Importance of Spatially Varying Ground Motion Models and Implications for Cascadia

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Summary of last ~20 years of ground motion modeling

- NGA-West (2008) ground motion models pooled data from all active tectonic regions
- NGA-West2 (2014) developed region models be grouping specific countries:
  - E.g., Campbell and Bozorgnia (2014) adjusted attenuation for Japan and Italy, and eastern China
  - E.g., Abrahamson et al. (2014) used regional V_{s30} and anelastic attenuation for Taiwan, Japan, and China.
- Landwehr et al. (2016) introduced the concept of spatially varying models
- NGA-Subduction (2021) included regional adjustments seven major subduction zones

What have we learned?

- Increased information has shown regions have consistent differences in earthquake ground motions
  - Initially, this was interpreted as earthquakes being unpredictable because all data was pooled together – unmodeled error
  - We are understanding now that earthquakes are much more predictable – given enough data
- Spatial variation in ground motion is important and ignoring it inflates the uncertainty of the ground motion
- Development of ground motion models needs to consider spatially varying parameters:
  - Increasing model complexity
  - Penalizes lack of knowledge/data with increased uncertainty

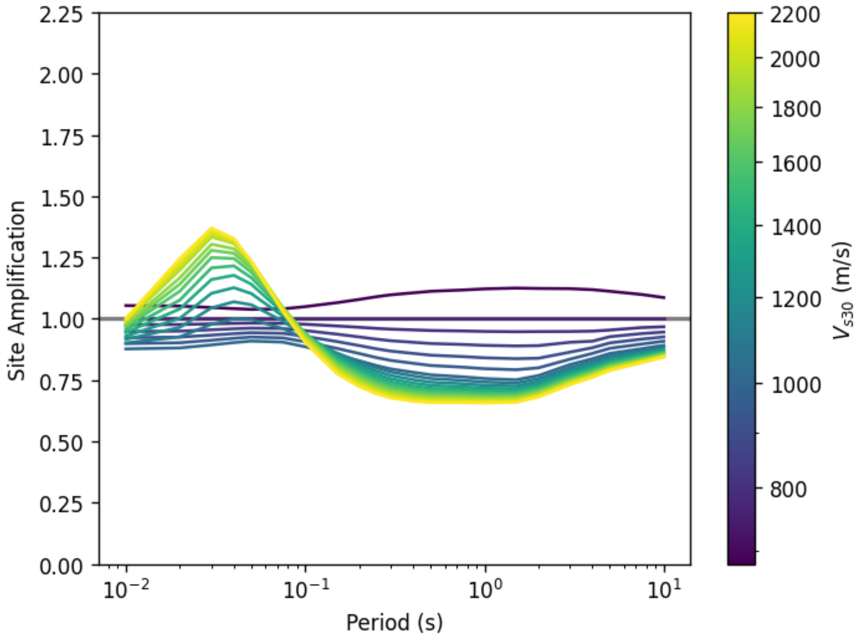
Recognized components of spatially varying models

- From Liou and Abrahamson (2025):

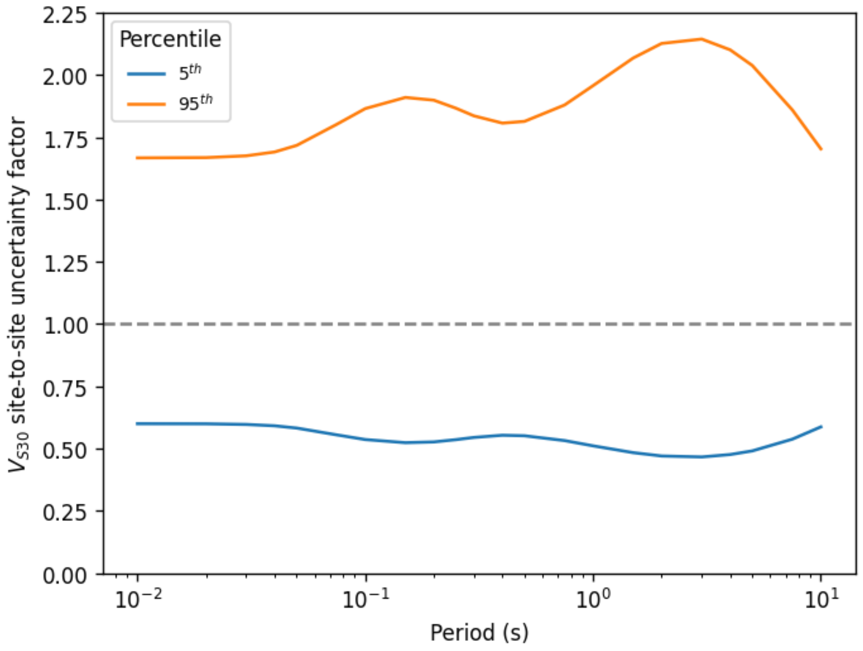
$$\ln(Y_{es}) = \underbrace{\mu_{\mathrm{Erg}}(M_e,\vec{R}_{es},S_s)}_{\text{Modeled effects}} + \underbrace{\underbrace{\delta L2L_e + \delta P2P_{Q,es} + \delta P2P_{V,es} + \delta S2S_s}_{\text{Class1}} + \underbrace{\delta B_e^0 + \delta P_{es} + \delta AF_{es}}_{\text{Class2}} + \underbrace{\delta_{0,es}}_{\text{Class3}}}_{\text{Unmodeled effects}}.$$

- A global (i.e., ergodic) model can be adjusted for many considered effects
- The Class 1 unmodeled effects reflect uncertainty associated with:
  - Differences earthquake location ($\delta L2L_e$)
  - Differences in the source-to-site path due to anelastic attenuation ($\delta P2P_{Q,es}$)
  - Differences in the source-to-site path due to anelastic attenuation ($\delta P2P_{V,es}$)
  - Differences to local site effects ($\delta S2S_s$)
- These effects are biases that affect all ground motions

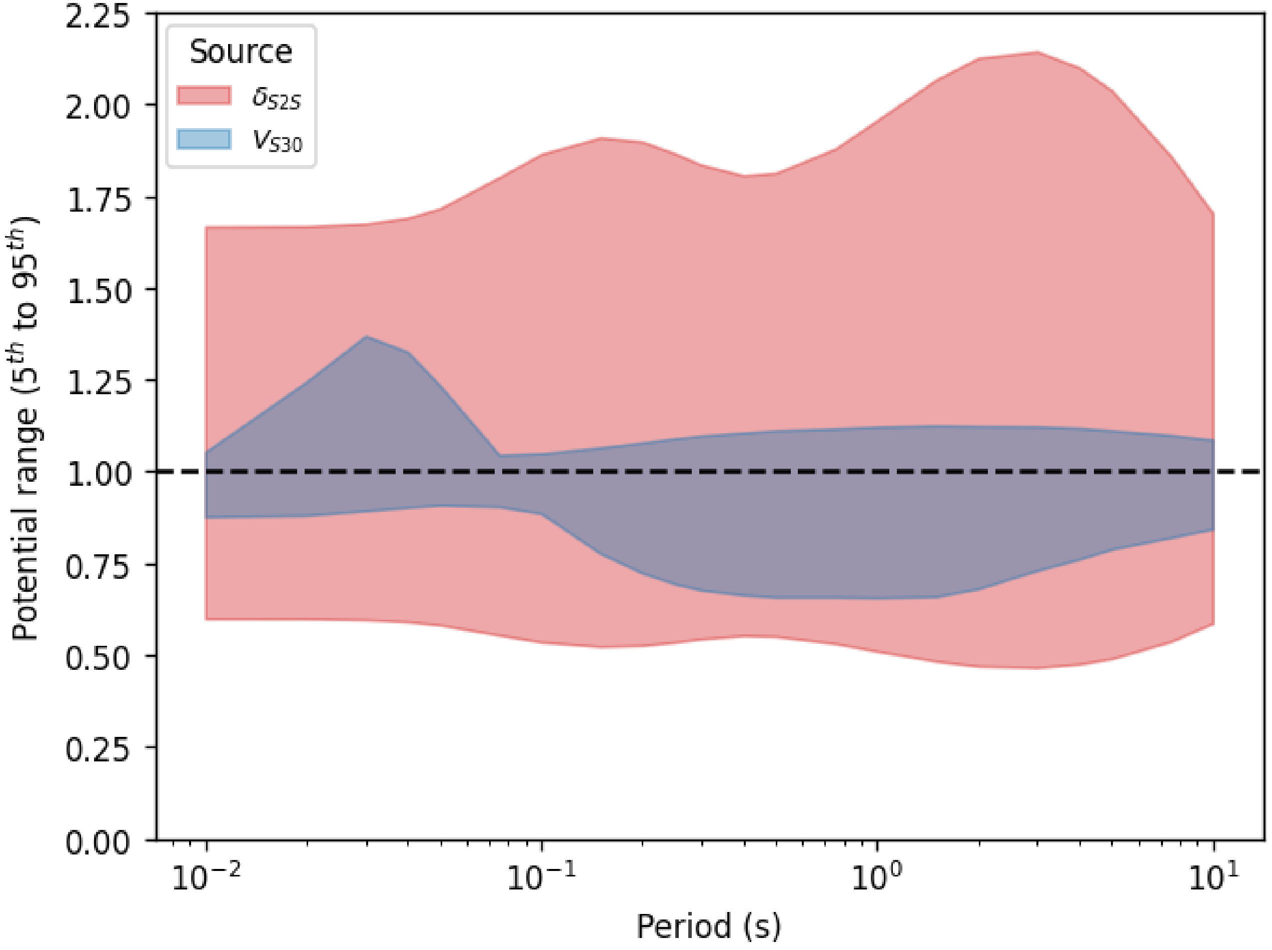
Uncertainty in the site term



Range in amplification for rock-like Vs30s (Al Atik et al. 2022)



90% confidence interval of amplification a Vs30 of 760 m/s (Al Atik et al. 2022)

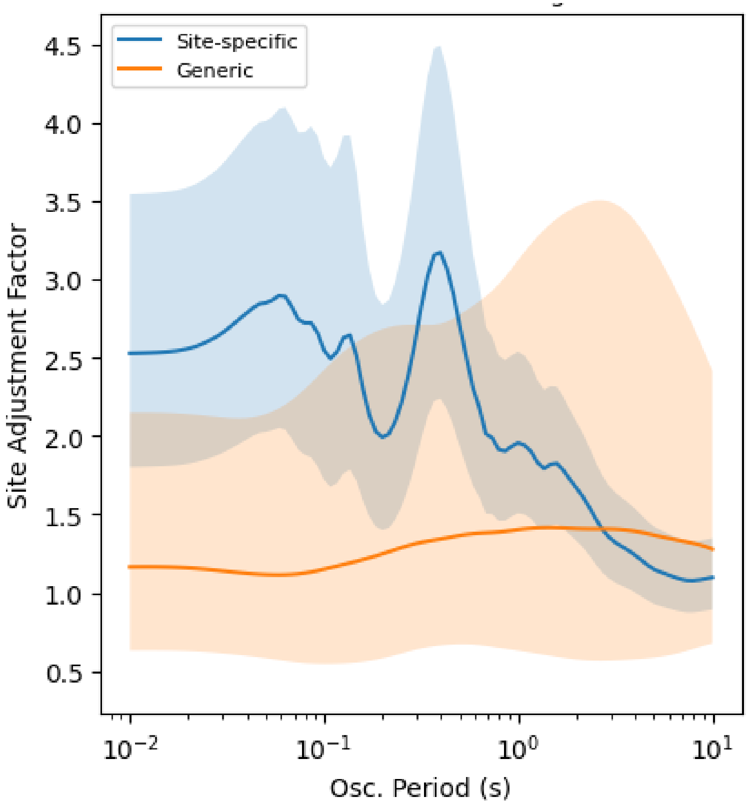


Uncertainty in local site effects are much larger than differences in the median V_{s30} behavior

For rock sites, it is better to record data than to measure velocity profile

Example of Vs30-estimated and measured site term

- Used a series of aftershocks to quantify site-term
  - Small-magnitudes (M2-3)
  - Used two different approach on Fourier amplitude spectra
  - Results consistent between approaches
- In this case, site has much stronger amplification that predicted by V_{s30}-based model
- Due to complex local velocity structure
- Ground motions at the site will have 2.3x higher PGA than expected



Implications for Cascadia

- Need to recognize ground motion models are going to get more complicated to capture spatial trends in ground motion
  - Move from unmodeled errors (randomness) to modeled error (uncertainty)
  - Allow for improved accuracy if more data is available
- But there is no data in Cascadia!

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Research questions

- What behavior is consistent between different earthquake sources (e.g., crustal, interface, interslab, oceanic fracture zones, etc.)?
  - Are site terms consistent for these different sources?
  - Do we understand the physical reasons for the similarity?
  - Test the approach elsewhere (Japan or Alaska) before applying to Cascadia
- How to adjust a model based on Japanese data to Cascadia?
  - Can simulations inform this adjustment?
  - Physical reasons for differences: geometry, geology, etc.
  - Might want to try approach to South, Central, and Northern sections Japanese subduction zone