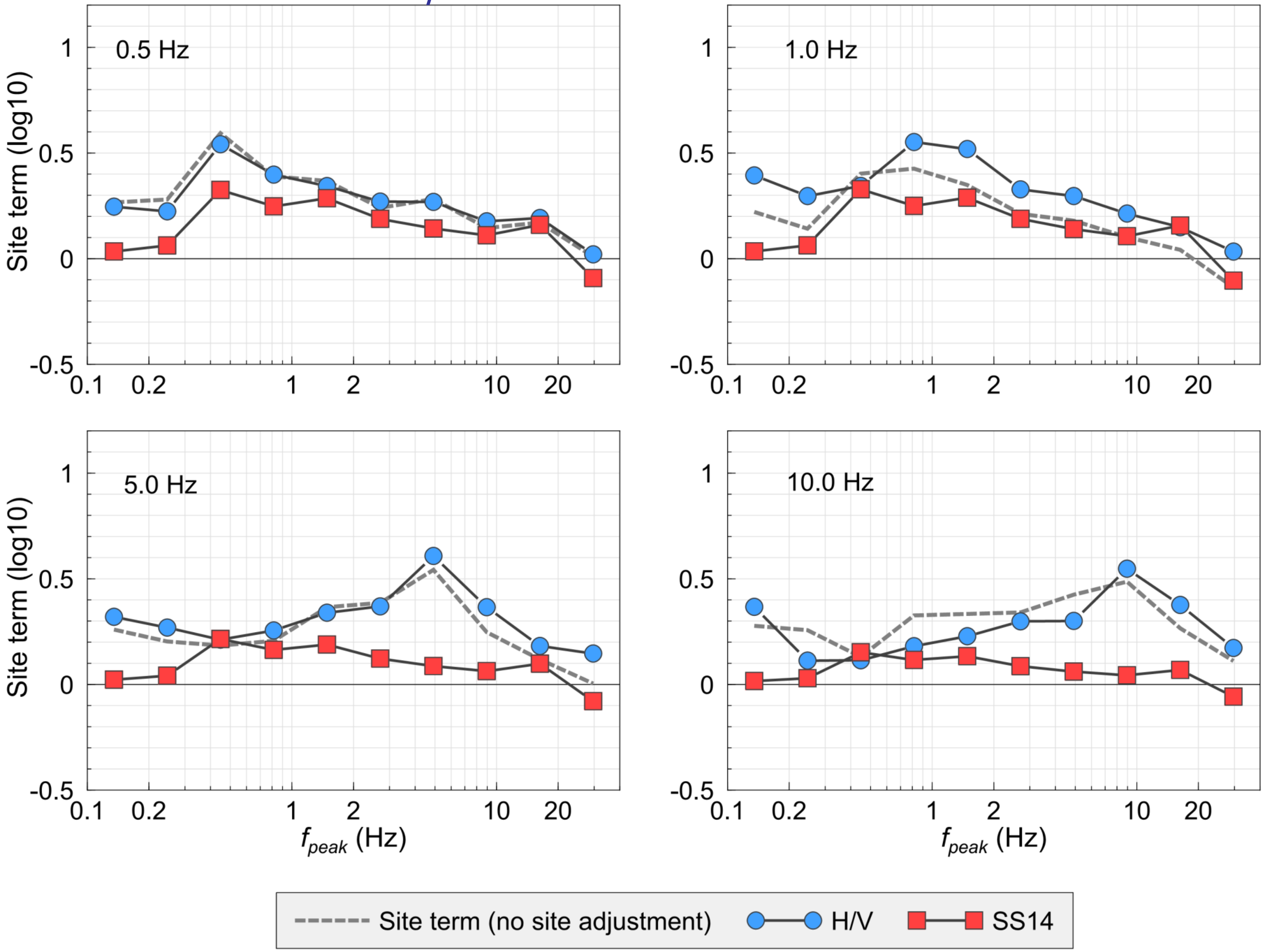
S: Residual Site term $\boldsymbol{\eta}$: Between-event term $\boldsymbol{\varepsilon}$: Within-event term

Abrahamson and Youngs (1992)

Site terms (individual stations) vs. f_{peak} for PSA at specified frequency



Overall trends in site terms (PSA residual at specified freq) vs. f_{peak}
-trends in residuals track H/V



Correlation between site terms and amplification calculated from Vs30 (with SS14 model)

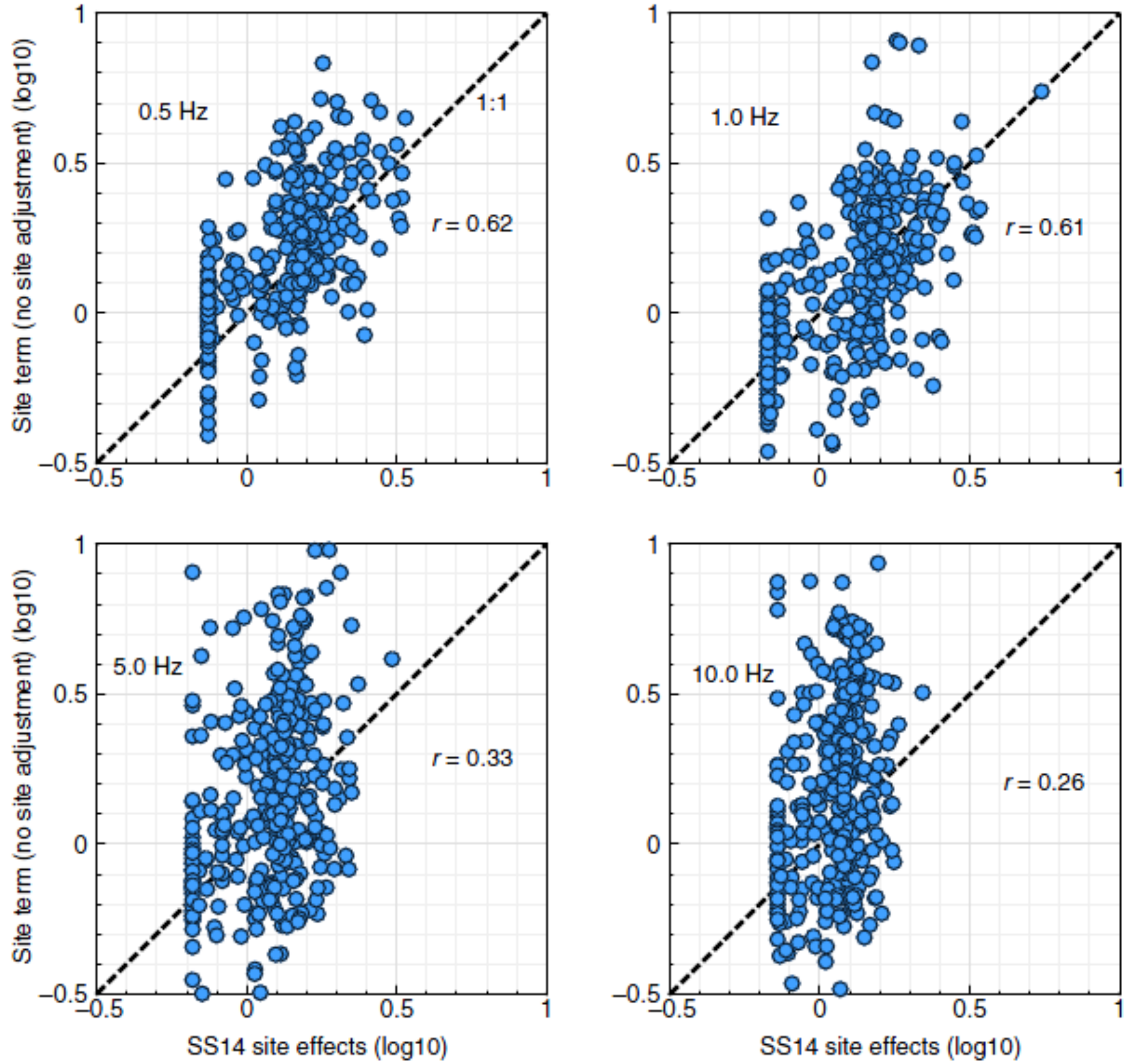


Figure 7. Total site terms (no site adjustment) are plotted versus SS14 site-effects terms as obtained using the reported V_{S30} values from the NGA-East database (circles). Correlation coefficients are also shown for the selected frequencies. The color version of this figure is available only in the electronic edition.

Correlation between site terms and amplification calculated as H/V

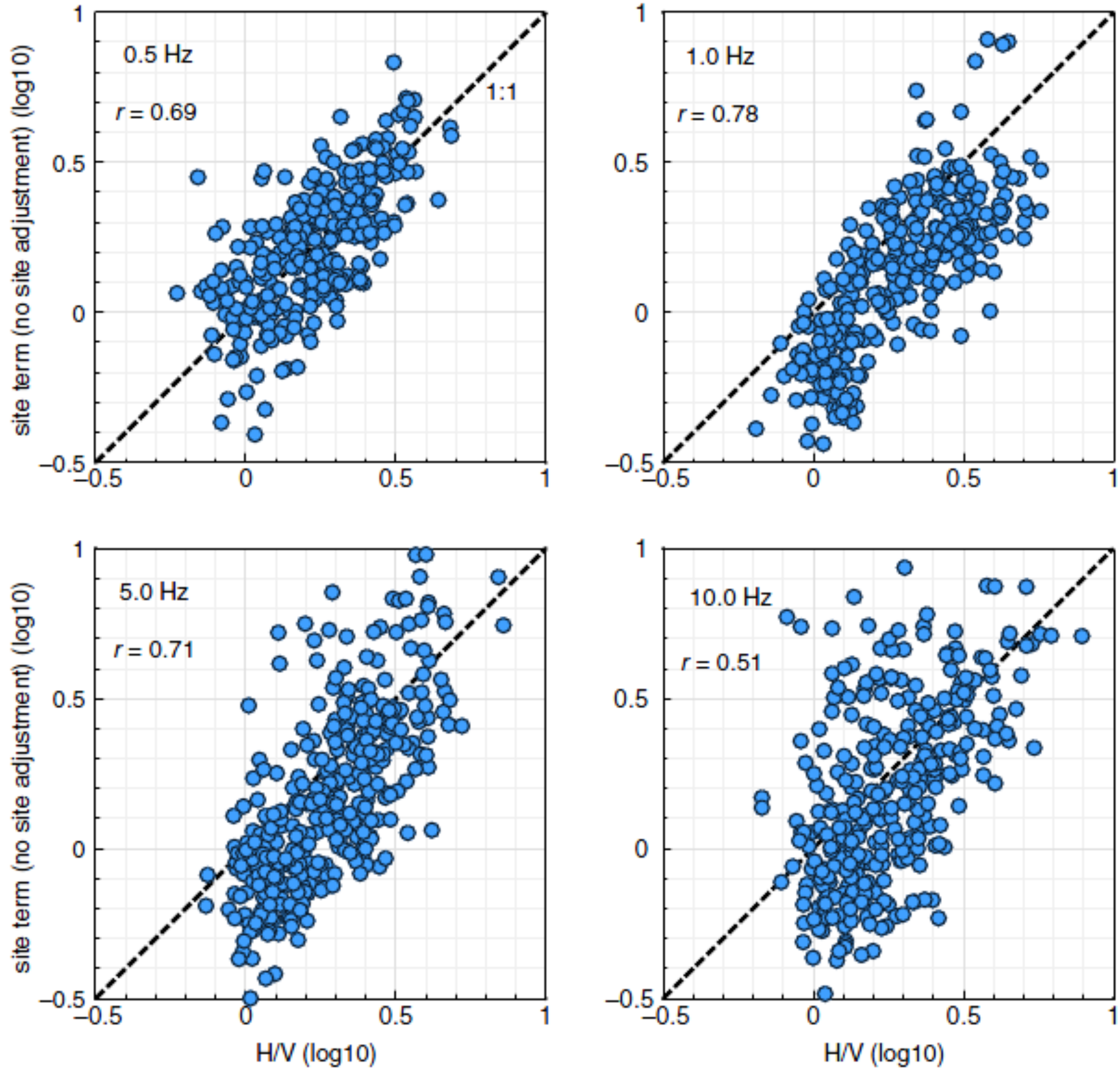
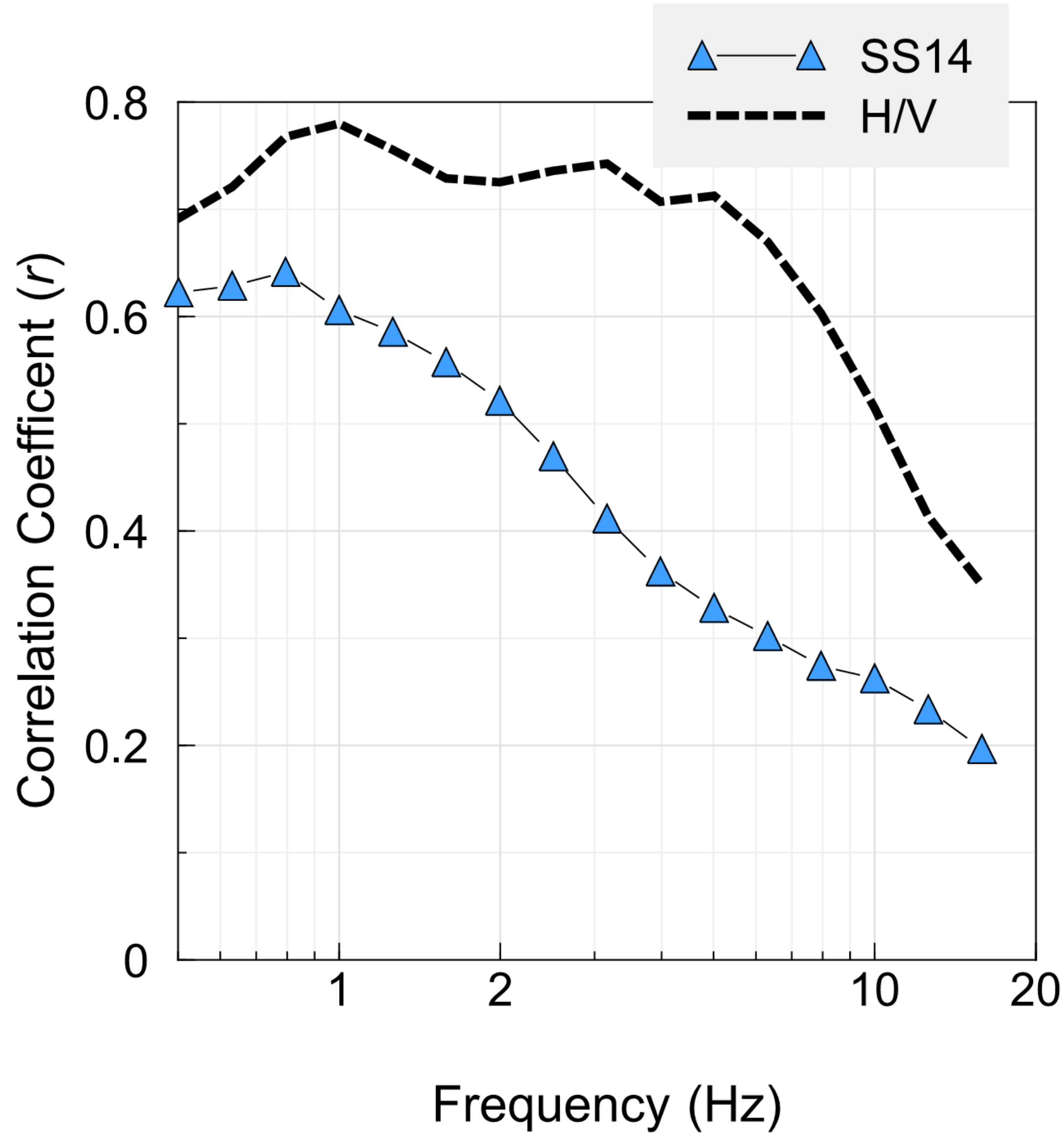


Figure 8. Total site terms (no site adjustment) are plotted versus the amplitude of the H/V spectral ratio, for four selected frequencies. Correlation coefficients are also shown. The color version of this figure is available only in the electronic edition.

Correlation coefficients comparison

H/V shows stronger correlation with site terms than does amplification calculated from SS14 model using Vs30

So maybe our model should use H/V – specifically f_{peak} from H/V



f_{peak}-based site amplification model for CENA (Hassani)

$$\boldsymbol{log(re_{ij}) = log(obs_{ij}) - log(pre_{ij,\,B/C\ or\ A})}$$

No site adjustment

Predicted for B/C (YA15) or hard-rock (A)

- Calculate site terms relative to two reference conditions:
  - Yenier and Atkinson (2015; YA15) model for B/C site conditions
  - Atkinson et al., (2015) model for hard rock (V_{S30} ~ 2000 m/s) (A sites)

$$\log(re_{ij}) = S_j + \eta_i + \varepsilon_{ij} \qquad \sigma = \sqrt{\tau^2 + \varphi^2}$$

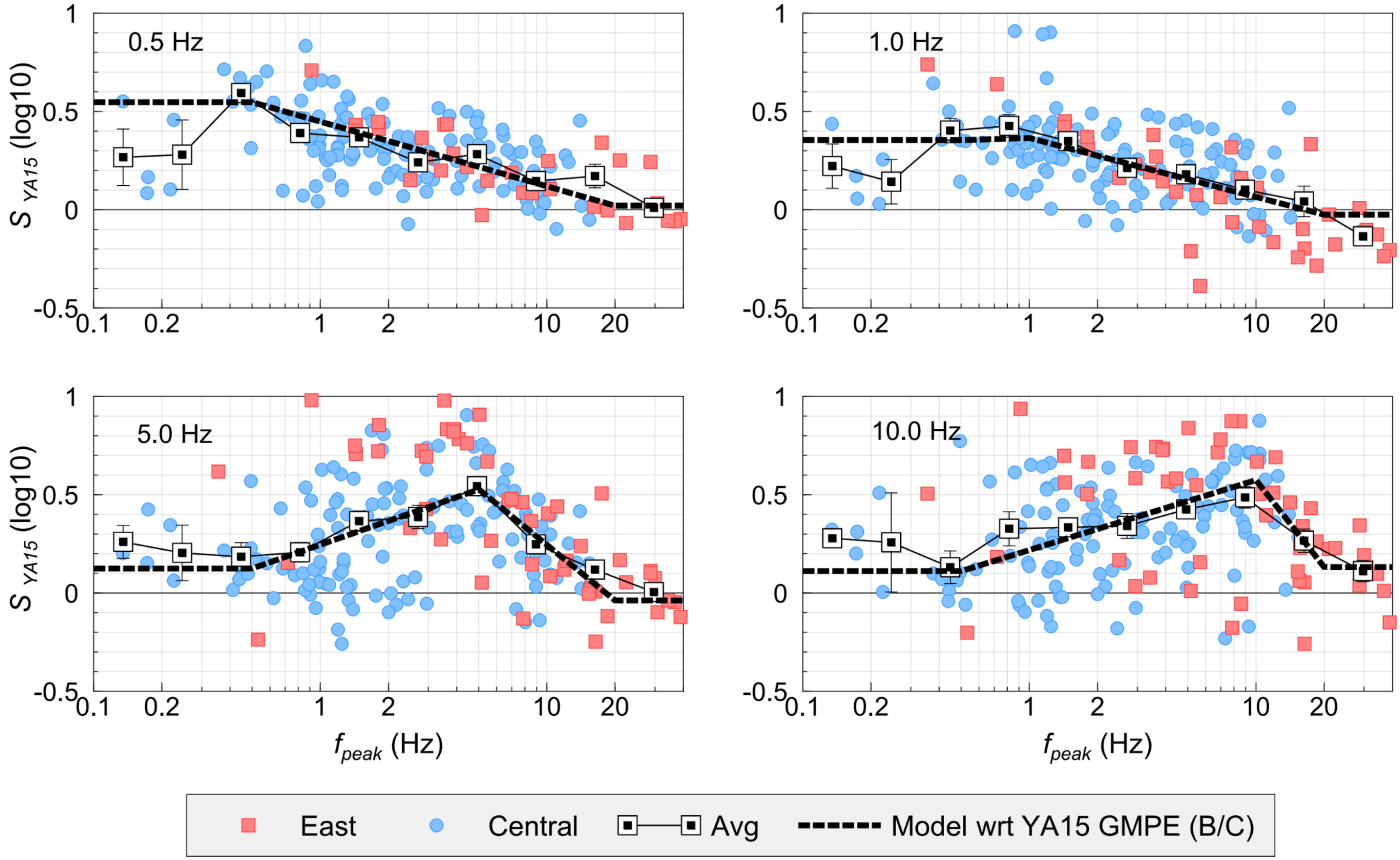
S: Site term

σ: total variability

$\boldsymbol{\tau}$: Between − event variability

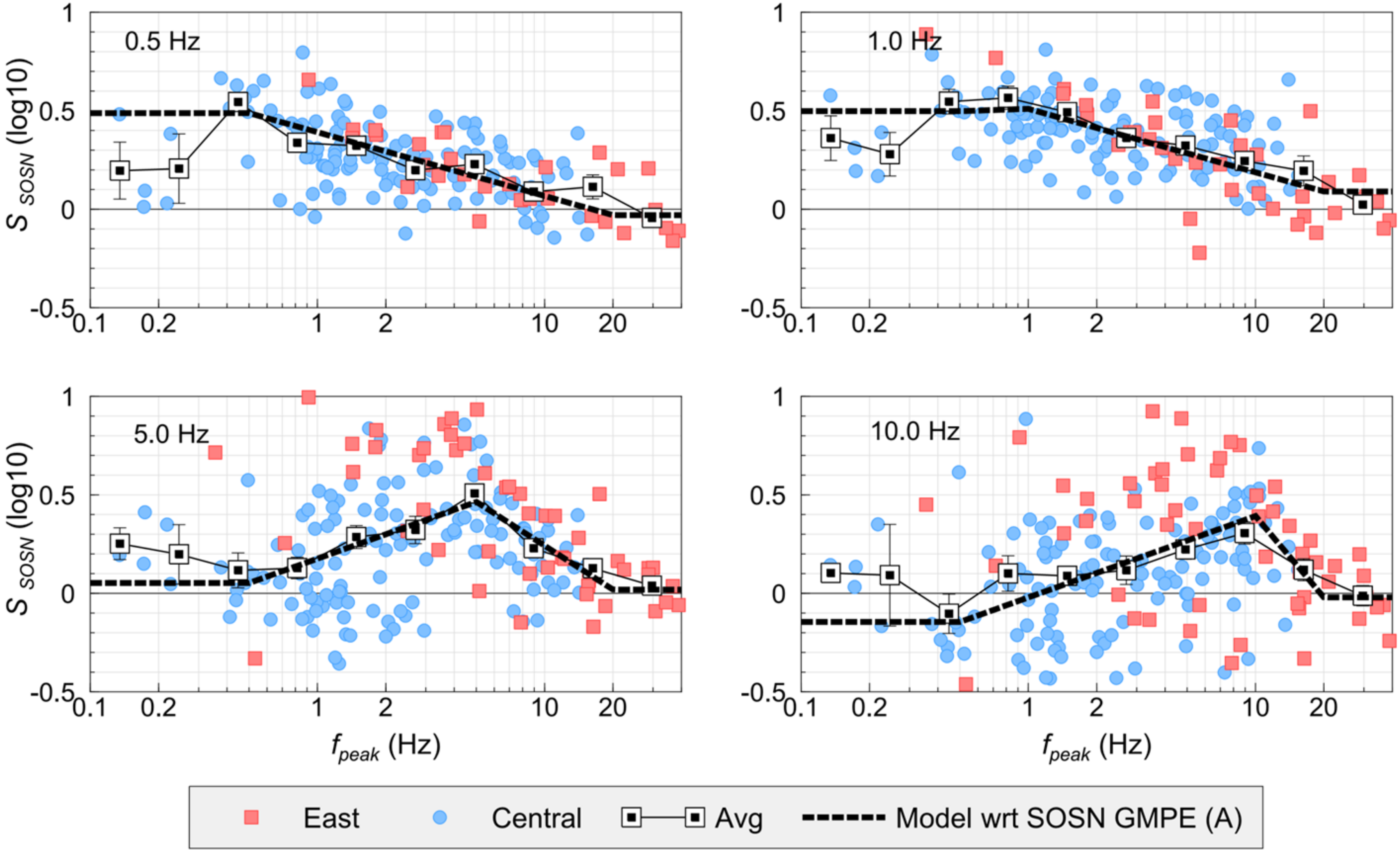
$\boldsymbol{\varphi}$: Within − event variability

Site term at selected frequencies wrt B/C vs. f_{peak} – dashed line shows model



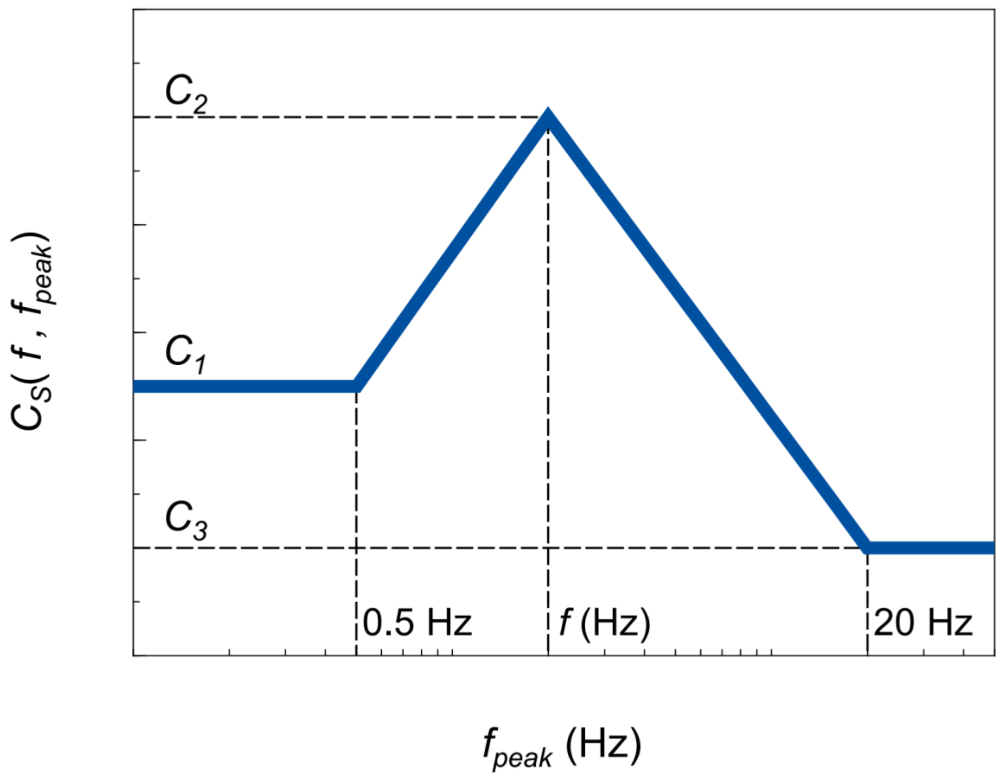
Yenier and Atkinson (2015; YA15) model for B/C site conditions.

Site term at selected frequencies wrt A vs. f_{peak} – dashed line shows model



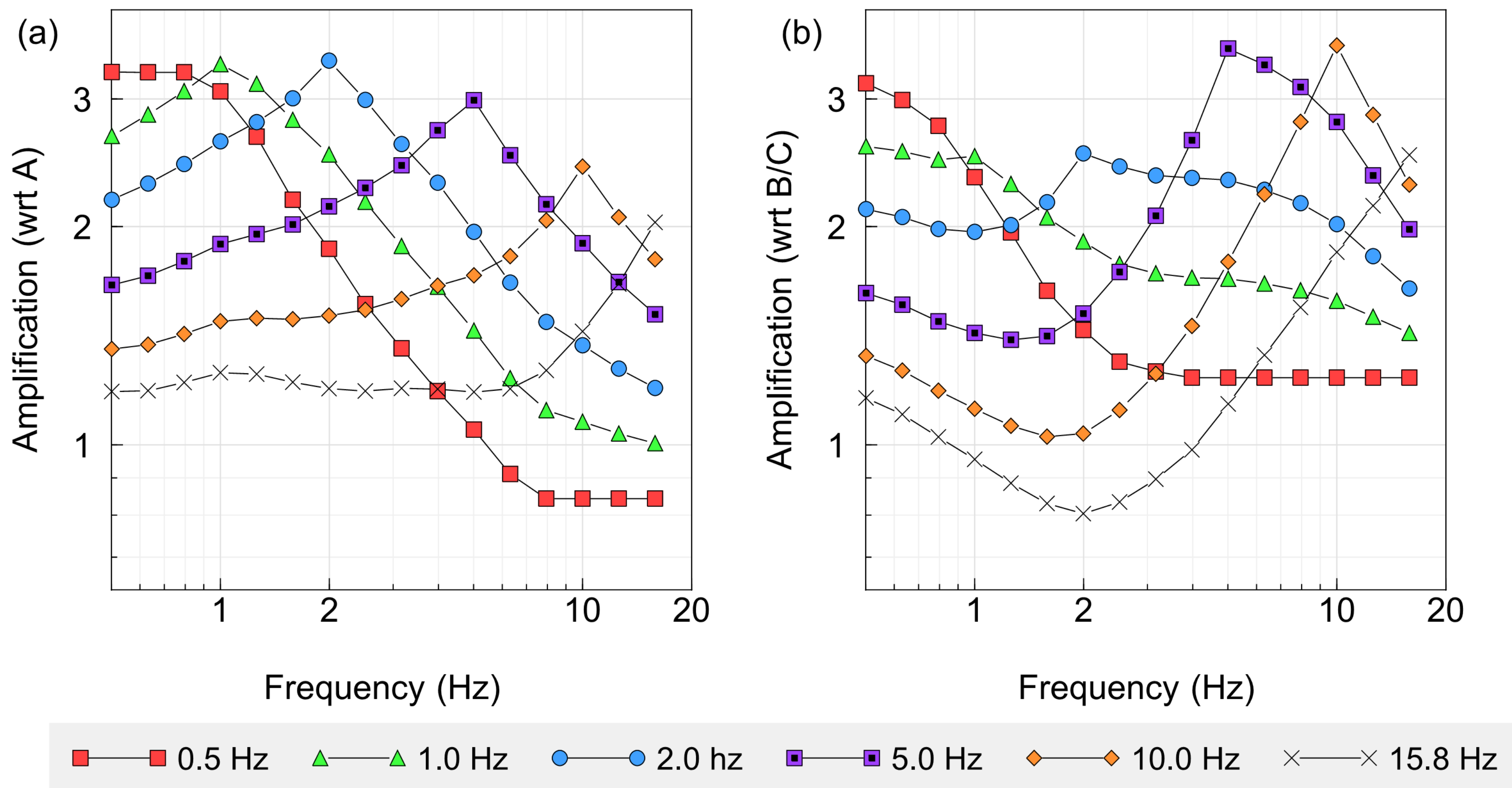
Atkinson et al. (2015) model for A site conditions (Vs30~2000 m/s)

General shape for f_{peak}-based site amplification model



$$C_s\left(f, f_{peak}\right) = \begin{cases} C_1 & f_{peak} < 0.5\ Hz \\ C_1 + \left[\dfrac{C_2 - C_1}{log10(f/0.5)}\right] \times log10\left(f_{peak}/0.5\right) & 0.5\ Hz \le f_{peak} < f \\ C_2 + \left[\dfrac{C_3 - C_2}{log10(20/f)}\right] \times [log10\left(f_{peak}/f\right)] & f \le f_{peak} < 20\ Hz \\ C_3 & 20\ Hz \le f_{peak} \end{cases}$$

Plot of f_{peak}-based site amplification model: relative to hard-rock (left) and B/C (right)



Curves show amplification for different values of site f_{peak}

Variability analysis: 10% reduction in sigma (σ) (mostly site-to-site component)

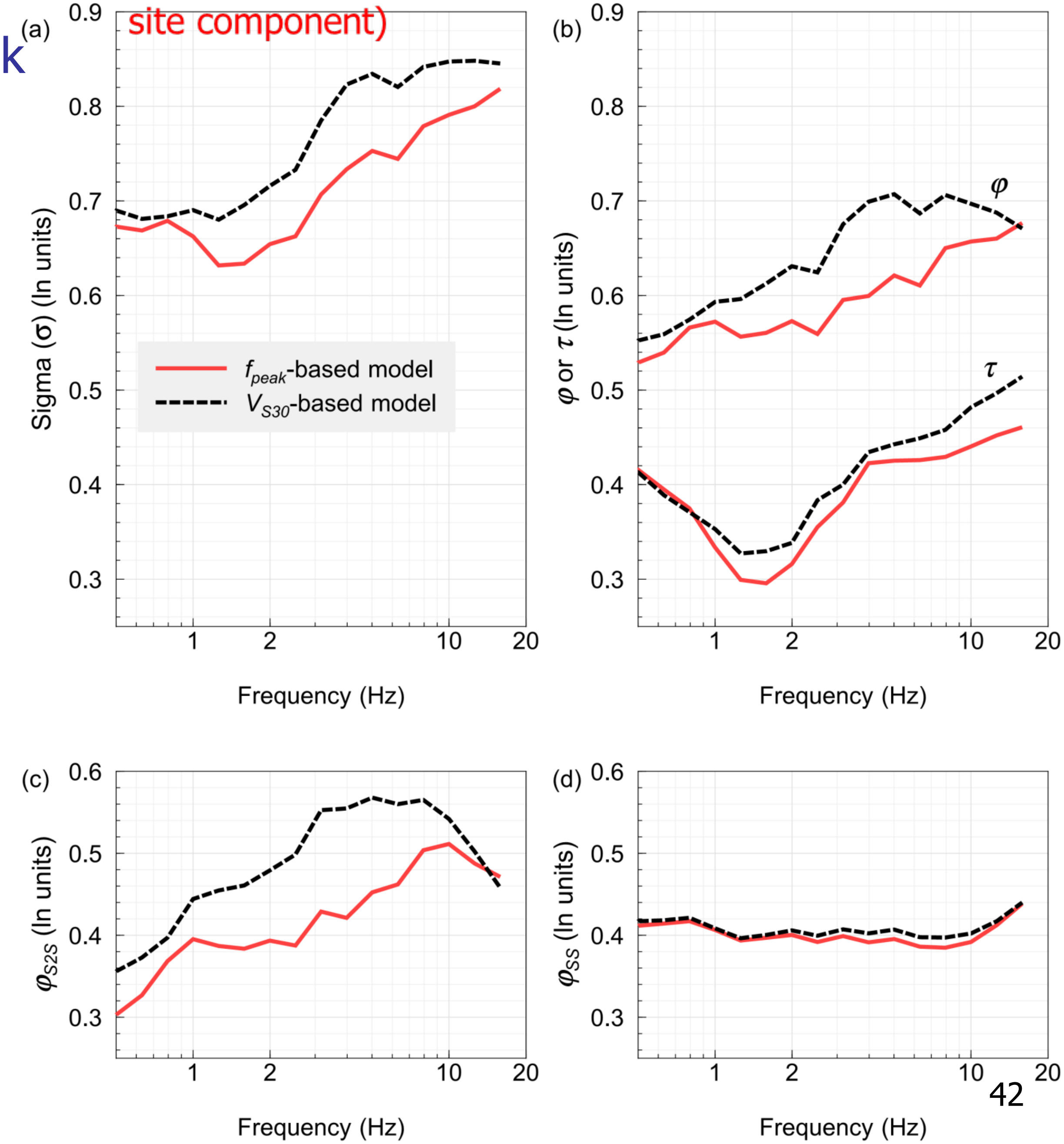
Advantages of using fpeak

$$\sigma = \sqrt{\tau^2 + \varphi^2}$$

$$\varepsilon_{ij} = \delta S2S_j + SWS_{ij}$$

$\delta S2S_j$: site-to-site variability (φ_{S2S})

SWS_{ij}: within-site variability (φ_{SS})

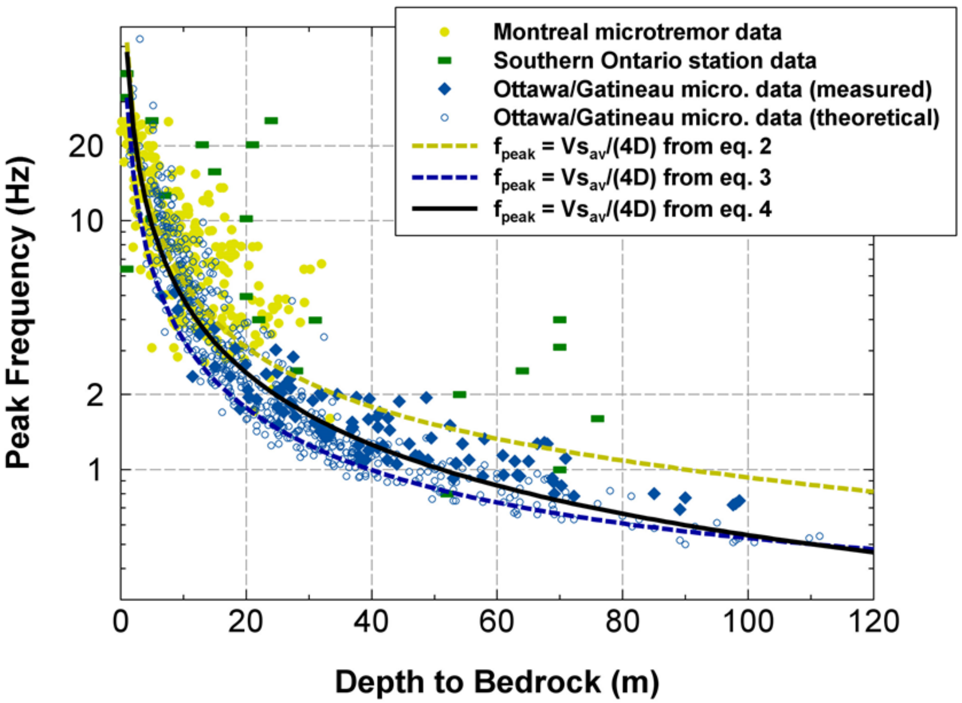


Summary

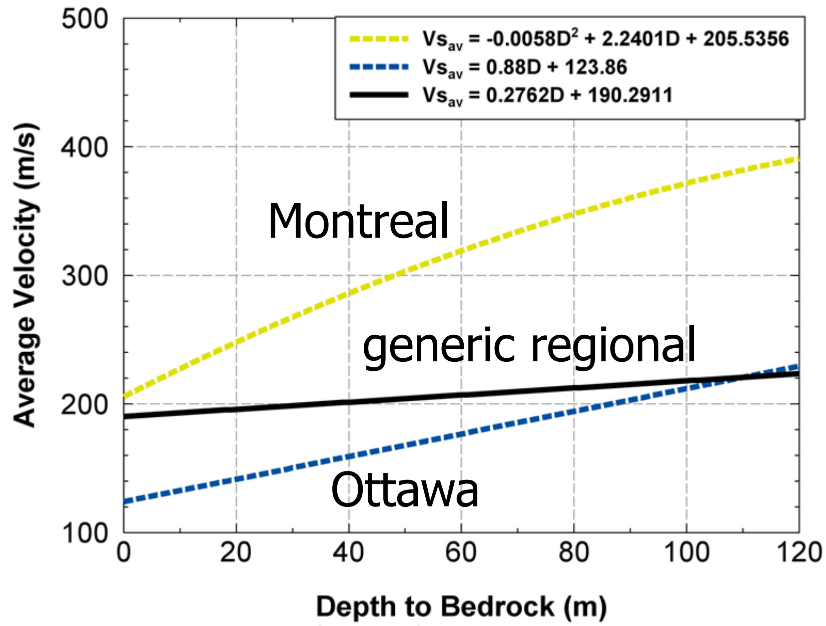
- H/V is a useful site response proxy; peak of H/V is the best single site variable we have found
- f_{peak} can be used a V_{S30} proxy; results in significantly smaller standard deviation relative to other proxies used in NGA-E
- f_{peak} is a better site response predictor for CENA sites than an NGA-West2 site effects model based on V_{s30}
- Empirical f_{peak}-based site amplification model proposed for sites in CENA.

A few last thoughts

- For many sites we do not know f_{peak}
- f_{peak} can be readily obtained (low cost) from microtremor measurements
- Alternatively it can be estimated from depth to bedrock (using either empirical or theoretical relations) – as shown below
- We can also develop regional or geology-specific relations between f_{peak} and V_{s30} so that if we know one we can get a default value for the other



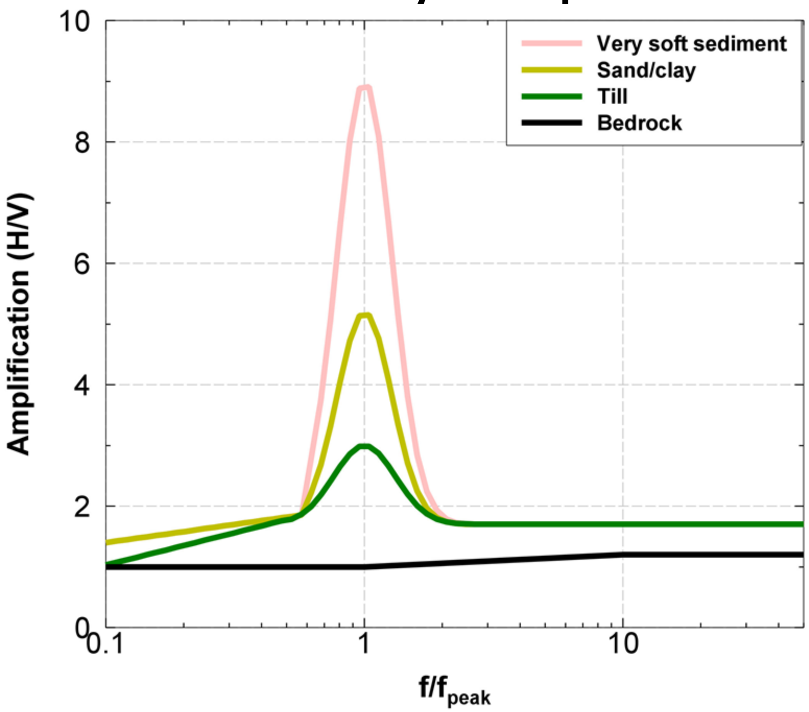
Theoretical (lines) and observed (points) relation between fpeak and depth to bedrock, eastern Canada



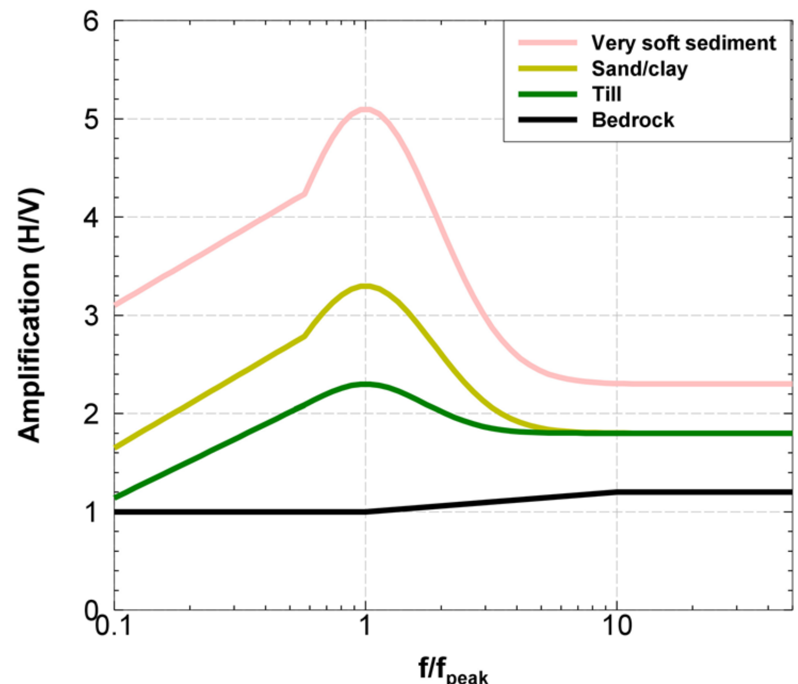
3 velocity profiles for sediments in eastern Canada

Effect of uncertainty in f_{peak}

- If f_{peak} has been estimated from depth to bedrock, the error in f_{peak} needs to be considered in site amplification function
- This uncertainty widens the response curve; effect can be estimated by simple Monte Carlo simulation

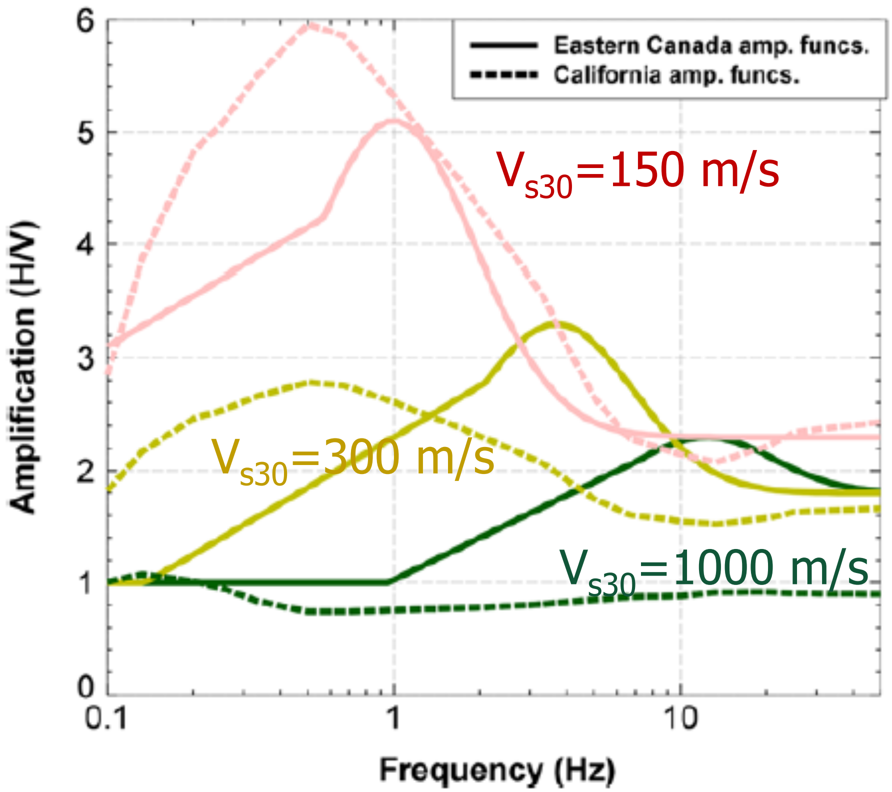


Amplification curve for measured f_{peak}



Amplification curve for f_{peak} estimated (from depth to bedrock)

Comparison to NGA-W2 amplification, considering uncertain f_{peak}



▲ **Figure 10.** The three proposed generic sediment amplification functions for eastern Canada and the corresponding functions for California (Seyhan and Stewart, 2012) assuming nominal values of V_{S30} of 1000 m/s, 300 m/s and 150 m/s for till, sand/clay, and soft soil, respectively. Light shades refer to very soft sediment/fill; intermediate shade refer to sand/clay; and dark shade refer to till. The color version of this figure is available only in the electronic edition.

- Uncertain f_{peak} broadens response peak and makes it more similar to a typical California model
- But the peak amplification, at least for sites in eastern Canada, is still shifted to significantly-higher frequencies relative to California
- Amplifications shown are for low levels of shaking (linear)

Concluding Suggestions

- Develop CENA site response model using both f_{peak} and V_{s30}
- Develop empirical/theoretical relationships to obtain f_{peak} from V_{s30} and vice versa on a regional basis; these can be default relationships to get one if only the other is known
- Include both f_{peak} and V_{s30} in future GMPEs
- Inclusion of both f_{peak} and V_{s30} will reduce sigma in CENA and also in other regions (e.g. NGA-subduction)

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