Implementing Simulations in Ground Motion Models: Practical Needs and Challenges

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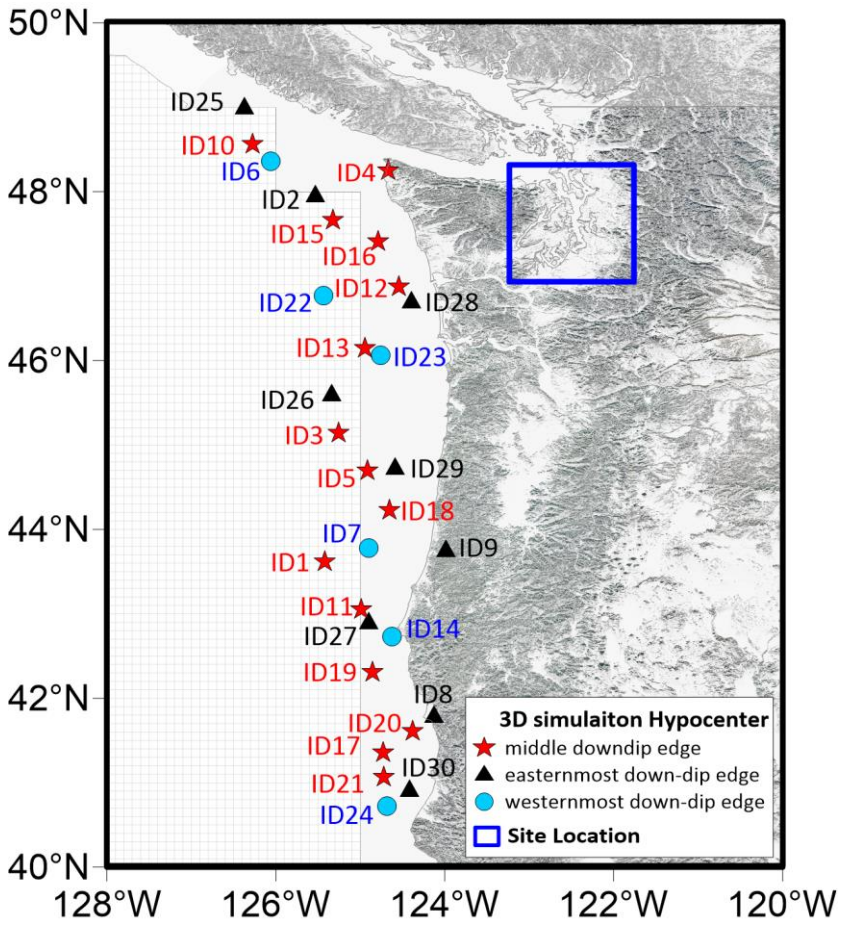
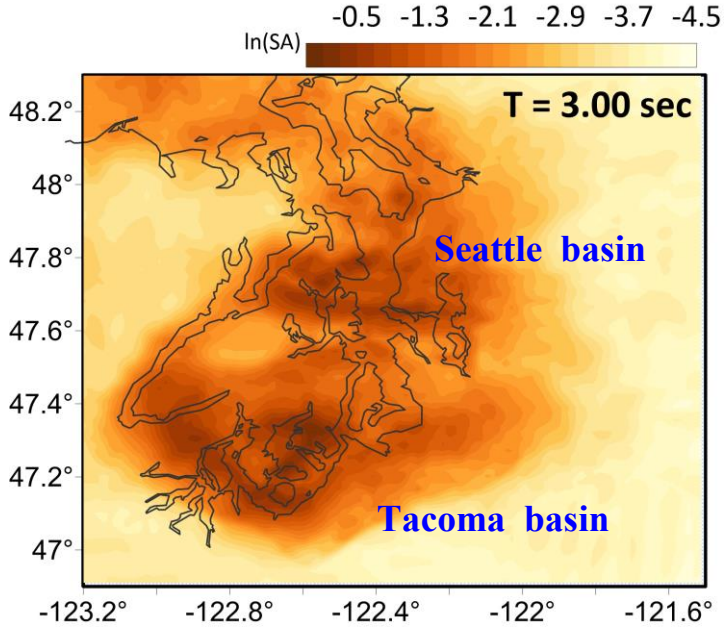
Why simulations are needed

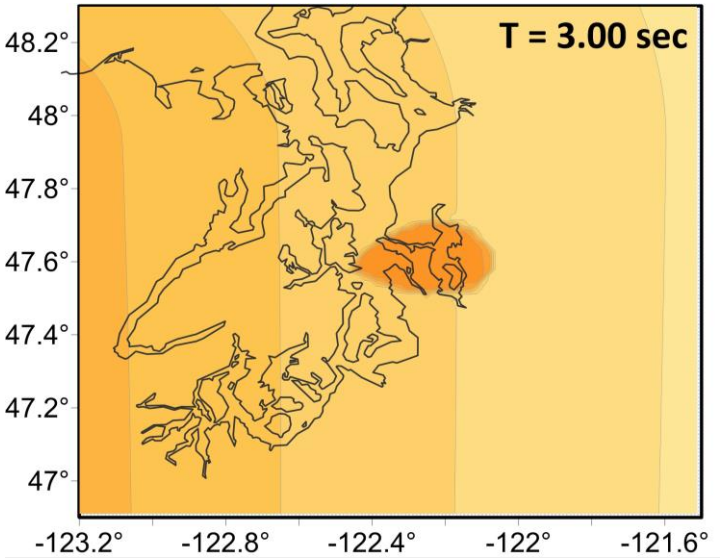


(Sung & Abrahamson, 2022)

- Empirical data are sparse for large subduction earthquakes
- Short distances and deep basins are poorly constrained
- Simulations provide physics-based constraints



3D-Simulation
(Frankel et al., 2018)



Ergodic GMM, AG22
(Abrahamson & Gulerce, 2022)

Non-ergodic GMMs based on the 3-D simulation

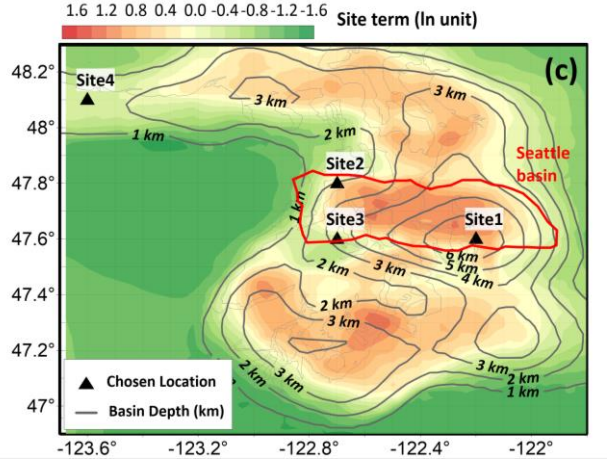
Ergodic GMM (EGMM)

3D-simulations

1. Non-ergodic GMM

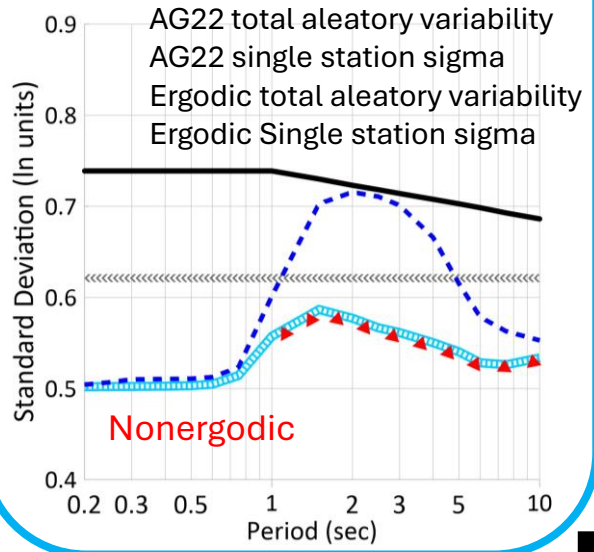
$$PSA_{NGMM} = PSA_{EGMM} + \Delta_{basin,3D} + \Delta_{NE} + C_{SIM}$$

- $\Delta_{basin,3D}$:Constraining the basin scaling in EGMMs using 3-D simulations
- Δ_{NE} : Non-ergodic terms are based on 3-D simulations
- C_{SIM} : Average amplitude from 3-D simulations



2. Aleatory Variability

Aleatory variability NGMMs



3.Epistemic uncertainty

Epistemic uncertainty for non-ergodic terms

(Sung & Abrahamson, 2022)

PSHA including 3D simulation results

- Spatial correlated adjustments
- Reduced aleatory variability
- Epistemic uncertainty

Challenge 1: Site and path effects

- All simulations correspond to a single M9 scenario
- Site and path effects cannot be separated

Site effect

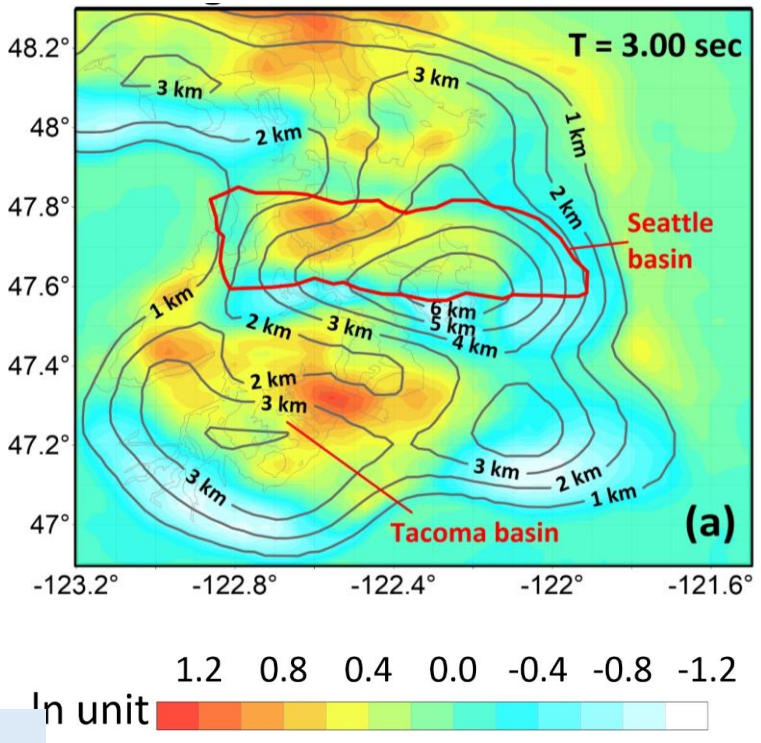
Constraining the basin scaling in EGMMs using 3-D simulations

$$PSA_{NGMM} = PSA_{EGMM} + \Delta_{basin,3D} + \Delta_{NE}$$

Non-ergodic terms are based on 3-D simulations

Site + Path effects

Nonergodic term (Δ_{NE})

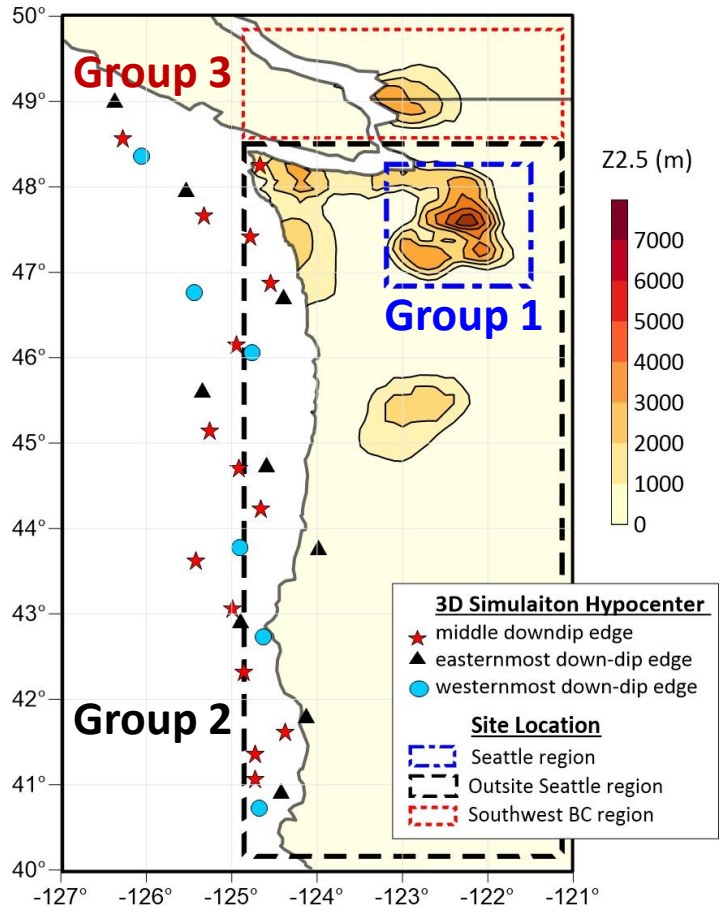


(Sung & Abrahamson, 2022)

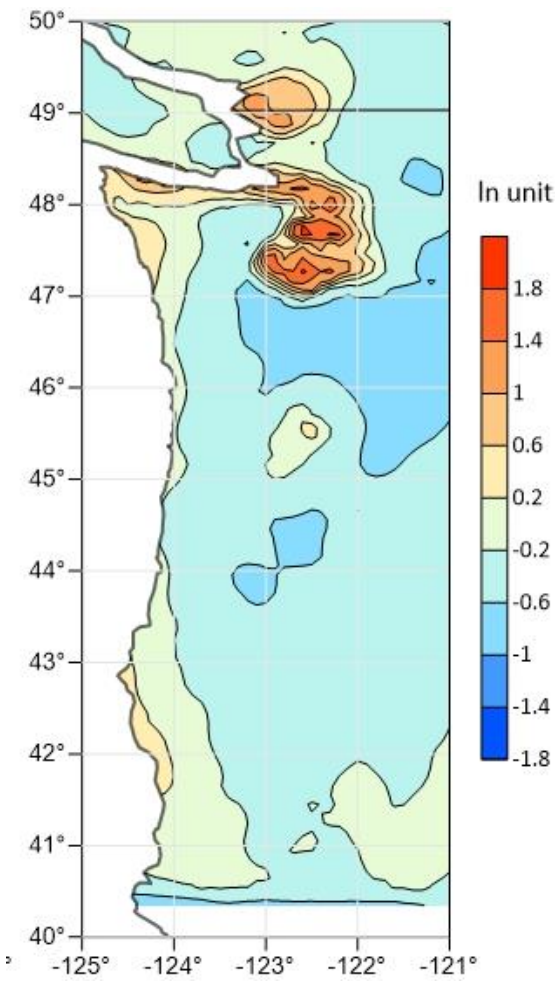
1. **Scenarios should be designed to span azimuthal path diversity for each site.**
2. **Need for validation using small earthquakes (M ≈ 3–5).**

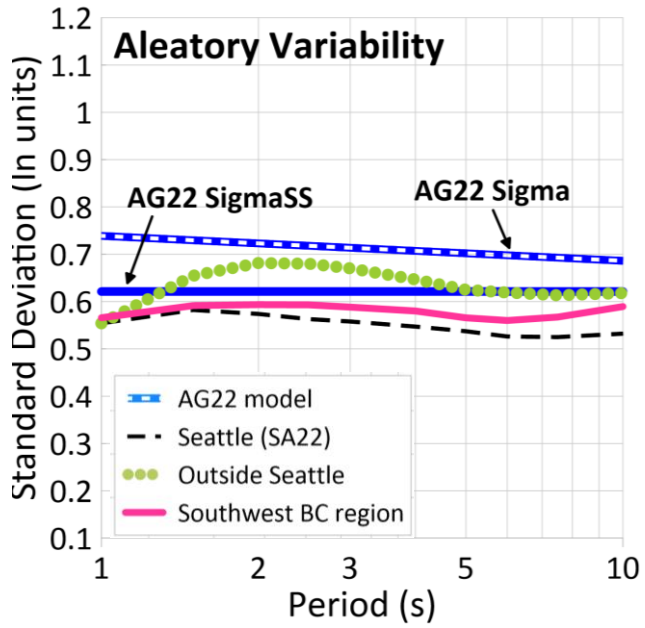
Challenge 2: Limited resolution constrains

Group 1: Seattle region (1-km space)
Group 2: Outside Group1 (20-km space)
Group 3: Canada (1-km space)



$\Delta_{basin,3D} + \Delta_{NE}$





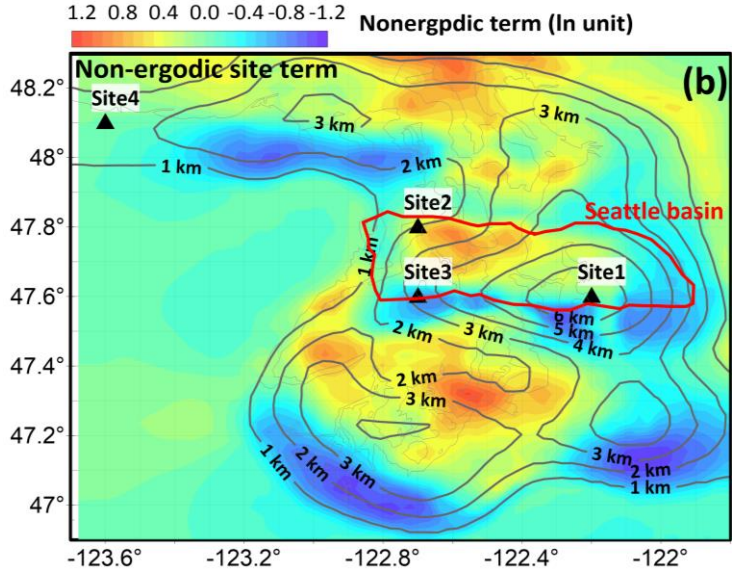
(Sung & Abrahamson, 2026)

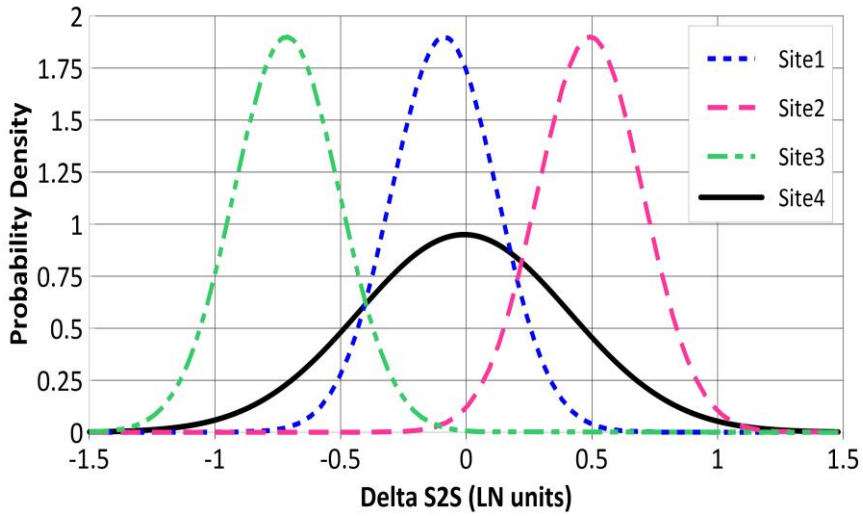
****Keep a common dense site grid across scenarios****

Challenge 3: Epistemic uncertainty is underestimated

- **30 realizations + dense sites**
  - Epistemic uncertainty < 0.1 (ln unit) = phiS2S/sqrt(30)
  - Single 3D velocity model
  - Missing epistemic uncertainty for the 3D velocity model
- Assume epistemic uncertainty for 3D velocity model
  - Inside simulation region
    - Epistemic uncertainty is taken as 25% of the variance of the single best-estimate 3D velocity model.
    - Assumption: Epistemic = 0.5 * phiS2S
  - Outside simulation region
    - Assumption: Epistemic = phiS2S

**** Alternative to the assumption**
use multiple 3D velocity models to quantify epistemic uncertainty **





(Sung & Abrahamson, 2022)

Challenge 4: Physics-based simulations are limited to long periods

- 3D simulations constrained to T ≥ 2 sec
- High-frequency motions are 1D stochastic simulations
  - the basin / path effects are not represented
- Limits applicability for engineering practice

**** Validation using small earthquakes is needed to determine the reliable period range****

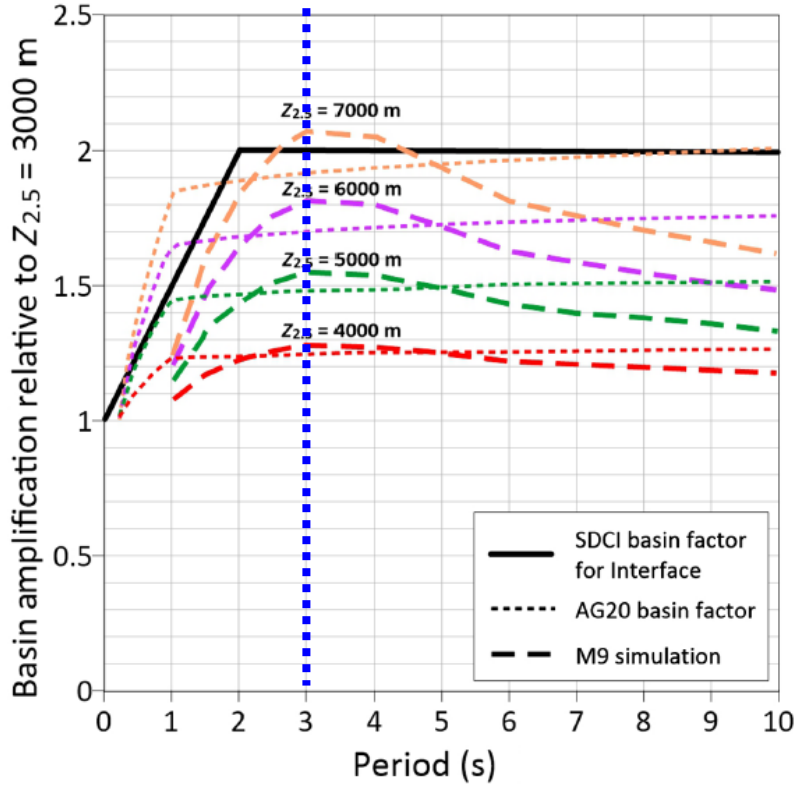
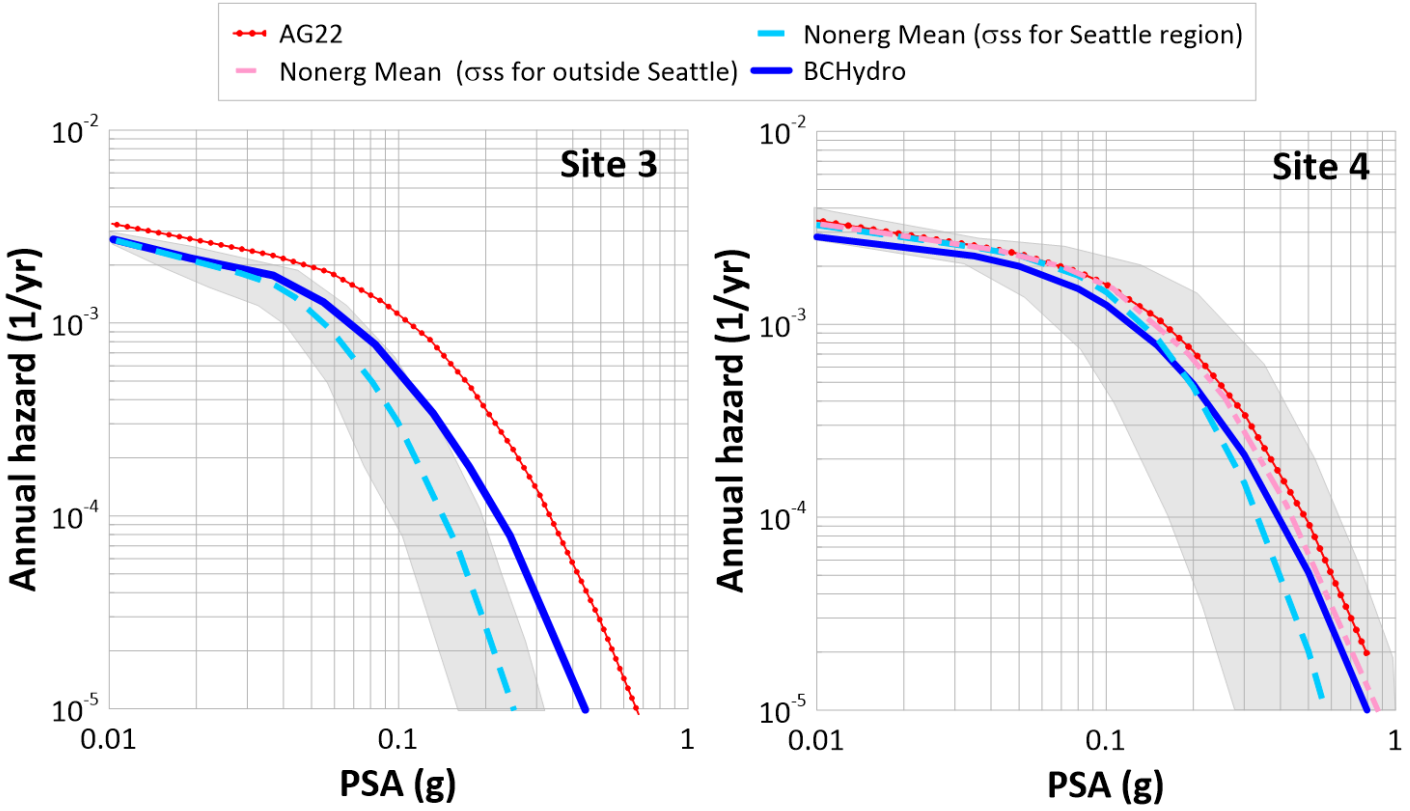


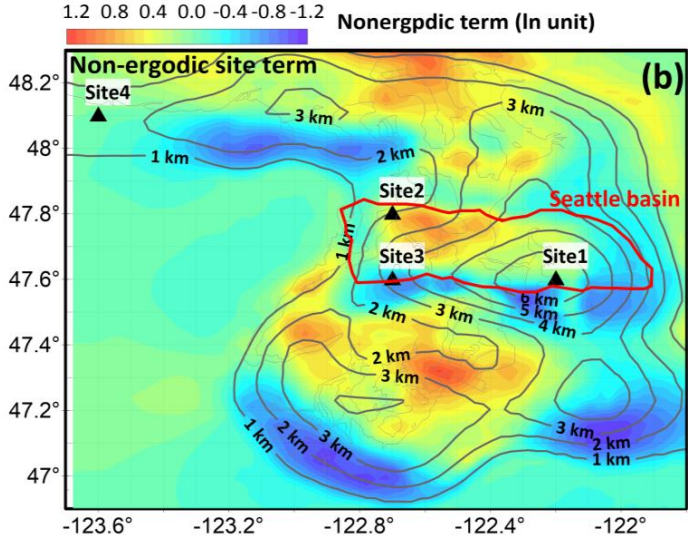
Figure 8. Comparison of the normalized basin factors from AG20 and from the 3D simulations with the basin factors used by the Seattle Department of Construction and Inspection (SDCI). The color version of this figure is available only in the electronic edition.

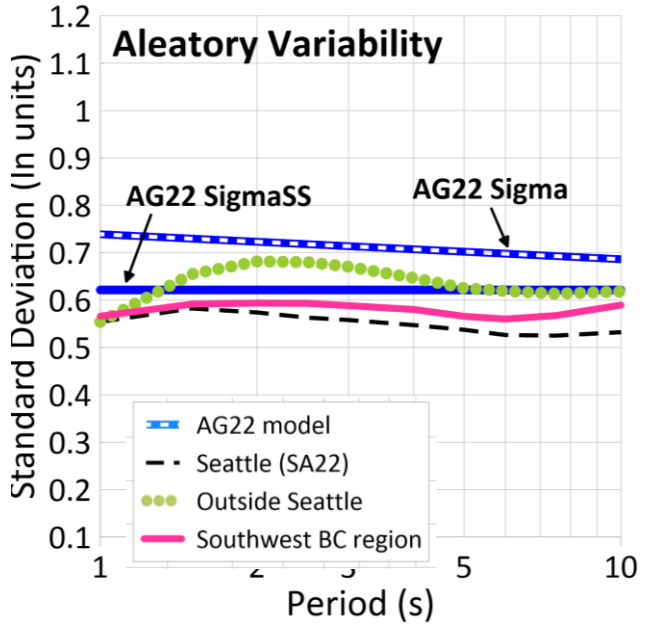
(Sung & Abrahamson, 2022)

PSHA implementation

$$P(PSA(T) > Z|M,R) = 1 - \Phi\left(\frac{z - (\mu_{erg}(M,R,T) + \Delta\mu_{ne}(Lat_s, Lon_s, M, T))}{\sigma_{ne}(M,R,T)}\right)$$







(Sung & Abrahamson, 2026)

Conclusions

- Multiple rupture scenarios are required so that path averaging is possible and site and path effects can be separated.
- A dense and consistent site grid, with spacing shorter than the correlation length of nonergodic terms, must be used across all scenarios to resolve site and basin effects rather than numerically smoothing them out.
- Validation is required to evaluate the accuracy and reliable period range of 3D simulations.
- Quantifying epistemic uncertainty requires ensembles of source models and multiple alternative 3D velocity models, not a single best-estimate model.