Frequency-Dependent Comparison of Vs30 and Site Period as Predictors of Earthquake Ground Motion Intensity Measures

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1. Abstract

Most existing studies use Vs30, the time-averaged S-wave velocity for the top 30 m of soils, as the site proxy to develop the site terms of the Ground Motion Model (GMMs). However, Vs30 is only related to the influence of shallow site conditions on ground motion. Meanwhile, limited attention has been given to their frequency-dependent predictive performance, leaving a gap in understanding whether Vs30 is an effective predictor for high-frequency (e.g., Peak Ground Acceleration (PGA) and Short-Period Spectral Acceleration) versus low-frequency (e.g., Peak Ground Velocity (PGV) and Long-Period Spectral Acceleration) intensity measures (IMs). Since high-frequency ground motions are generally more affected by these shallow layers, it is reasonable to expect that Vs30 may perform better than site period (Ts) in predicting high-frequency IMs. Conversely, Ts, which corresponds to the peak amplification at the site of interest, can capture both shallow and deep site effects. Thus, Ts could outperform Vs30 for low-frequency IMs. This study aims to explore whether Vs30 or Ts is a better proxy for characterizing site conditions.

A subset of the NGA-West2 GM database across California was selected to test these hypotheses by comparing with the site term of GMM residuals. Data points were plotted and analyzed in ArcGIS Pro, with regions grouped into three geographic clusters: Group 1 (Los Angeles, Ventura, San Bernardino, and Orange counties), Group 2 (Sonoma, Solano, Napa, Marin, Contra Costa, San Francisco, Alameda, San Mateo, Santa Clara, Santa Cruz, Monterey, and San Benito), and Group 3 (Riverside and Imperial counties). Within each group, the correlations between the site proxy (Vs30 and Ts) and site residuals were examined through linear regression analyses. The linear regression results indicate that Vs30 slightly outperformed Ts in predicting both high- and low-frequency IMs across most regions. However, the small R2 (e.g., 0.03 for the regression between Vs30 and PGA) for the regressions suggests that linear regression may not fully capture the trend between Vs30 or Ts and site residuals. Although the linear correlations with Ts were not obvious, this work still observed that the performance of Ts is better in Northern California, which potentially supports the inclusion of Ts into the site term for the region-specific GMM in this area. For future work, nonlinear regression will be adopted to further study the performance of Vs30 and Ts in ground motion predictions.

2. Introduction and Key Concepts

Motivation

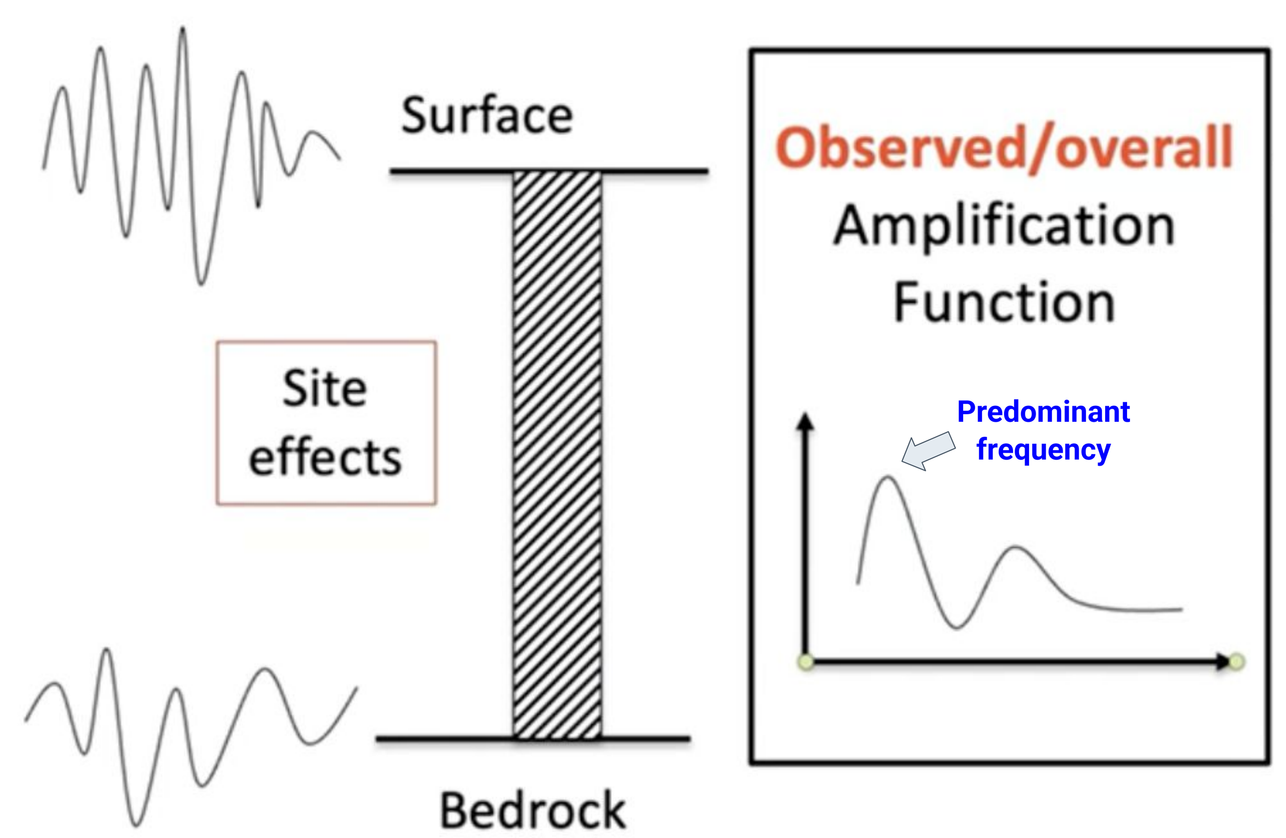
- Site effects, occurred beneath the site of interest, can significantly alter GM characteristics
- Site effect is a complicated function of multiple factors including soil properties and bassin effects

Objective

Investigate the appropriate soil proxies (i.e., Vs30 and Ts) characterizing earthquake GM IMs

- **Vs30**: time-averaged shear-wave velocity in the upper 30 m
- **Site period**: Ts, soil characteristic natural period hereafter defined as 1/predominant frequency

Figure 1: Illustration of site effects and frequency-dependent soil amplification



3. Ground Motion Residual Analysis

We utilize earthquake ground motion data across California to study how site effect varies with Vs30 or site period. Residual site terms for each of the records of the NGA-West2 database (Ancheta et al.,2014) are determined relative to the BSSA14 GMPE. In the residual formula below (EQ-1), reij is the residual estimated for event i at station j, obsij is the observed ground-motion parameter, and preij is the predicted ground-motion amplitude for the corresponding record determined using the BSSA14 GMPE model.

$$\log\left(re_{ij}\right) = \log\left(obs_{ij}\right) - \log\left(pre_{ij}\right) \qquad \text{EQ-1}$$

The residuals can then be broken down into a residual site term (ReSj) for station j, random event term for event i (ηi), and within-event residual term for station j recorded at event i (εij) (EQ-2) via mixed-effect regression.

$$\log\left(re_{ij}\right) = ReS_j + \eta_i + \varepsilon_{ij} \qquad \text{EQ-2}$$

To remove systematic path effect related source, we modify the mixed-effect decomposition (EQ-3). Within the formula, Ci is a constant conditioned on event index. After, ReSj was utilized to explore which proxy (between Site period and Vs30) is better predictor for site effect (ReSj)

$$\log\left(Re_{ij}\right) = c_i \times Rjb_{ij} + ReS_j + \eta_i + \varepsilon_{ij} \qquad \text{EQ-3}$$

Residual site terms are plotted and analyzed in ArcGIS Pro and grouped into three geographic areas (Figure 2). Within each group, regression plots were generated using log-transformed Vs30 and Ts as predictor variables, with PGA, PGV, and spectral acceleration as response variables. The data was retrieved utilizing Ground Motion Residual Analysis.

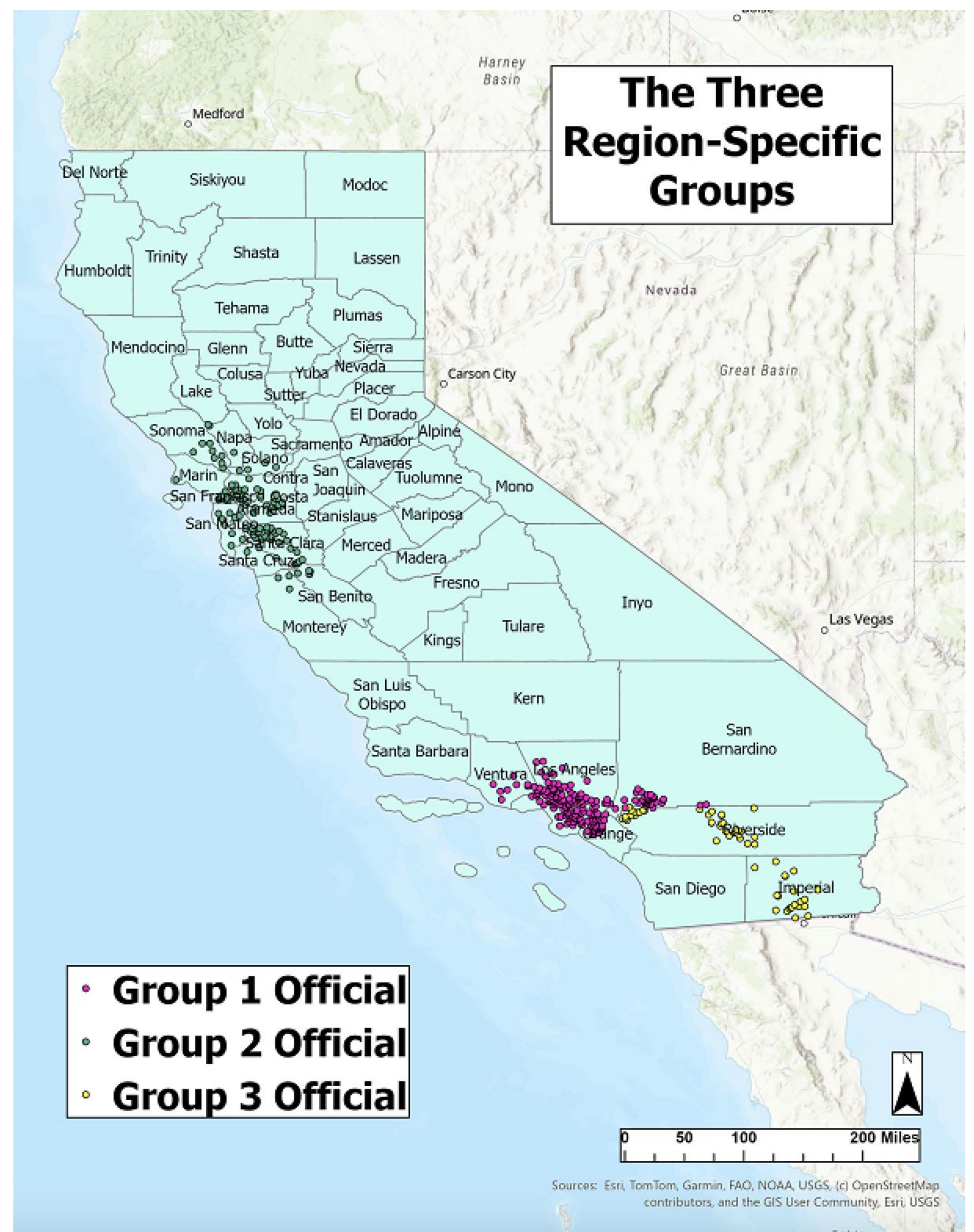


Figure 2: Map of the data points divided into three region-specific groups across California.

4. Results

- Vs30 outperformed Ts for most high- and low-frequency intensity measures
  - Exception: In Group 3, Ts outperformed Vs30 for high-frequency measures (PGA, short-period SA).
    - Most likely due to basin or sedimentary effects boosting Ts's high-frequency response
- Group 1: highest mean Vs30 values → stiffer sites, stronger high-frequency shaking
- Group 2: highest mean Ts values→ softer, deeper sites, stronger low-frequency shaking.
- Performance differences varied by region
- **Overall Outcome**: Geographic setting influences which predictor is superior

	R2 Values Based on Intensity Measures					
	Group 1		Group 2		Group 3	
	Vs30	Ts	Vs30	Ts	Vs30	Ts
PGV	0.34	0	0.12	0	0.2	0.06
PGA	0.19	0.02	0.03	0.02	0.04	0.14
SA 0.3s	0.29	0	0.09	0	0.04	0.06
SA 1s	0.4	0.03	0.2	0.18	0.3	0.03
SA 2s	0.48	0.02	0.16	0.13	0.42	0.05
SA 3s	0.45	0.01	0.15	0.08	0.52	0.03
SA 5s	0.43	0.02	0.15	0.09	0.53	0

Table 1: A Summary Table of the Linear-Regression Analysis R2 Values.

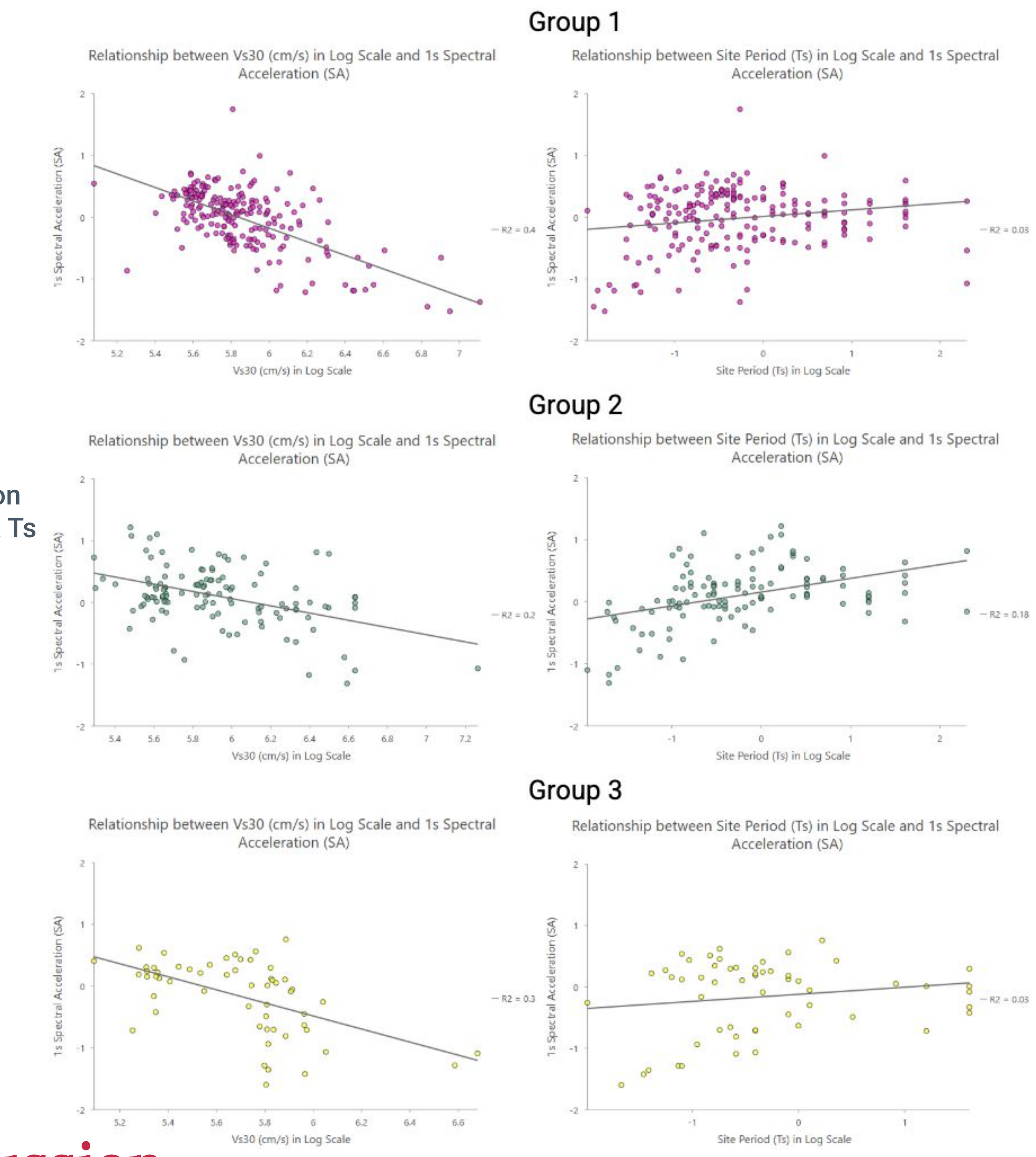


Figure 3: The linear-regression plots of Vs30 & Ts vs. 1-second spectral acceleration.

6. Discussion

Revisiting these datasets with an improved modeling framework is recommended because linear regression may not fully capture the complex, non-linear relationships between site parameters (Vs30, Ts) and ground-motion intensity measures. Additionally, while Vs30 outperforms site period but in the Bay area (group 2), the Vs30 dependency is strongly reduced for GM < 1s, which means ergodic Vs30-based site model may introduce bias in site effect in the Bay area (Figure 4). In contrast, non-linear site period trend is stronger than that in LA (Figure 4).

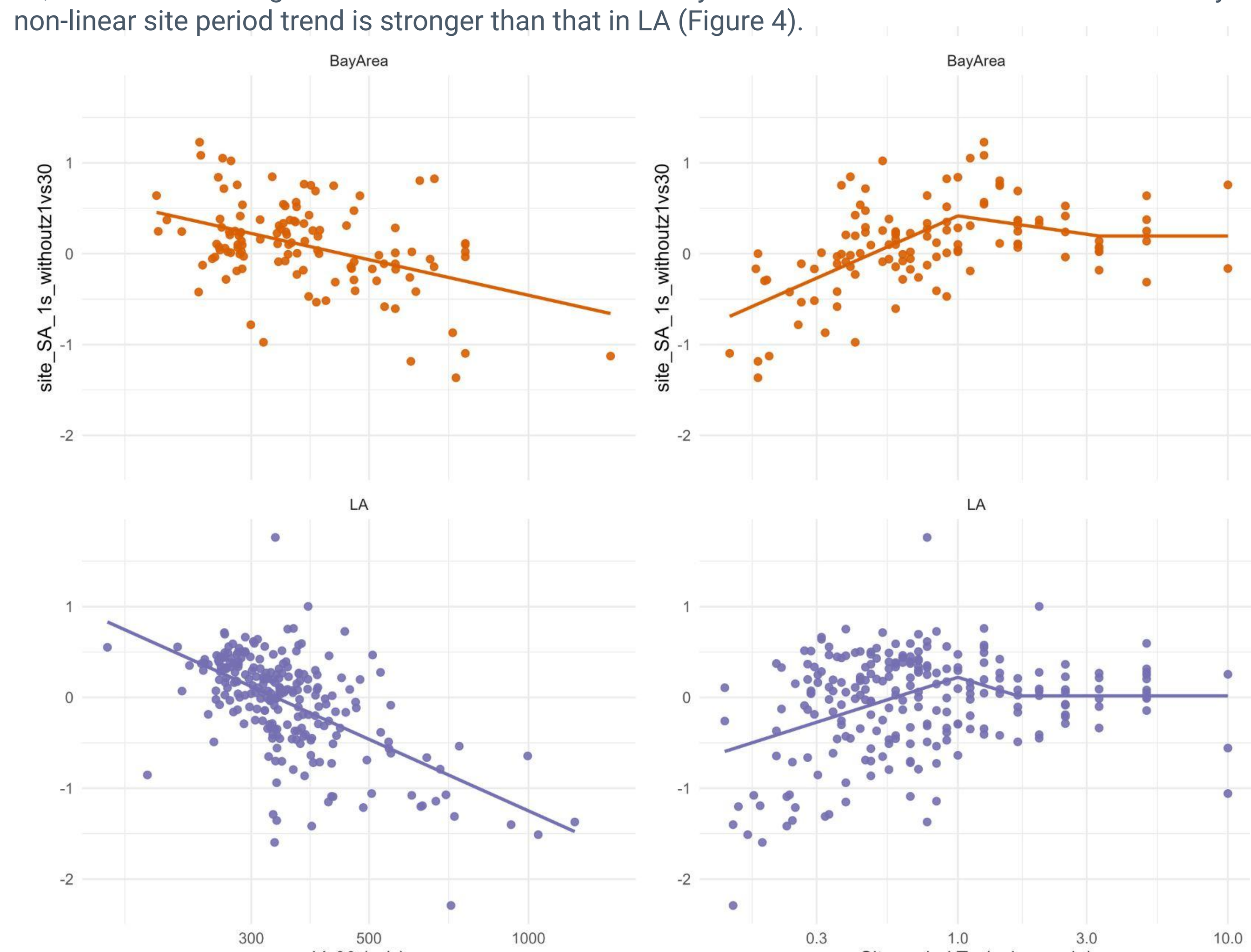
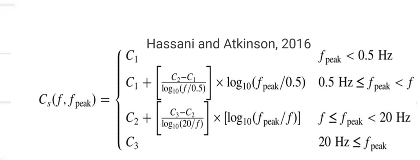


Figure 4: Residual site terms of 1s (in the Bay area and Los Angeles) varying with Vs30 and site period and best fitting models (linear regression regarding Vs30 and nonlinear regression regarding site period). The nonlinear formula follows Hassani and Atkinson (2016)



7. Conclusion

- Vs30 is an valuable site parameter in GMM, while Ts reflects deeper site conditions and it appears less reliable as a standalone predictor
- For Group 3, Ts exceeded Vs30 for a single high-frequency IMs, indicating that local geological or basin effects uniquely influenced site response.
- Regional geologic and geographic conditions strongly influence the effectiveness of Vs30 and Ts
- Vs30 remains the more effective and practical metric for empirical GM across both short- and long-period IMs.

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Acknowledgements

This research was supported by the Statewide California Earthquake Center (Contribution #14791). SCEC is funded by NSF Cooperative Agreement EAR-2225216 and USGS Cooperative Agreement G24AC00072. Additional support was provided by Verisk Extreme Event Solutions Earthquake Hazard Team, Statewide California Earthquake Center SOURCES Program, and Dr. Gabriela Noriega.