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Region-Specific Fourier-Based Site Amplification Modeling

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Outline

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(1) Overview

- We infer site response in northern and southern California from earthquake recordings and develop appropriate models for frequency-dependent amplification of horizontal-component Fourier amplitude ordinates as a function of site parameter V_{s30} and the peak ground acceleration on reference rock (PGA_r).

- The nonlinear term decreases the overall amplification for strong shaking levels (quantified through the PGA_r).

- The model is applicable over the frequency range 0.1-100 Hz and the V_{s30} range 180-1500 m/s, although it is not well constrained for V_{s30} values greater than 1000 m/s or below 200 m/s

- The data analysis implies considerable regional variations in the linear V_{s30} scaling

(1) Ground Motion Data

- We use the Effective Amplitude Spectrum (EAS) component of the FAS. The EAS is smoothed following PEER NGA-East (Goulet et al 2018) and Bayless and Abrahamson (2019)

$$EAS(f) = \sqrt{\frac{1}{2}[FAS_{HC1}(f)^2 + FAS_{HC2}(f)^2]}$$

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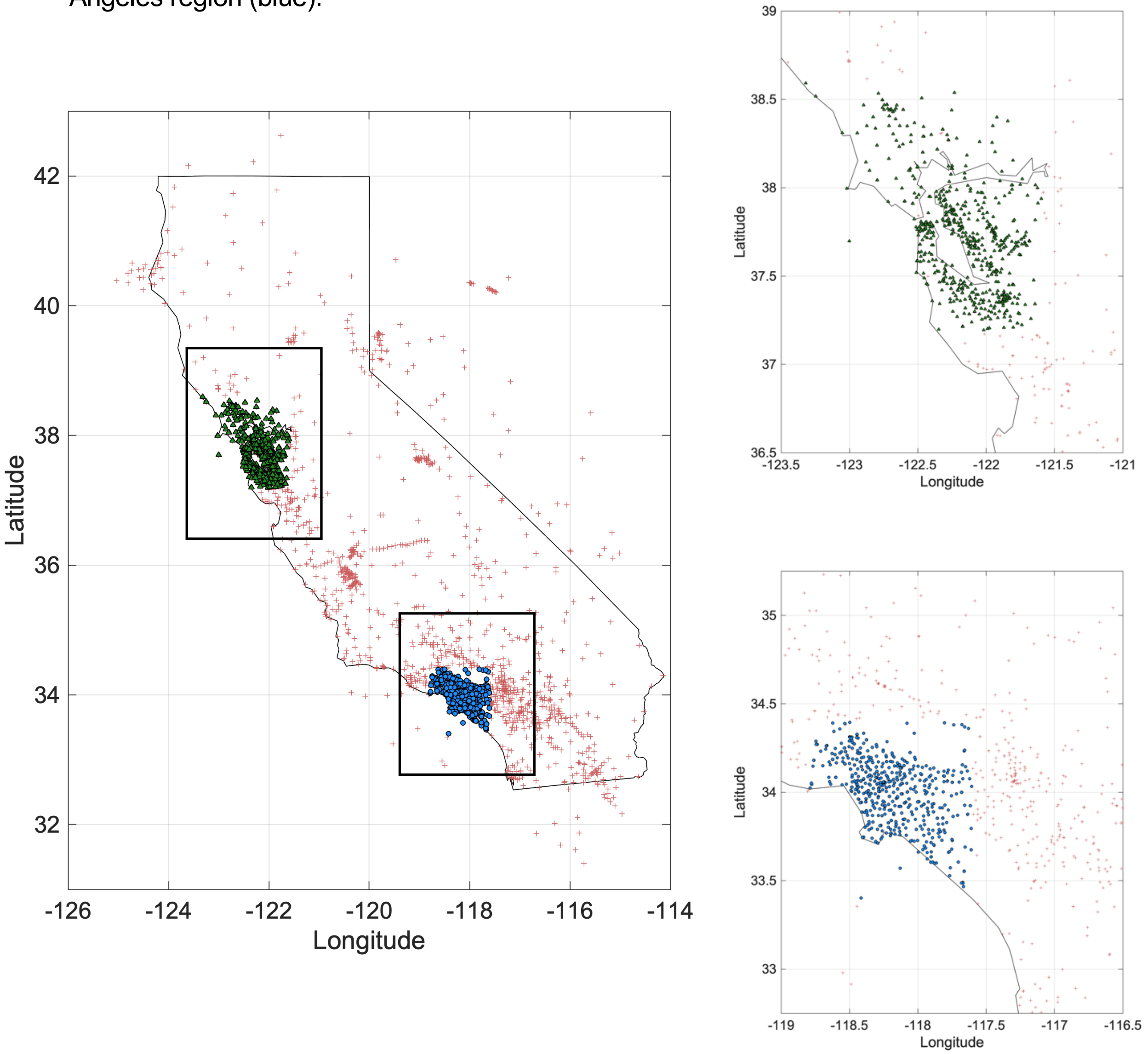
(1) Ground Motion Data

- Three different EAS databases are utilized:
  1. NGA-West2
  2. Wang and Stewart (2019)
  3. Buckreis et al. (2019)

- Wang and Stewart (2019) extends the NGA-West2 database with earthquakes and recordings in California and northern Mexico since 2011. This database includes 29 new events with 6,584 three-component ground motion recordings

- Buckreis et al (2019) further supplements the NGA-West2 data, mostly with recordings in central and northern California. This database includes 39 events (5 already existing in NGA-West2 and 34 new additions) with 3,721 new three-component ground motion recordings.

Maps of the recording stations in proximity to California used to build the nonlinear model (red, green, and blue), the linear model for the Bay Area region (green) and the linear model for the Los Angeles region (blue).



(3) Approach

- Our analysis of site terms from empirical data follows the procedures in Seyhan and Stewart (2014) and Stewart et al. (2017) using FAS from observations and residuals calculated from predictions by the Bayless and Abrahamson (2019) FAS model.
  - the nonlinear model is formed based on interpreting the behavior of the data
  - After the nonlinear effect is removed, the linear model is determined

- The observed site response of the FAS is termed Fs in natural log units

- Where these are modeled as

$$F_S = F_{lin} + F_{nl} \tag{1}$$

$$F_{lin} = f_0 \ln\left(\frac{\min(V_{s30}, V_c)}{V_{ref}}\right) \tag{2}$$

$$F_{nl} = f_1 + f_2 \ln\left(\frac{IM_{ref} + f_3}{f_3}\right) \tag{3}$$

$$f_2 = f_4[\,\exp\{\,f_5\,(\min\{V_{s30}, V_a\} - V_b)\} - \exp\{\,f_5\,(V_a - V_b)\}\,] \tag{4}$$

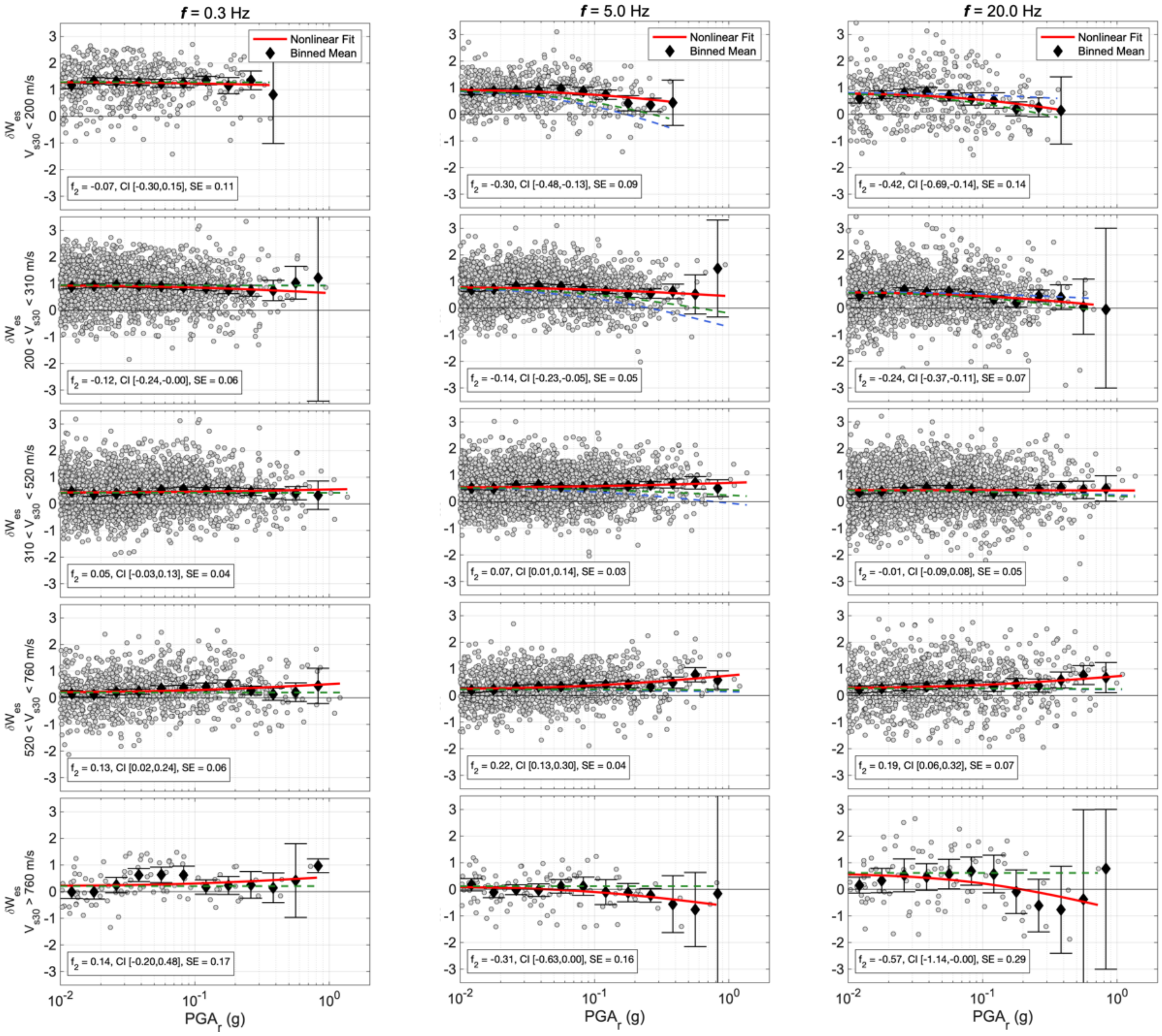
(4) Nonlinear Model

- We examine the nonlinearity of the site amplification first, using FAS residuals from the reference condition GMM binned by the parameter Vs30 and plotted against input peak acceleration.

- At right, the red line is the nonlinear fit to the residuals (Equation 2) and the blue and green dashed lines are the nonlinear models by Hashash et al., (2018) and Seyhan and Stewart (2014). The black diamonds represent the residual binned means with 95% confidence intervals

- f_2 is the slope of the nonlinear fit; larger negative values represent larger reduction in residuals (e.g. model over-predictions) for large ground motions

$$F_{nl} = f_1 + f_2 \ln\left(\frac{IM_{ref} + f_3}{f_3}\right)$$

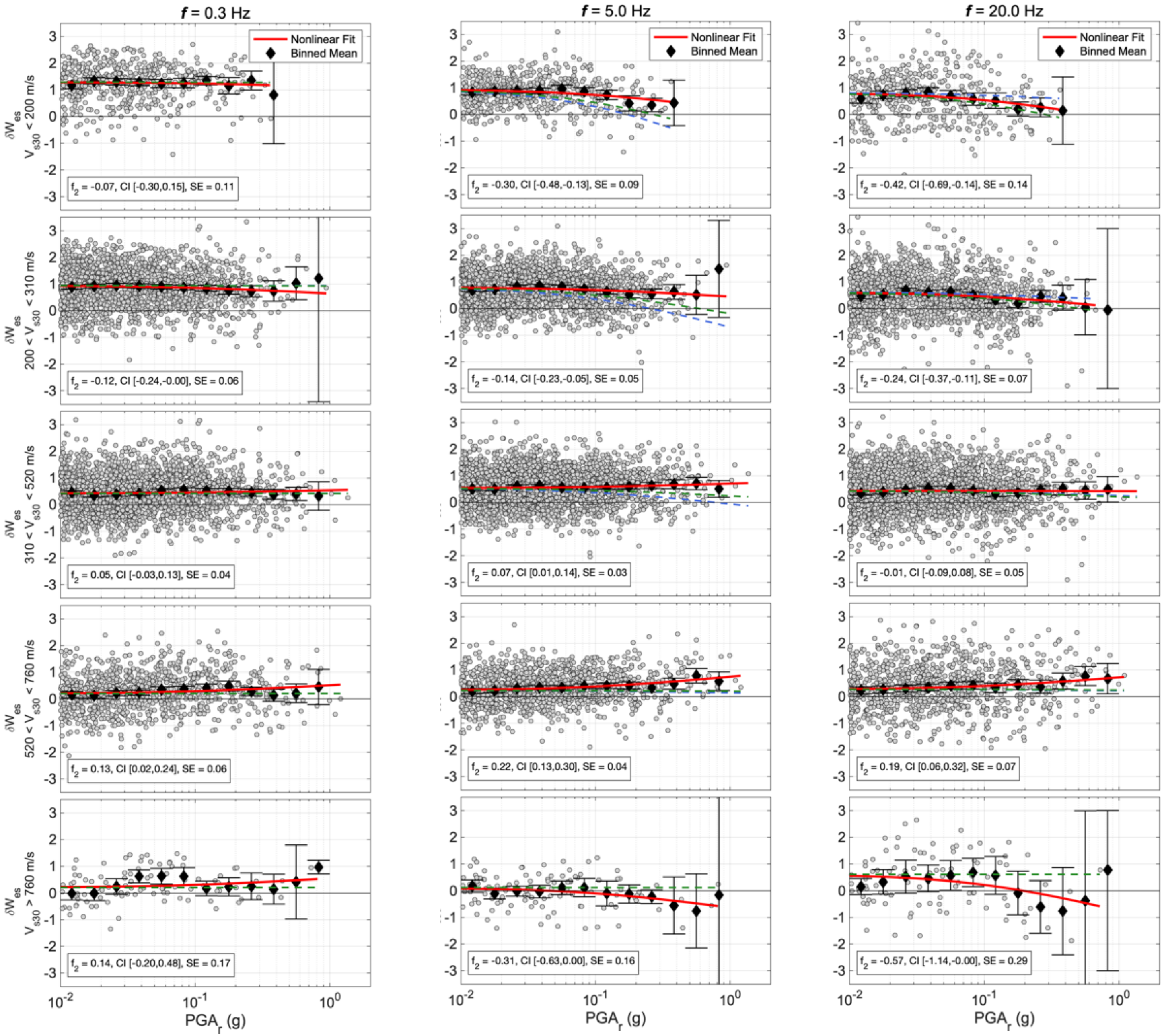


Variation of within-event residuals from the rock condition EAS GMPE versus peak ground acceleration on rock, binned by $\boldsymbol{V_{s30}}$ (rows) and for 3 frequencies (columns).

(4) Nonlinear Model

- estimates of coefficient f_2 are judged to be statistically significant when the absolute value of f_2 is larger than its standard error

- Using this benchmark for statistical significance:
  - *nonlinearity decreases with increasing V_{S30}*
  - *nonlinearity decreases as frequency decreases, being statistically significant only for f >~0.5 Hz, except for the softest soil sites*
  - *i.e. the apparent nonlinearity is strongest for the lowest $Vs30$ bins and for higher frequencies*



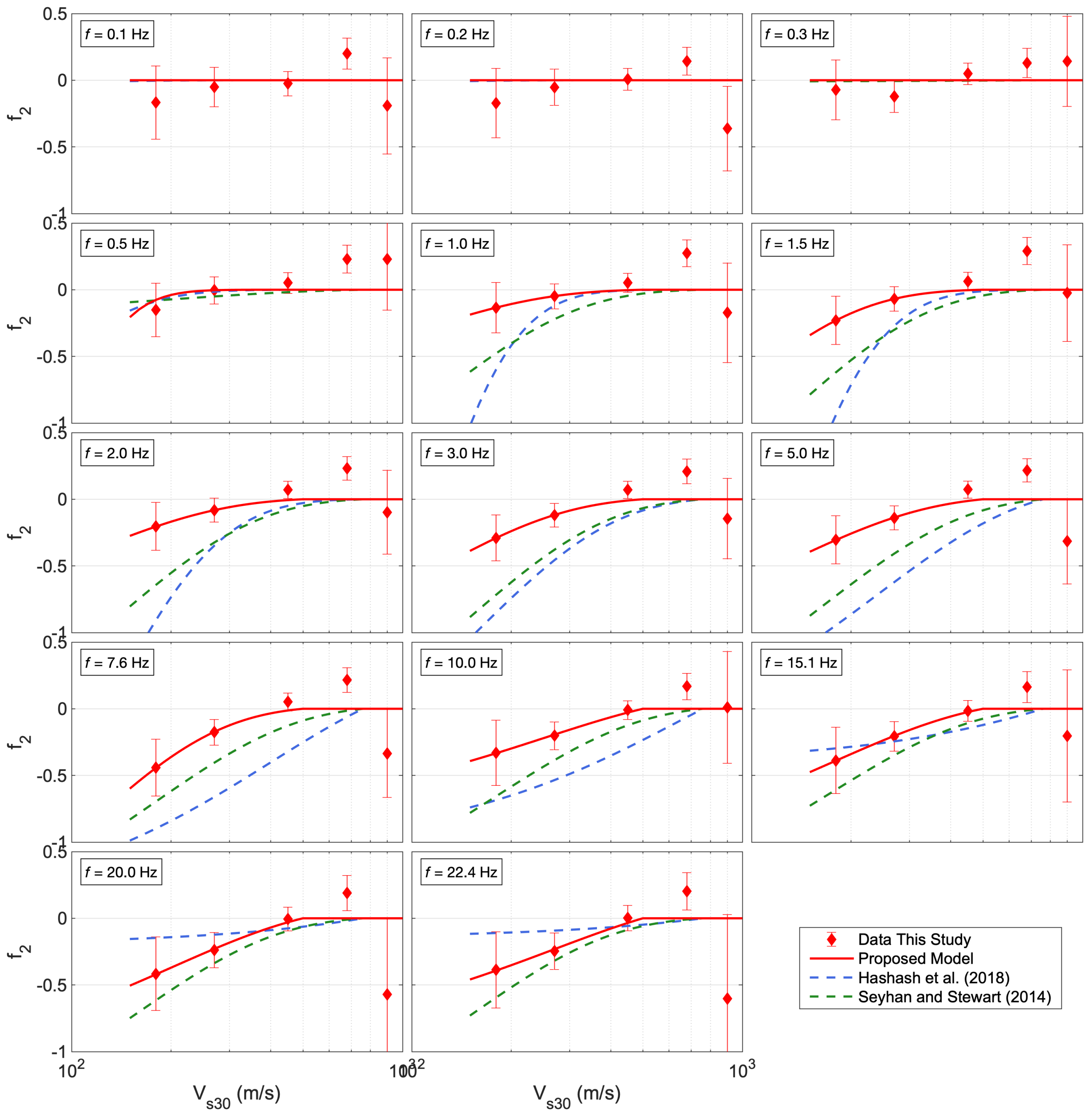
Variation of within-event residuals from the rock condition EAS GMPE versus peak ground acceleration on rock, binned by $\boldsymbol{V_{s30}}$ (rows) and for 3 frequencies (columns).

(4) Nonlinear Model

- We then we then examine the dependence of $\boldsymbol{f_2}$ on $\boldsymbol{V_{s30}}$ and frequency

- At right, the red symbols are the coefficients previously estimated, the error bars show the 95% confidence intervals in these estimates, and the proposed model (Equation 4) is shown by the solid red lines

- This model suggests generally weaker nonlinear effects than both SS14 and H18, except at the highest frequencies, where the proposed model exhibits stronger nonlinearity than H18 but weaker nonlinearity than SS14.



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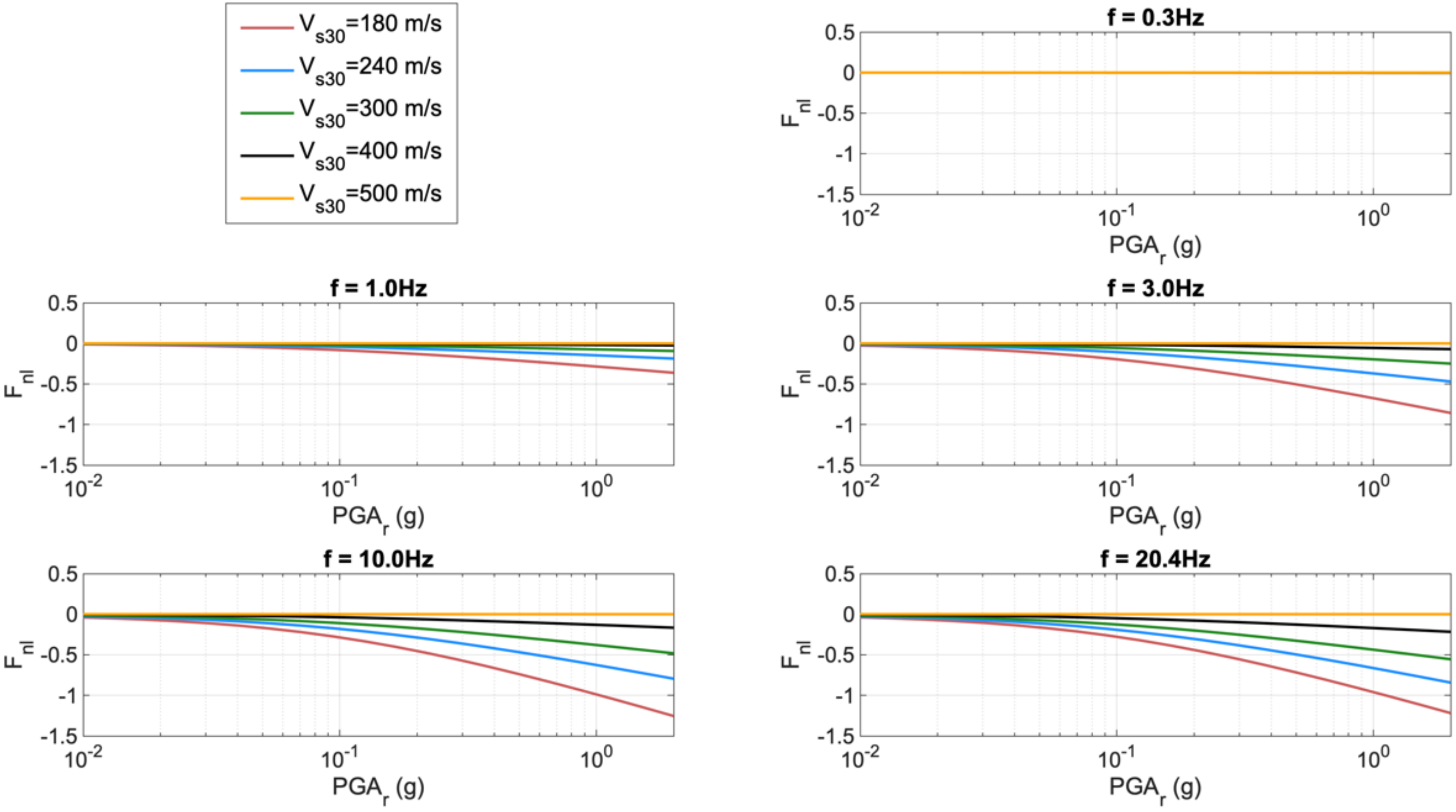
(4) Nonlinear Model



Model predictions of $\boldsymbol{F_{nl}}$ (ln units) for a series of frequencies and $\boldsymbol{V_{s30}}$, versus $\boldsymbol{PGA_r}$.

(5) Linear Models

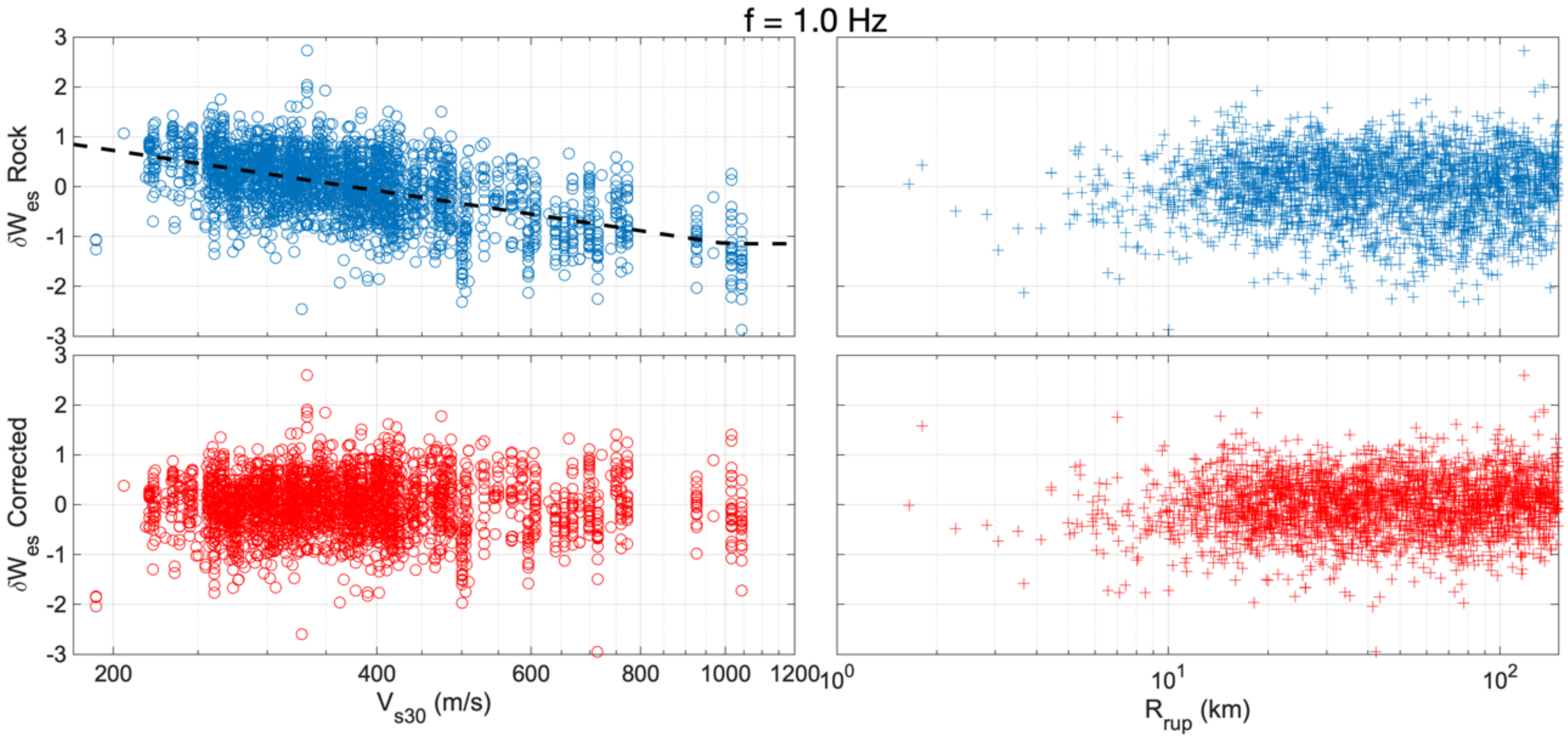
- The linear site response is modeled using the remaining within-event residuals after correcting for nonlinearity, to obtain estimates of the linear site amplification slope parameter f_0

$$F_{lin} = f_0 \ln\left(\frac{\min(V_{s30}, V_c)}{V_{ref}}\right)$$

- This is repeated separately using data within the Los Angeles and Bay Area regions and again with all available data in the proximity of California

(5) Linear Models

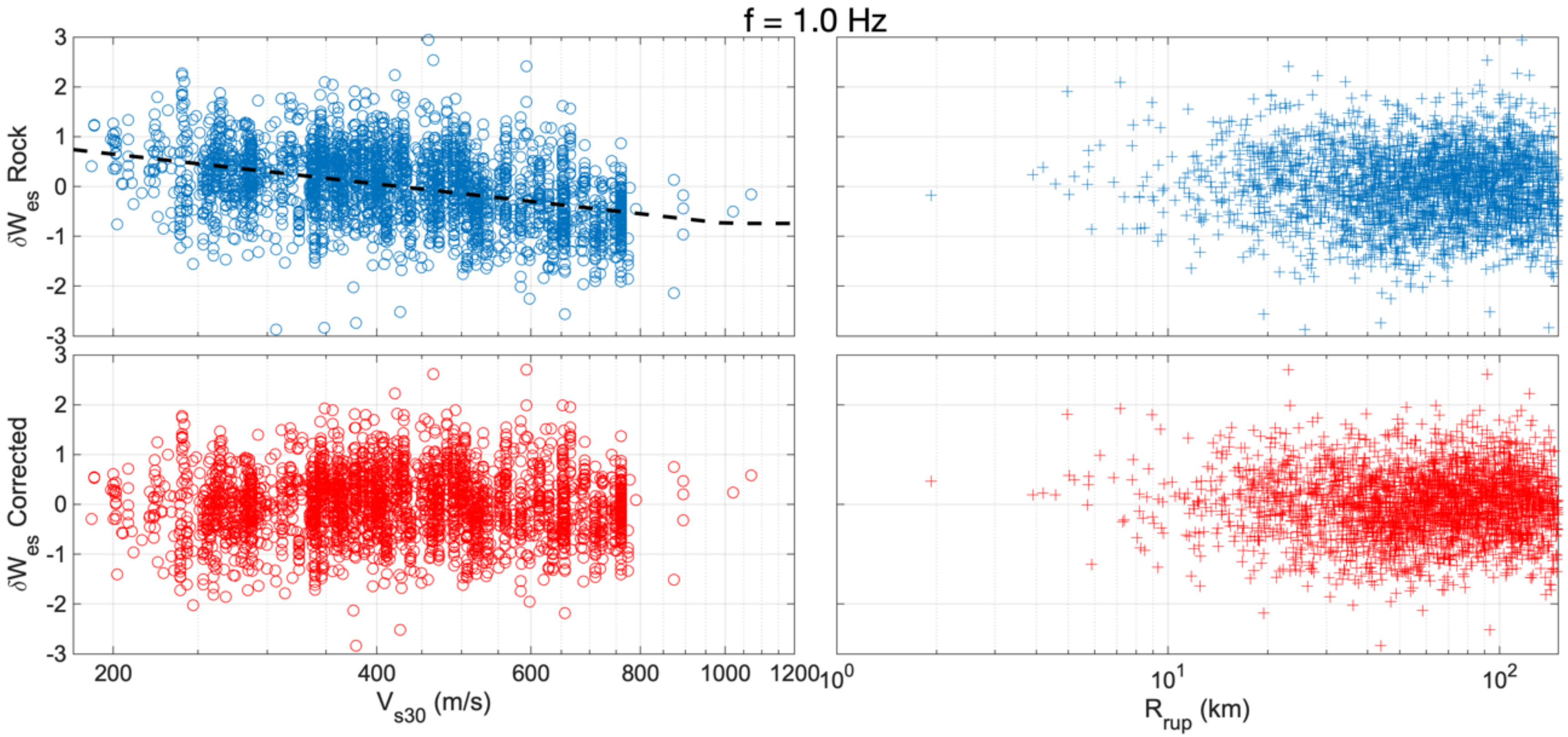
– Los Angeles region



Within-event residuals for rock conditions (blue) and after regressing for the linear site response (red) versus $\boldsymbol{V_{s30}}$ and $\boldsymbol{R_{rup}}$. Data shown is at 1 Hz

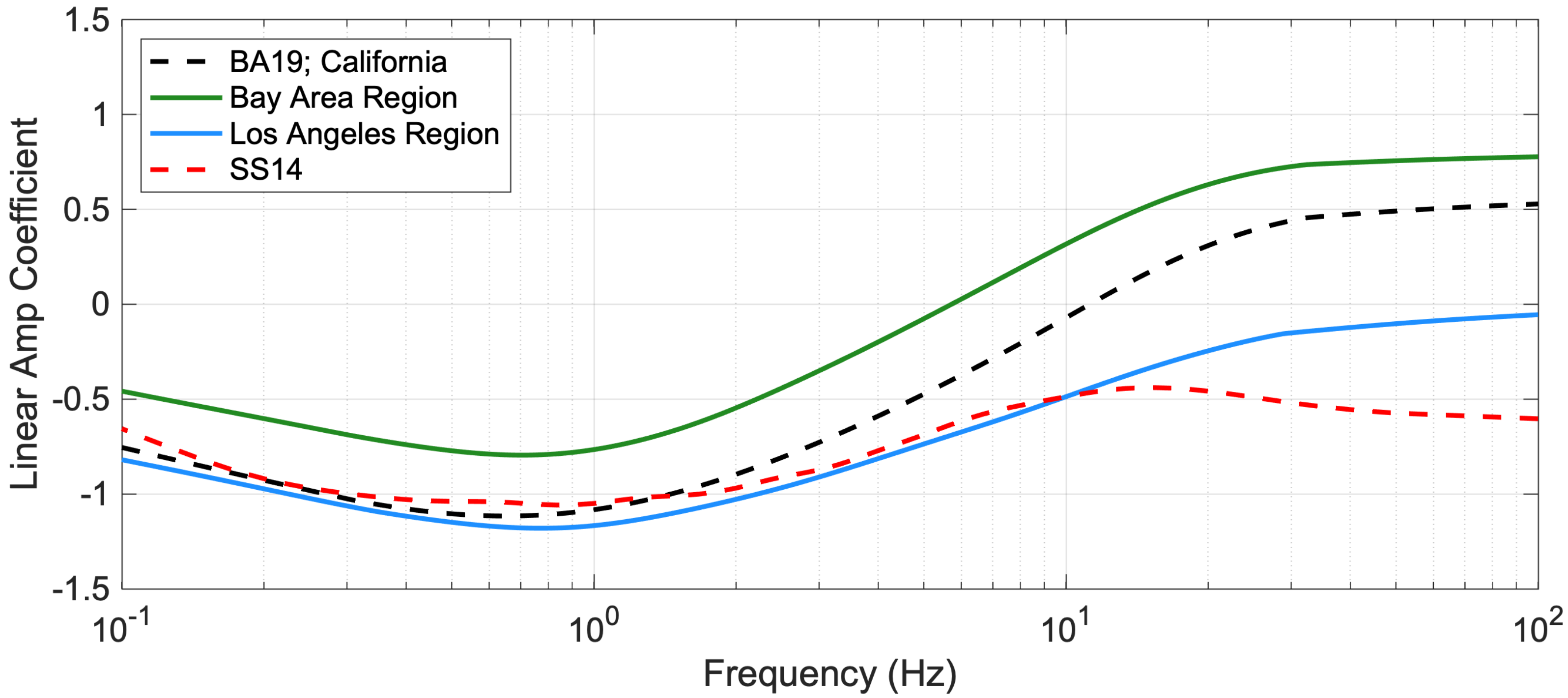
(5) Linear Models

– Bay area region



Within-event residuals for rock conditions (blue) and after regressing for the linear site response (red) versus $\boldsymbol{V_{s30}}$ and $\boldsymbol{R_{rup}}$. Data shown is at 1 Hz

(5) Linear Models



The frequency dependence of the regionalized linear site amplification coefficients, f_0 after applying smoothing in log frequency space.

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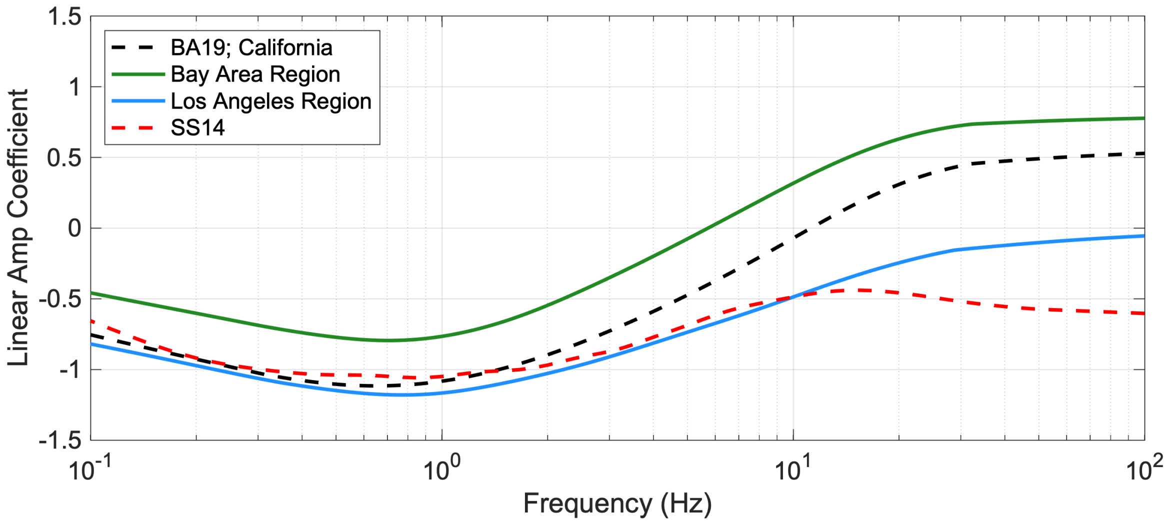
(5) Linear Models



Observation on Linear Models

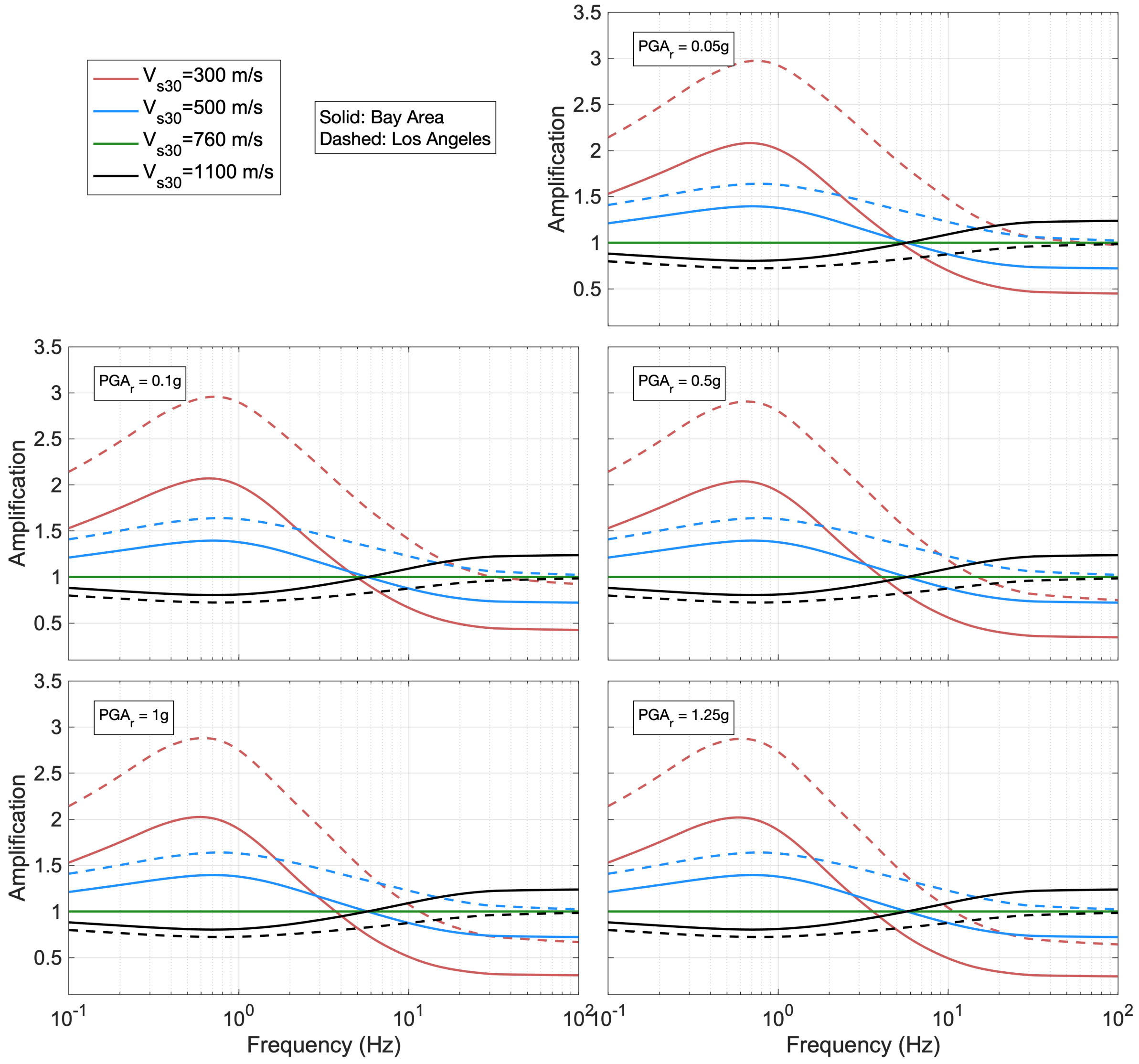
- Negative values of the coefficient f_0 represent amplification for V_{s30} values less than V_{ref}, and de-amplification for V_{s30} values greater than V_{ref}.

- For the data within the Bay Area, this coefficient crosses from negative to positive values at about 6 Hz
  - This contrasts most linear V_{s30} scaling models (based on response spectra), which predict amplification of the ground motions at sites with low V_{s30}, even for high frequencies (short periods). For this FAS based model, we expect differences from response-spectra based models at high frequencies.

- amplification factors derived from analytical ground response simulations (e.g. Hashash et al18) produce transfer functions with a characteristic shape.
  - a series of peaks are near the site's modal frequencies
  - As frequency increases beyond the first 2-4 modal frequencies, transfer function amplitudes tend to systematically decrease, becoming negative, as a result of soil damping effect
  - a low V_{s30}-valued profile may feature amplification at low (resonant) frequencies and de-amplification at very high frequencies; PSA models would not capture this

(6) Examples

Total amplification (linear and nonlinear) factors for a range of V_{s30} (different colored lines as identified in the legend) and PGA_r (different panels as indicated within each.) The solid lines are for the Bay Area model, the dashed lines are for the Los Angeles region model



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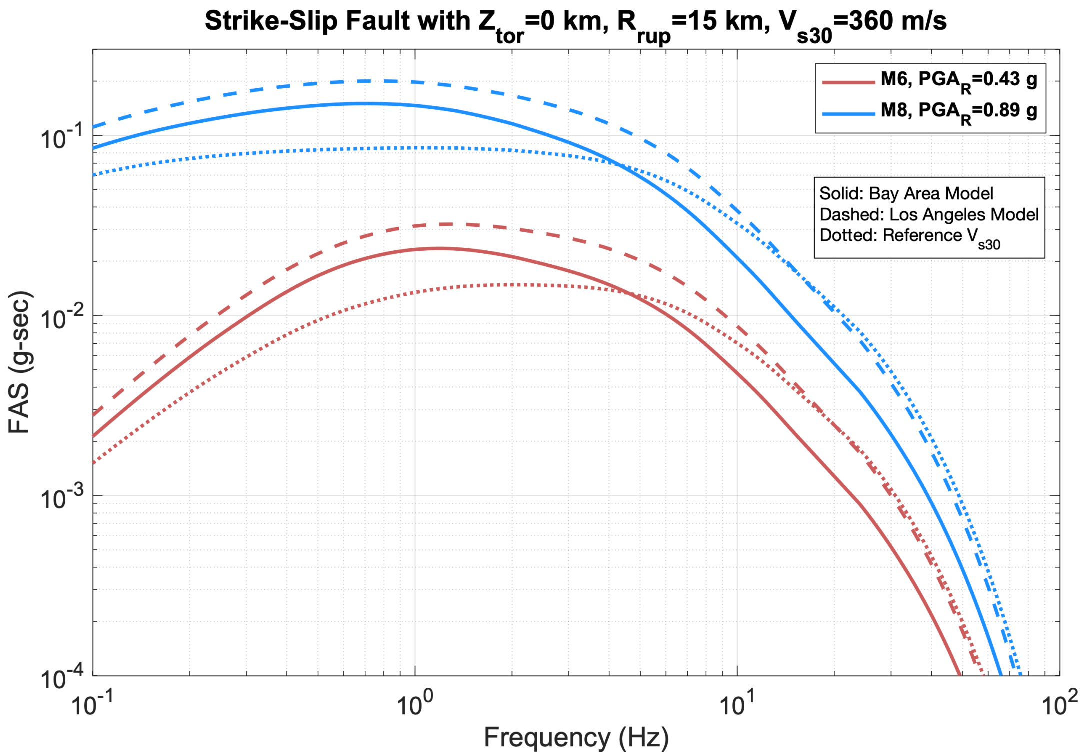
(6) Example

Example EAS spectra



(7) Conclusions

- Overall, the linear V_{s30} scaling models compare favorably with other empirically-based models (e.g. Bora et al. 2019; Seyhan and Stewart, 2014); especially at low frequencies. The Hashash et al. (2019) model is most different because it features peaks in amplification over distinct frequency bands which correspond to resonance with the modal frequencies of the V_s profile.

- the Los Angeles region has stronger linear V_{s30} scaling of FAS than the Bay Area region at low frequencies. The model previously developed for all of California (BA19) falls between these two.

- There is a fundamental differences between response spectra and FAS at high frequencies; the FAS is capable of capturing the peak in the site response transfer function encountered at a site's modal frequencies where the PSA is less suited to do so

- Because the current regional models predict the same EAS spectrum for the reference Vs30 condition (for the reference condition there is no Vs30-based amplification), we will check to see if it is appropriate to include a regional constant in addition to the regional Vs30 models

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