UNIVERSITY OF MARYLAND

Framework for Modeling Ground Motion Variability in a Nuclear Power Plant Site for Use in a Seismic Multi-Unit Probabilistic Risk Assessment

Jonathan DeJesus Segarra*, Michelle Bensi, and Mohammad Modarres

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Acronyms and Terms

- ξ_{jk} – separation distance between locations j and k
- ε – intra-event variability
  - σ_{ε}^{2} - variance of ε
- η – inter-event variability
  - σ_{η}^{2} - variance of η
- $\lambda(SA^{r} > sa^{r})$ - annual rate of exceedance
- λ_{m} - rate of earthquakes with magnitude greater than m
- $AF(f)$ – amplification factor at frequency f
- CCDP – conditional core damage probability
- Loc – earthquake location
- M or m – earthquake magnitude
- MUPRA – multi-unit probabilistic risk assessment
- MURM – multi-unit risk metric
- NPP – nuclear power plant
- PGM – probabilistic graphical model
- PRA – probabilistic risk assessment
- PSA – probabilistic safety assessment
- PSHA – probabilistic seismic hazard analysis
- R or r – earthquake source-to-site distance
- $SA(f)$ – spectral acceleration at frequency f
- SA_{j}^{r} – spectral acceleration at bedrock for location j
- SA_{k}^{r} – spectral acceleration at bedrock for location k
  - $\sigma_{\ln(SA_{k}^{r})}$ - standard deviation of $\ln(SA_{k}^{r})$
- SA_{j}^{s} – spectral acceleration at soil for location j
- SA_{k}^{s} – spectral acceleration at soil for location k
- ΔSA_{jk} – difference of the natural logarithms of SA_{j} and SA_{k}
  - $\mu_{\Delta \mathrm{SA}_{jk}}$ - mean of ΔSA_{jk}
  - $\sigma_{\Delta SA_{jk}}$ - standard deviation of ΔSA_{jk}
- $Source$ – earthquake source

Problem Statement

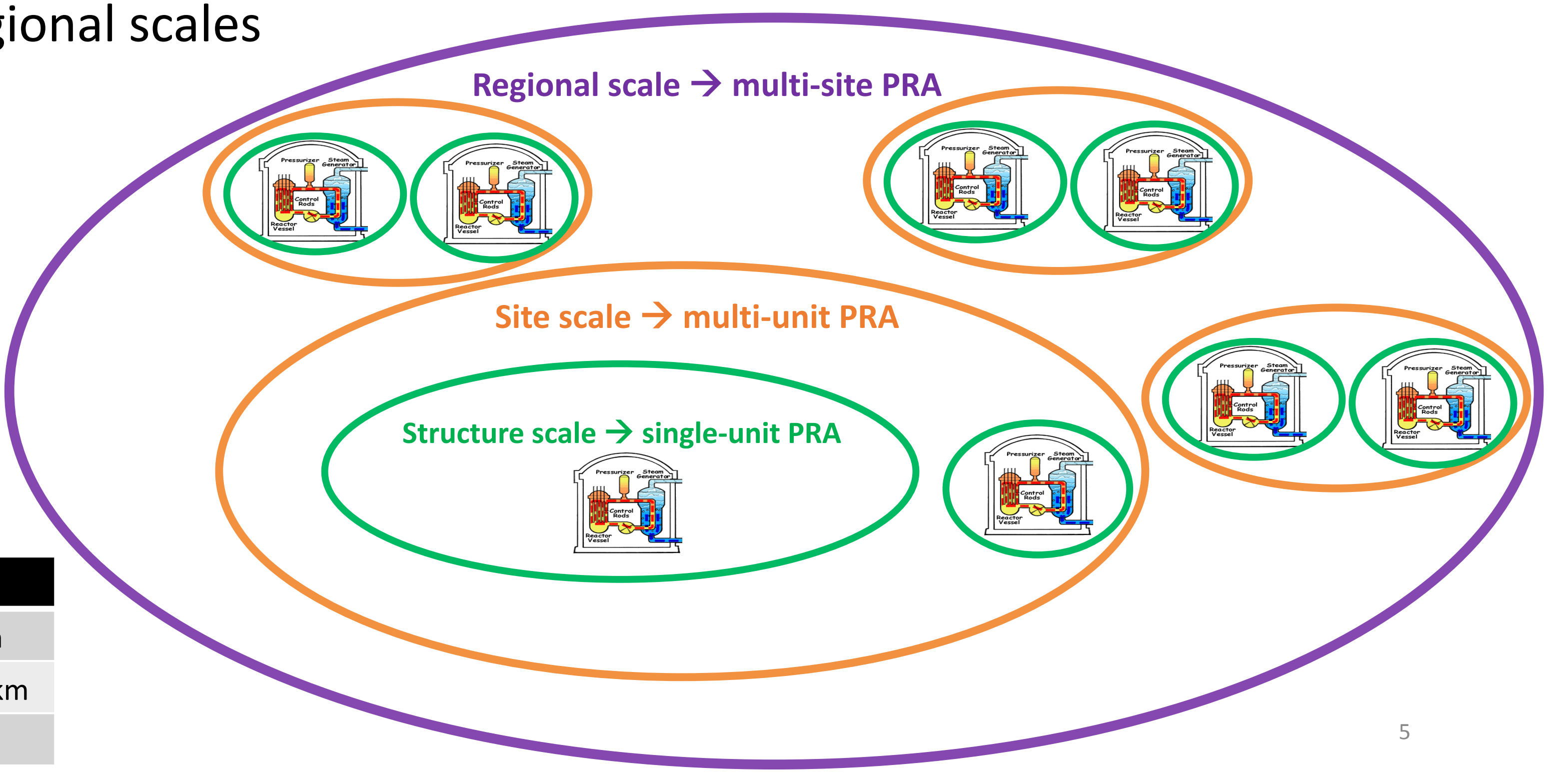
- Fukushima Daiichi accident demonstrated the importance of accidents involving multiple units and highlighted the need for considering multi-unit accidents as part of a PRA.
- In order to properly understand the risk at a multi-unit NPP site, one must account for the dependencies among the units
  - Schroer and Modarres [1] classification schema → earthquakes classified as definite initiating events, i.e., they will affect always affect multiple units
- Unit-by-unit basis of performing PRA
  - Analyst performing a multi-unit seismic PRA assumes that the same ground motion intensity is experienced by all the units at the NPP site (i.e., perfect correlation)
- Analyst assumption is not realistic because, **at a NPP site scale, there is spatial variability in the ground motion** due to various factors.

Research Objective

- The overall objective of this research is to develop a method that allows the inclusion of the spatial variability of ground motions at a NPP site for use in a seismic MUPRA.
  - Method should be tractable and practical.
  - Method should use existing PSHA results.
- This will be achieved by
  - characterizing the spatial variability of ground motions,
  - integrating the model of ground motion variability with the results of existing PSHA results, and
  - developing a method that allows the spatial ground motion variability to be addressed in a seismic MUPRA.

Scales

- Based on the idea that ground motions vary on a structural, site/local, and regional scales



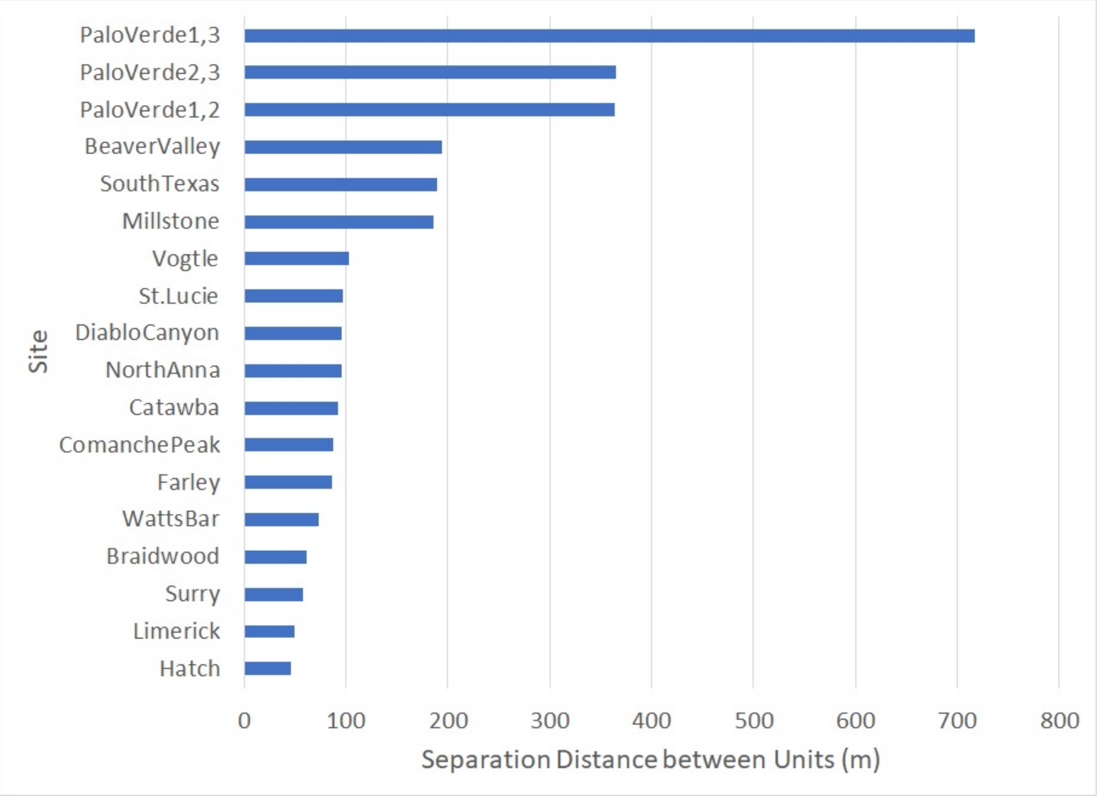
Regional scale → multi-site PRA

Site scale → multi-unit PRA

Structure scale → single-unit PRA

Scale	Range
Structure	Up to 150 m
Local/Site	150 m to 1 km
Regional	> 1 km

Distance Between U.S. NPP Units



Spatial Variability of Ground Motions

- Definition: “the differences in the amplitude and phase of seismic ground motions recorded over extended areas.”

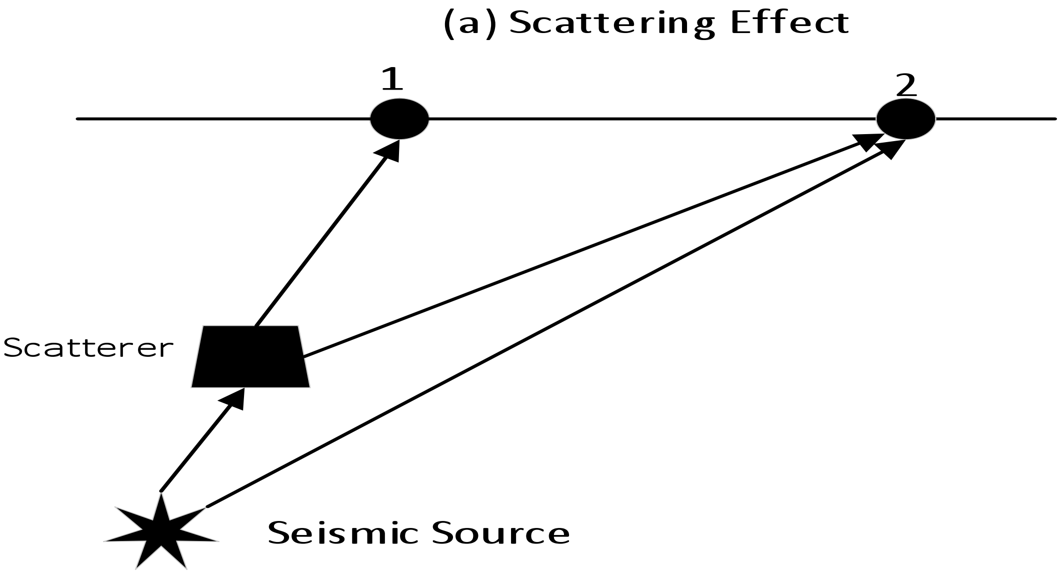


Figure adapted from: Zerva (2009) [2]

Probabilistic Seismic Hazard Analysis

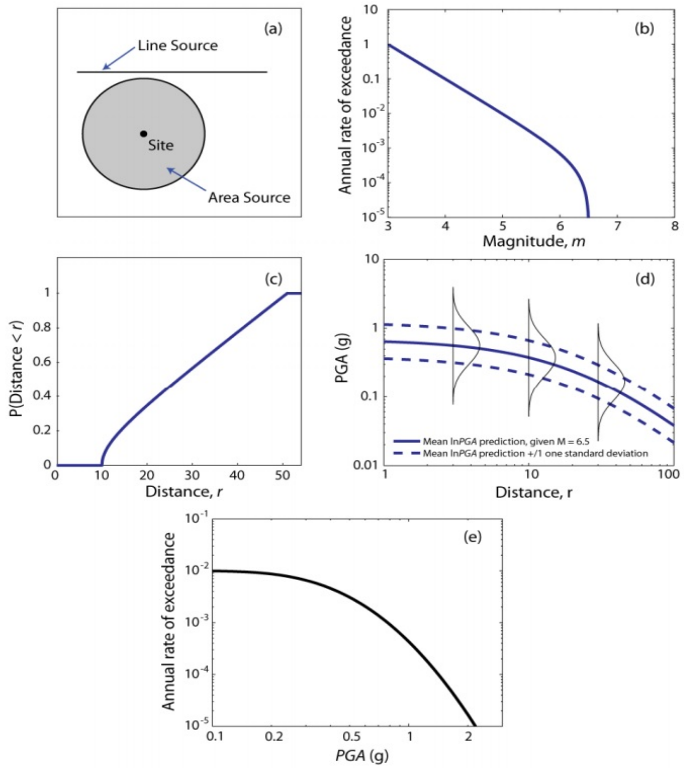


Figure credit: Baker, J.W. (2008), "An Introduction to [PSHA]." [3]

(a) Identification of earthquake sources

(b) Characterize distribution of earthquake magnitude from each source

$$\log_{10}\lambda_m = a - bm \qquad f_M(m) = \frac{b\ln(10)\,10^{-b(m-m_{min})}}{1-10^{-b(m_{max}-m_{min})}}$$

(c) Characterize distribution of source-to-site distances from each source

(d) Predict distribution of ground motion parameter (e.g., PGA or $SA(f)$)

$$\ln\big(SA^r(f)\big) = g(m,r)+\eta+\varepsilon$$

$$P(SA^r > sa^r|m,r) = 1-\Phi\left(\frac{ln(sa^r)-g(m,r)}{\sqrt{\sigma_\eta^2+\sigma_\varepsilon^2}}\right)$$

(e) Compute annual rate of exceeding a given value of a ground motion parameter

$$\lambda(SA^r > sa^r) = \sum_{i=1}^{n_{sources}} (\lambda_m)_i \sum_{j=1}^{n_M}\sum_{k=1}^{n_R} P\big(SA^r > sa^r|m_j,r_k\big)\,P\big(M_i = m_j\big)\,P(R_i = r_k)$$

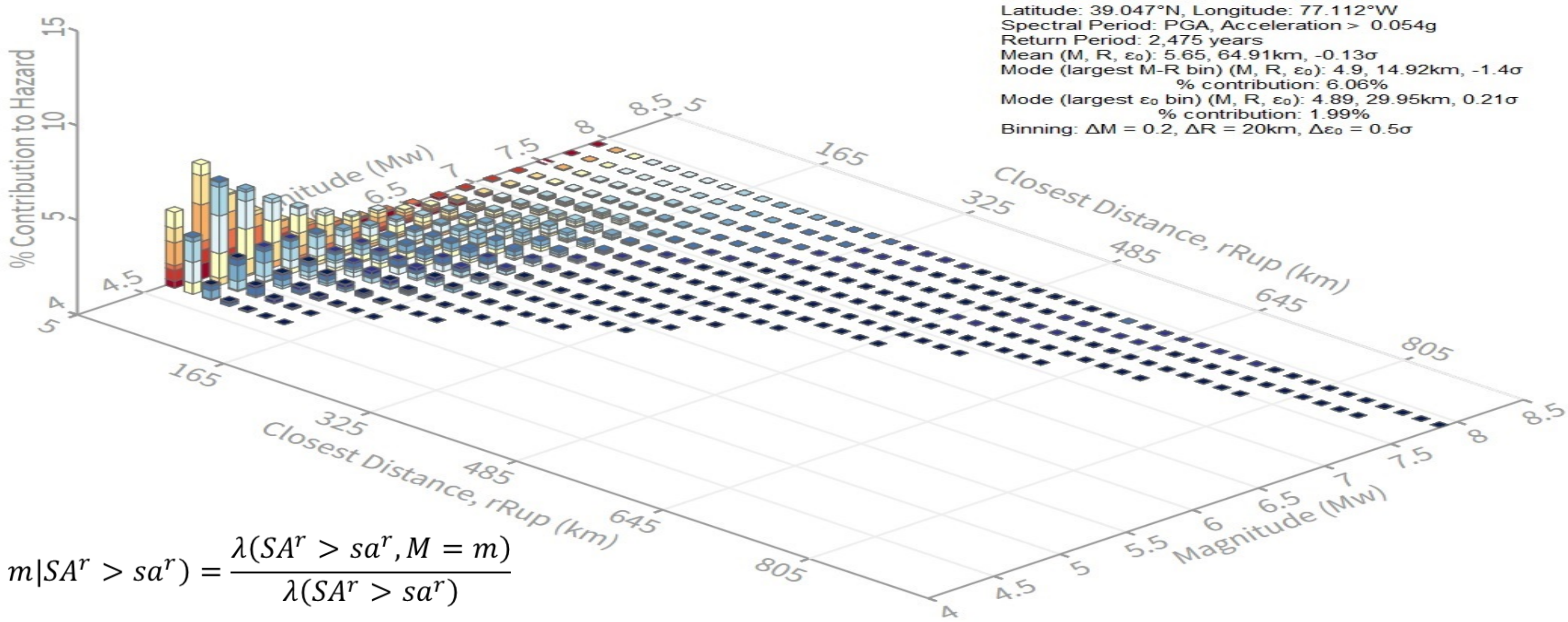
For soil sites, modify the rock hazard curve (above) with site-specific amplification factor [4,5]

$$AF(f) = \frac{SA^s(f)}{SA^r(f)}$$

$$P(SA^s > sa^s) = \sum_{all\ sa_j^r} P\left(AF > \frac{sa^s}{sa^r}|sa_j^r\right)P\big(SA^r = sa_j^r\big)$$

PSHA results are provided for a "control point" elevation at the site (e.g., reactor building foundation) [6]

Disaggregation of the Seismic Hazard



Latitude: 39.047°N, Longitude: 77.112°W
Spectral Period: PGA, Acceleration > 0.054g
Return Period: 2,475 years
Mean (M, R, ε_0): 5.65, 64.91km, -0.13σ
Mode (largest M-R bin) (M, R, ε_0): 4.9, 14.92km, -1.4σ
% contribution: 6.06%
Mode (largest ε_0 bin) (M, R, ε_0): 4.89, 29.95km, 0.21σ
% contribution: 1.99%
Binning: ΔM = 0.2, ΔR = 20km, $\Delta\varepsilon_0$ = 0.5σ

$$P(M = m | SA^r > sa^r) = \frac{\lambda(SA^r > sa^r, M = m)}{\lambda(SA^r > sa^r)}$$

$$\lambda(SA^r > sa^r, M = m) = \sum_{i=1}^{n_{sources}} (\lambda_m)_i \sum_{k=1}^{n_R} P(SA^r > sa^r | m, r_k)\, P(M_i = m)\, P(R_i = r_k)$$

Figure credit: https://earthquake.usgs.gov/hazards/interactive/

Existing Work

- Spatial Correlation of Intra-Event Variabilities [7]

$$\rho_{\varepsilon}(\xi, T_n) = exp\left(-\alpha \xi^{\beta}\right)$$

  - Developed using regional ground motion databases
  - If used in seismic MUPRA, correlation will be close to 1.0

- Spectral Amplitude Variability [8]

$$\Delta \mathrm{SA}_{jk}(f) = ln\left[\mathrm{SA}_j(f)\right] - ln[\mathrm{SA}_k(f)]$$

$$\mu_{\Delta \mathrm{SA}_{jk}(f)} \approx 0$$

$$\sigma_{\Delta \mathrm{SA}_{jk}}\left(M, \xi_{jk}, f\right) = c_1(f, M)\left(1 - exp\left\{-\xi_{jk}\, c_2(f)\right\}\right)$$

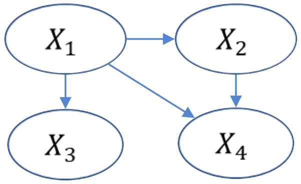
$$\Delta \mathrm{SA}_{jk} \sim N(0, \sigma_{\Delta \mathrm{SA}_{jk}})$$

Brief Background on PGMs

- A PGM provides a representation of the probabilistic dependence among random variables and their joint distribution

$$f_{X_1,X_2,\ldots,X_n}(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} f_{X_i|pa(X_i)}(x_i|pa(x_i))$$

- Example PGM

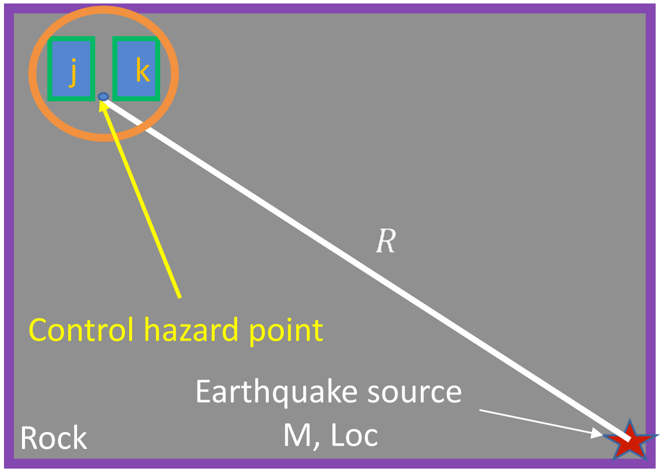


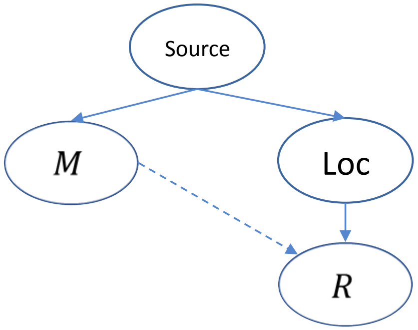
$$f_{X_1,X_2,X_3,X_4}(x_1, x_2, x_3, x_4) = f_{X_1}(x_1)\, f_{X_2|X_1}(x_2|x_1)\, f_{X_3|X_1}(x_3|x_1)\, f_{X_4|X_1,X_2}(x_4|x_1, x_2)$$

- Once the joint distribution is established, any joint, marginal, or conditional distribution can be calculated.

Proposed Framework
General Ground Motion Variability Model
PGM representation and illustration of variables

Top view

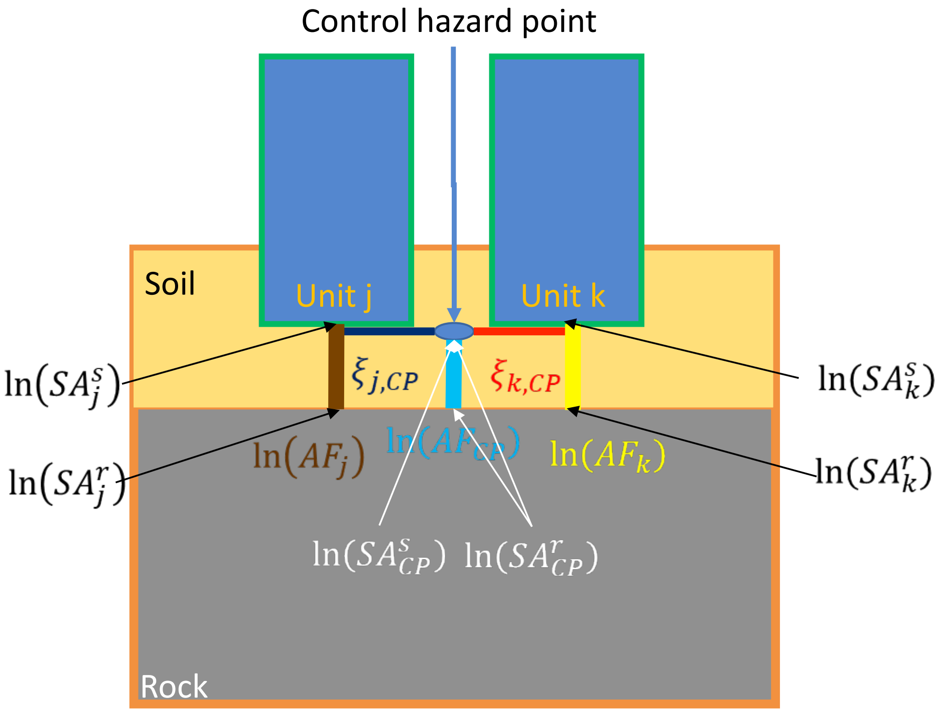


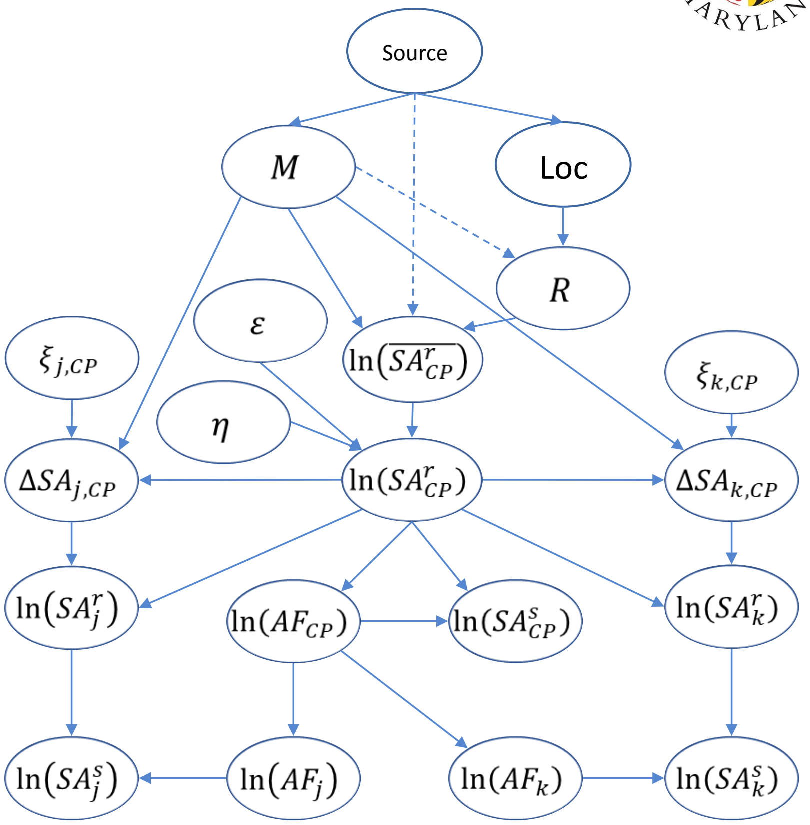


Proposed Framework
General Ground Motion Variability Model

PGM representation and illustration of variables

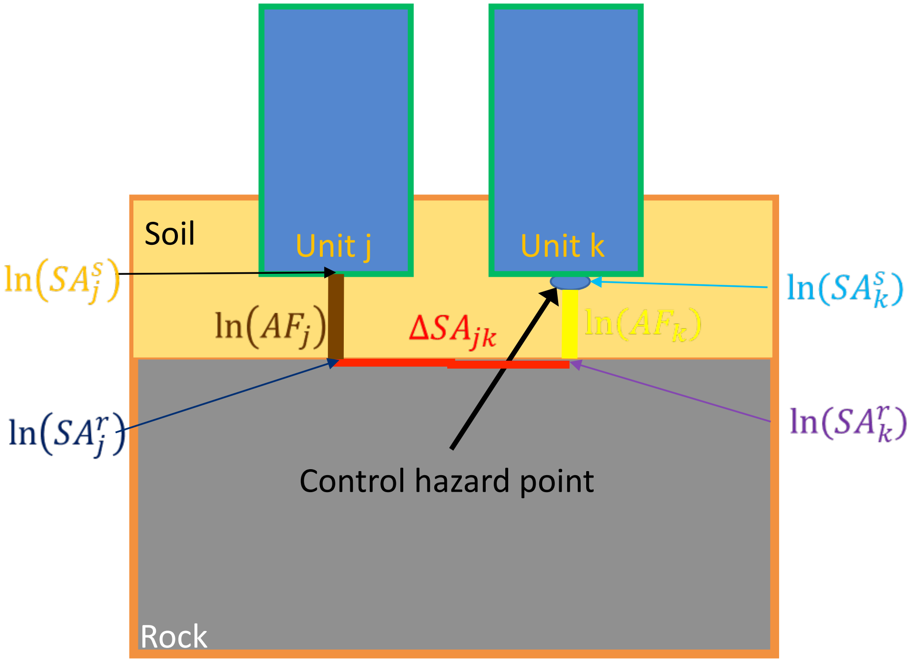
Side view
(i.e., looking through Earth)

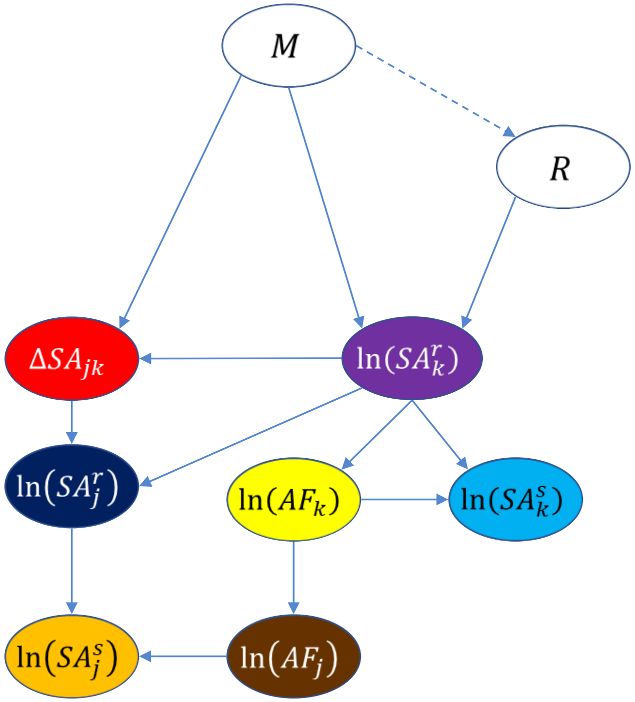




Proposed Framework Streamlined Ground Motion Variability Model

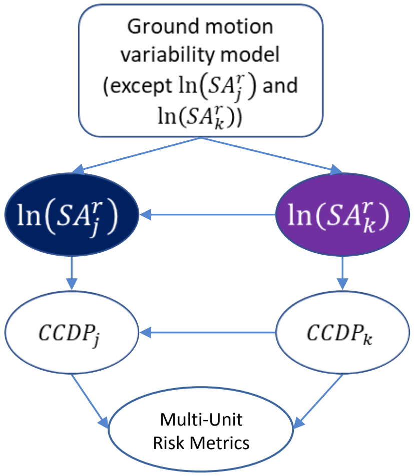
PGM representation and illustration of variables



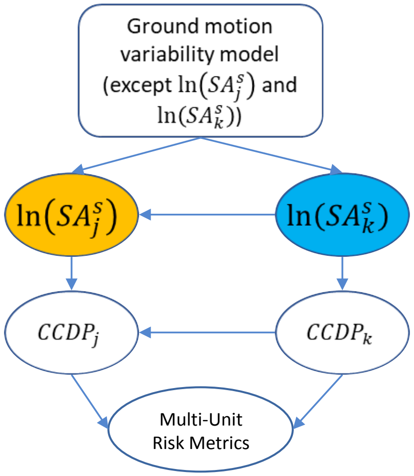


Proposed Framework for MUPRA Metrics

Rock Site



Soil Site



$$P(MURM)=\sum_{\ln(SA_k^r)}\sum_{\ln(SA_j^r)}\sum_{CCDP_k}\sum_{CCDP_j}P(\ln(SA_k^r))\boldsymbol{P}\left(\boldsymbol{\ln}\left(\boldsymbol{SA_j^r}\right)|\,\boldsymbol{\ln}(\boldsymbol{SA_k^r})\right)P(CCDP_k|\ln(SA_k^r))P\left(CCDP_j|\ln\left(SA_j^r\right),CCDP_k\right)P\left(MURM|CCDP_j,CCDP_k\right)$$

$$P(MURM)=\sum_{\ln(SA_k^s)}\sum_{\ln(SA_j^s)}\sum_{CCDP_k}\sum_{CCDP_j}P(\ln(SA_k^s))\boldsymbol{P}\left(\boldsymbol{\ln}\left(\boldsymbol{SA_j^s}\right)|\,\boldsymbol{\ln}(\boldsymbol{SA_k^s})\right)P(CCDP_k|\ln(SA_k^s))P\left(CCDP_j|\ln\left(SA_j^s\right),CCDP_k\right)P\left(MURM|CCDP_j,CCDP_k\right)$$

Conclusion

- Developed a framework for modeling ground motion variability across a NPP site for use in a seismic MUPRA.
- Next steps
  - Develop ground motion variability model for different site conditions (i.e., rock or soil) and obtain conditional distribution of the ground motion hazard at a non-reference location given the reference (or “anchor”) ground motion hazard. For example,

$$P\left(ln\left(SA_j^r\right) \mid ln(SA_k^r)\right)$$

  - Test the ground motion variability model using the results of a PSHA from a hypothetical site.

References

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