Surrogate Models of Highway Bridges for Regional-Scale Simulations of Transportation Networks

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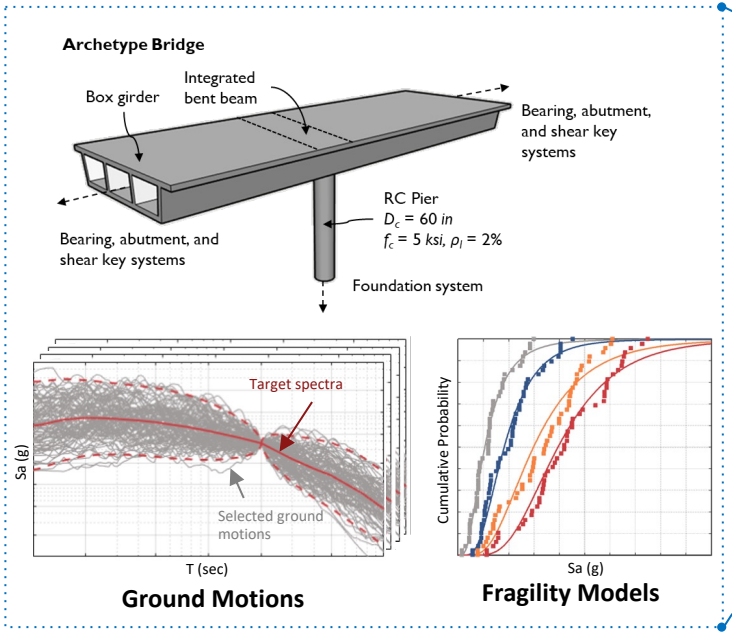
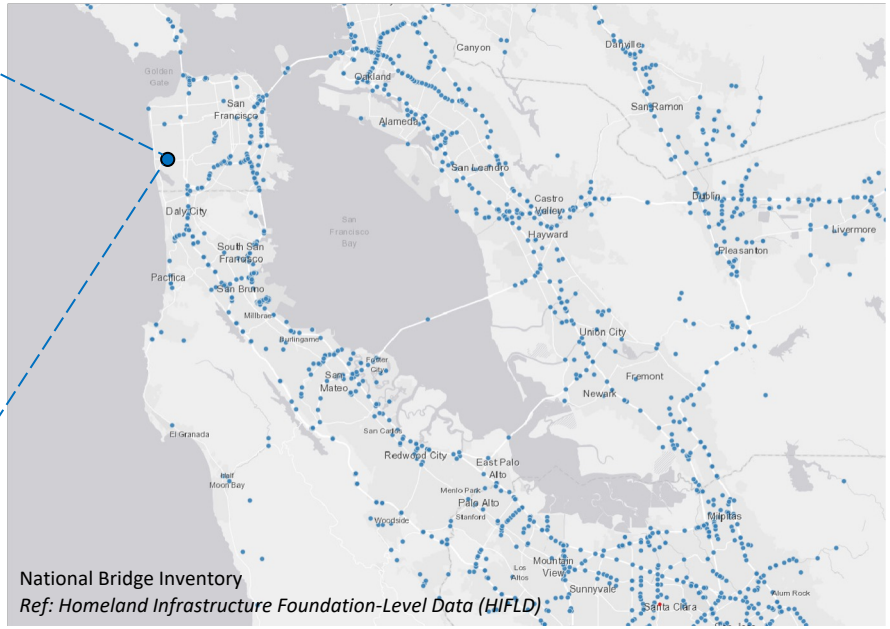
PEER 2023 Annual Meeting

Seismic risk analysis of regional distributed transportation infrastructure to support planning for design, retrofit, and post-earthquake recovery

- Bridge design/modeling parameters and inventory data
- Regional earthquake ground motion hazard data
- Bridge response and damage assessment

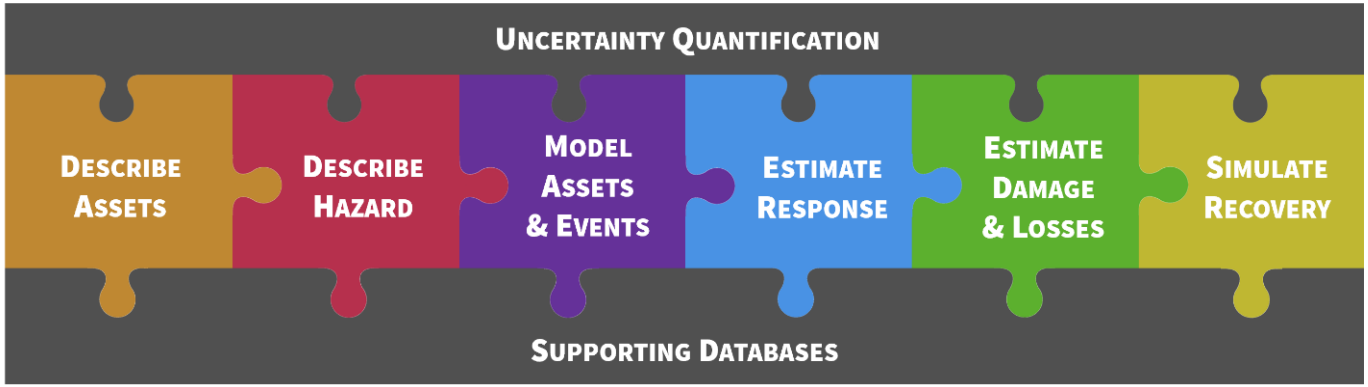


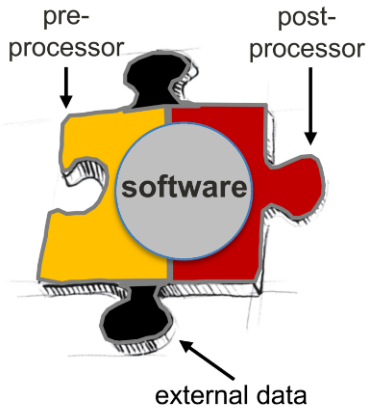


Outline for Today

- **Overview of supporting SimCenter tools**
  - quoFEM, EE-UQ, R2D
- **Surrogate modeling of bridge performance (quoFEM, EE-UQ)**
  - Surrogate modelling methods: SAF-IDA, Gaussian Process, PLoM
  - Scope of design studies - archetype bridge models
  - Training and assessment of surrogate models
- **Regional simulation of bridges in highway network (R2D)**
  - Characterization of ground motion hazard
  - OpenSees vs Surrogate
- **Next Steps**

SimCenter Computational Framework

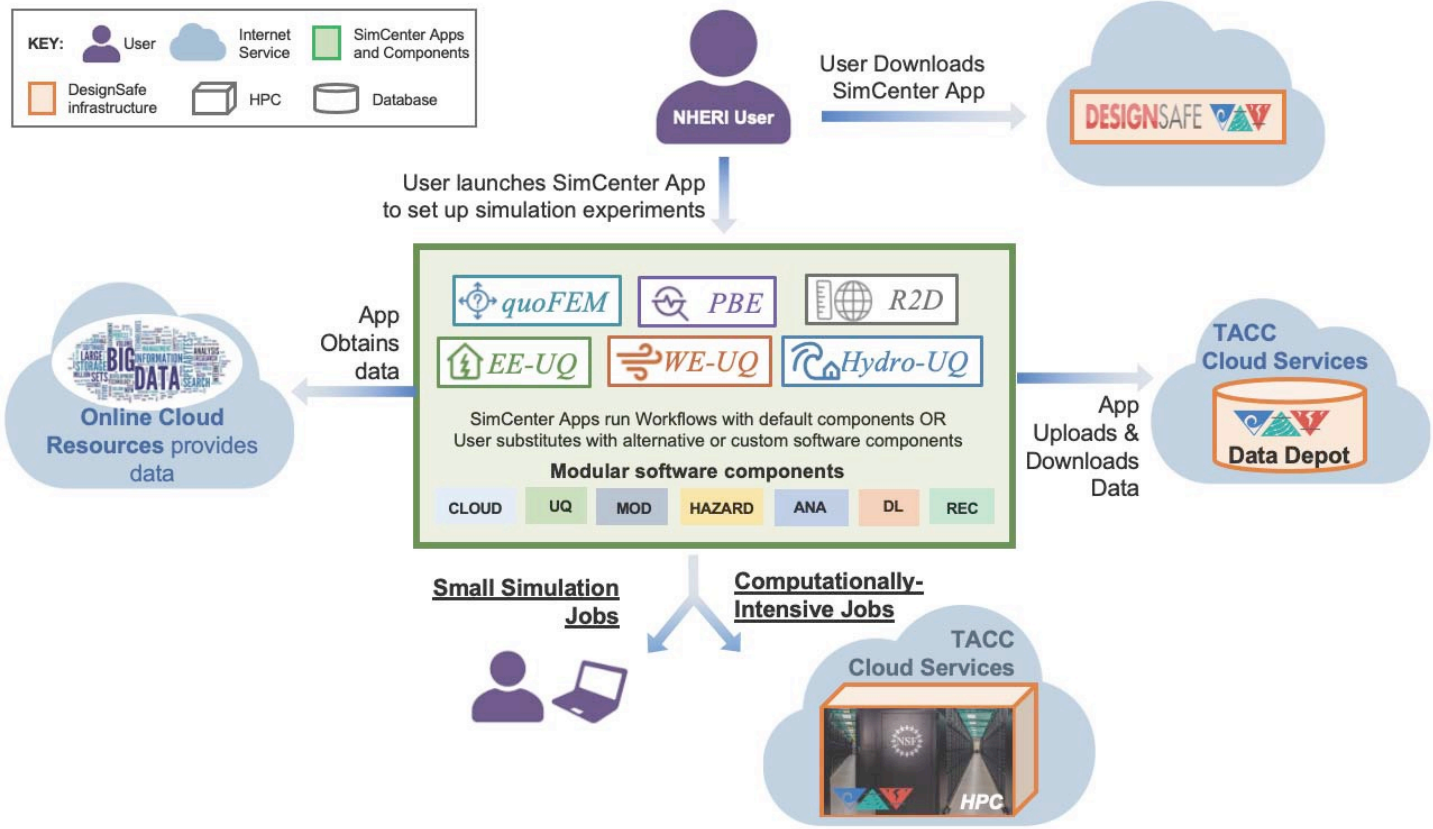




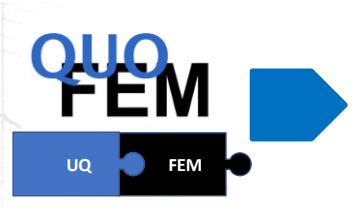
$$v(DV) = \iiint G\langle DV \mid DM \rangle \mid dG\langle DM \mid EDP \rangle \mid dG\langle EDP \mid IM \rangle \mid d\lambda(IM)$$

Impact | **Performance (Loss) Models and Simulation** | **Hazard**

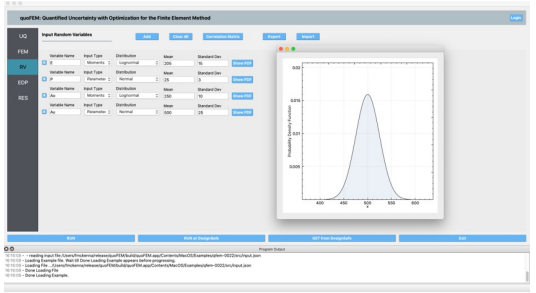
Computational Eco-system

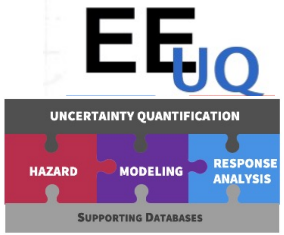


Integration in SimCenter Software

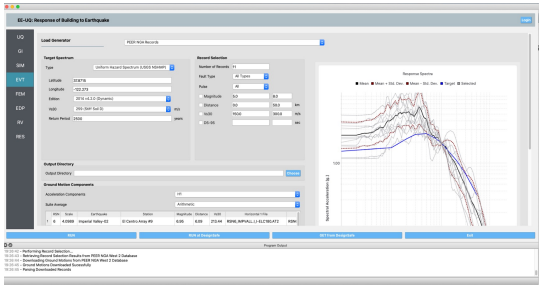


Coupling: Quantification of Uncertainties & Optimization with FEM, including capabilities for surrogate modeling (GP, PLoM)



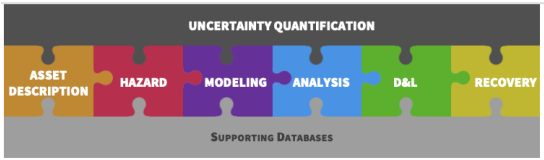


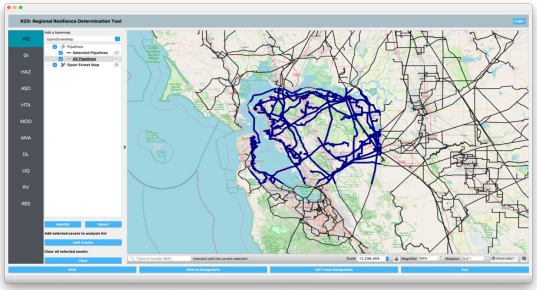
Response of structures to ground shaking with SAF-IDA, GP, PLoM features to develop surrogate models



R2D

Regional assessment of facilities and systems to natural hazards





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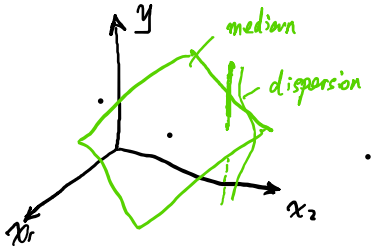
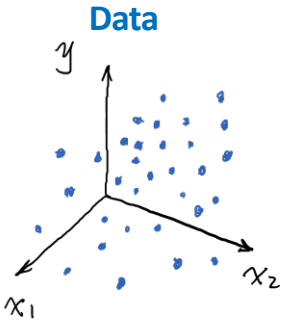
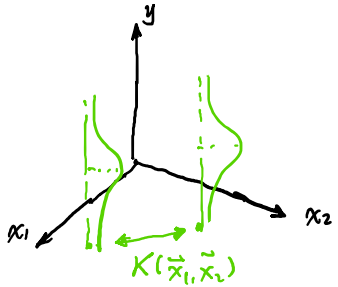
Surrogate Model Alternatives



Site-specific Adjustment Framework for IDA (SAF-IDA)

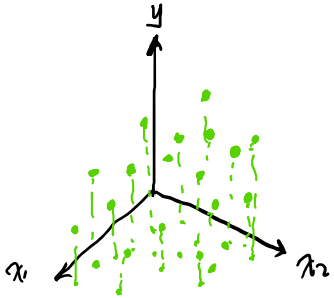
- Log Linear (parametric) and local linear regression (piecewise parametric)
- Training coefficients/weights (*w*)
- Predict median/dispersion of independent performance metrics
- Models are expensive (and loose accuracy) for high-dimension datasets





Gaussian Process Regression (GP)

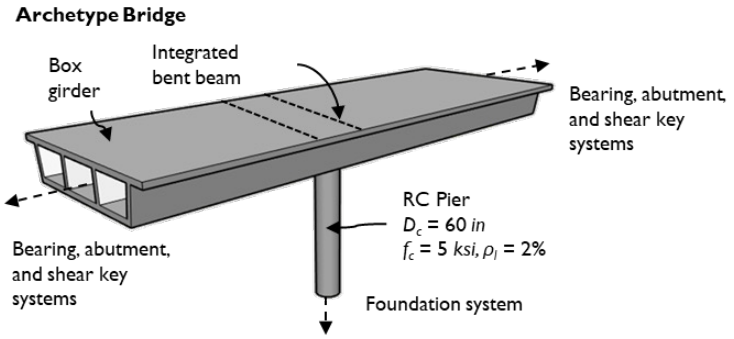
- Non-parametric
- Selecting the covariance function (*K*) and training its hyper-parameters
- Predict median/dispersion
- Expensive for high-dimension/large-size datasets (sparse GP can improve)

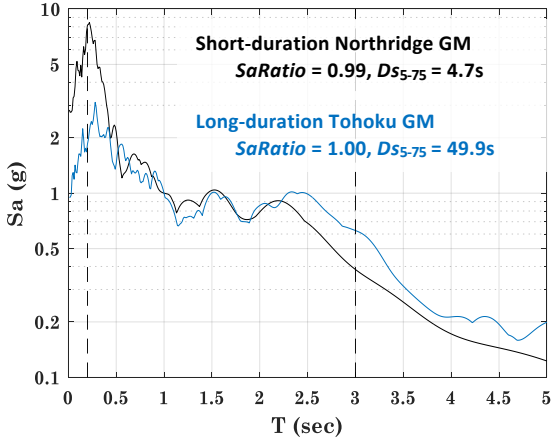


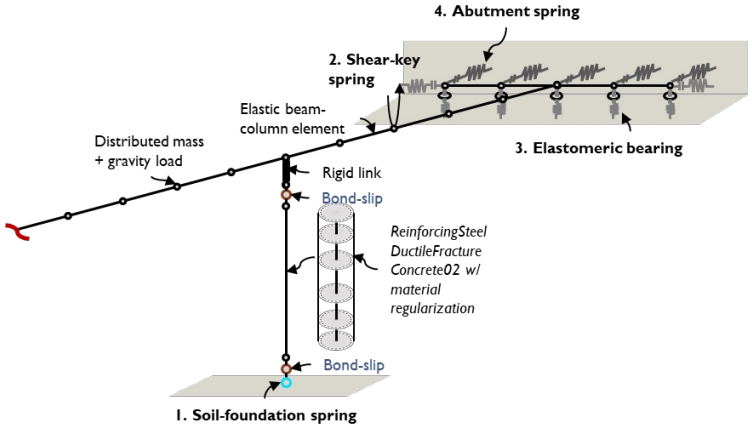
Probabilistic Learning on Manifolds (PLoM)

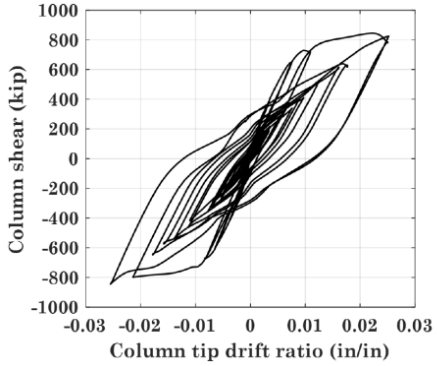
- Non-parametric
- Training its diffusion-map hyper-parameters (β, ε)
- Predict correlated samples directly
- Efficient for high-dimension correlated datasets

Simulation of RC Bridge Pier: EQ Duration Effects

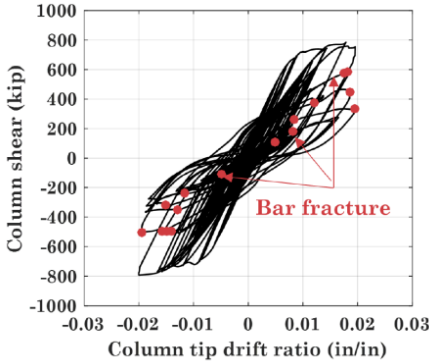








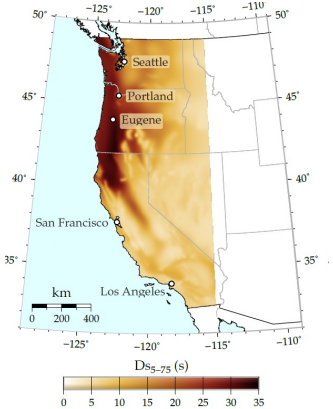
Short Duration



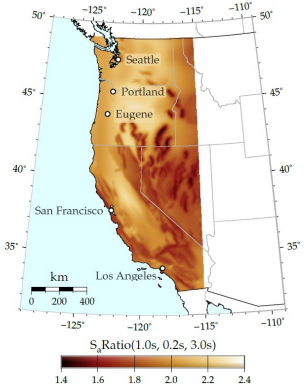
Long Duration

Zhong et al. (2023), "Accounting for Ground Motion Duration in Performance-Based Evaluation and Design of Bridge Columns". PEER Report

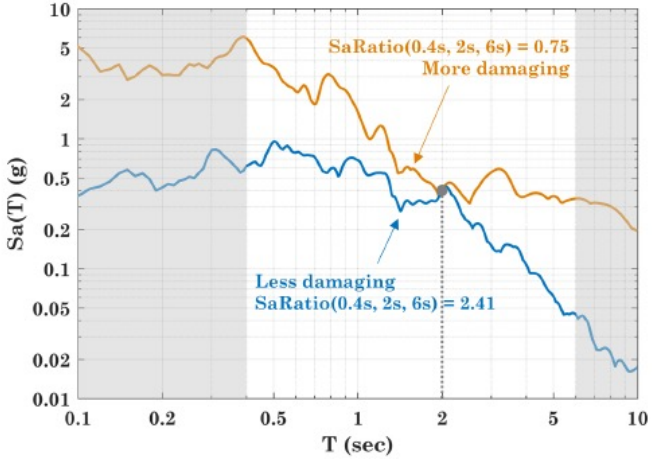
Site-specific Adjustment Framework for IDA

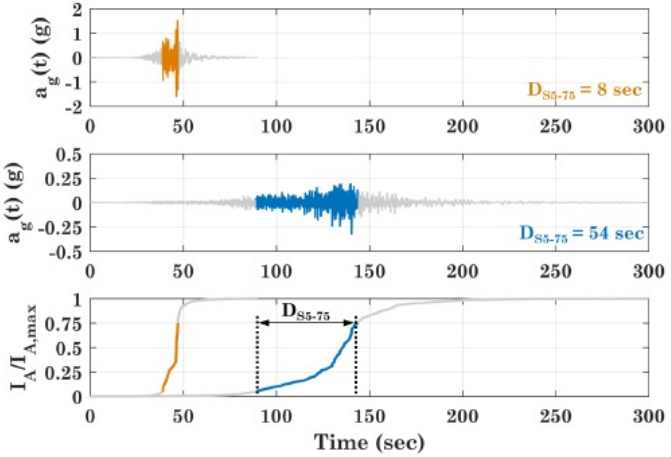


Significant Duration



Spectral Shape



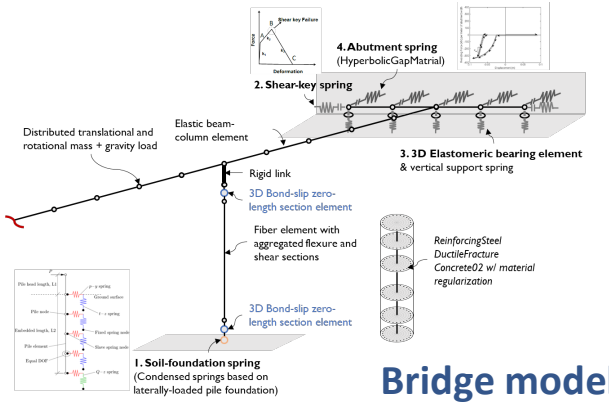


Adjust structural response from IDA to account for:

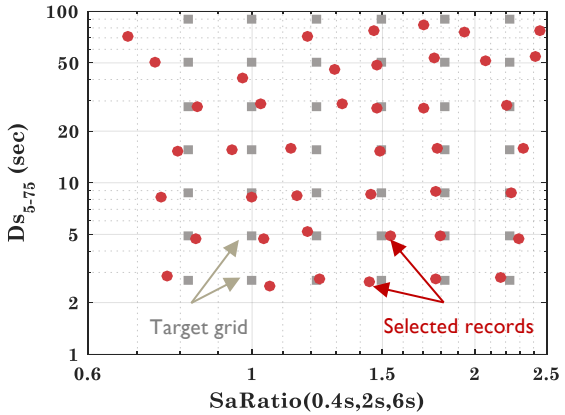
- Spectral Intensity, Sa(T1)
- Spectral Shape, SaRatio (T_S,T1,T_L)
- Significant Duration, D_{S5-75}

Zhong, K., Chandramohan, R., Baker, J.W., Deierlein, G.G. (2021), "Site-Specific Adjustment Framework for Incremental Dynamic Analysis (SAF-IDA), *Earthquake Spectra*

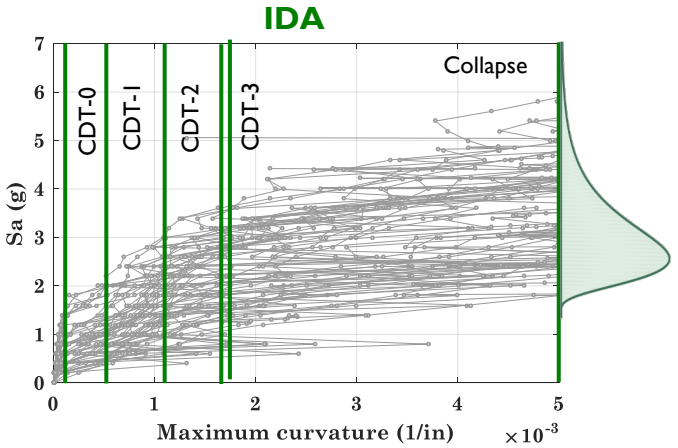
SAF-IDA: Ground Motions and Model Training Data



Bridge model



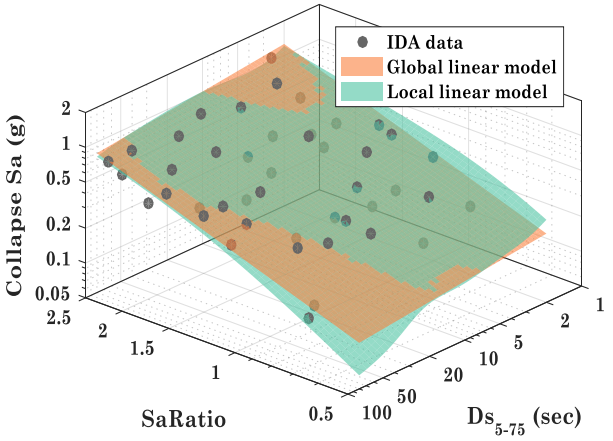
Grid (7x7) ground motion set



Using the statistics to develop limit-state fragility functions:

- CDT: curvature-based component damage thresholds (*Mangalathu, 2017*)
- First bar fracture
- 50% bars fracture
- **Collapse**

SAF-IDA: Collapse Capacity

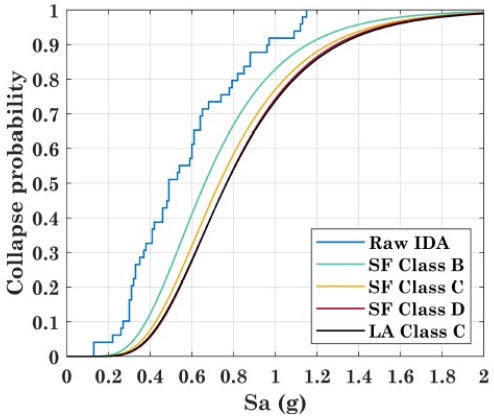


$$\ln\left(Sa_{collapse}\right) = 1.00 + 0.41\ln\left(SaRatio\right) - 0.13\ln\left(Ds_{5-75}\right) + \varepsilon$$

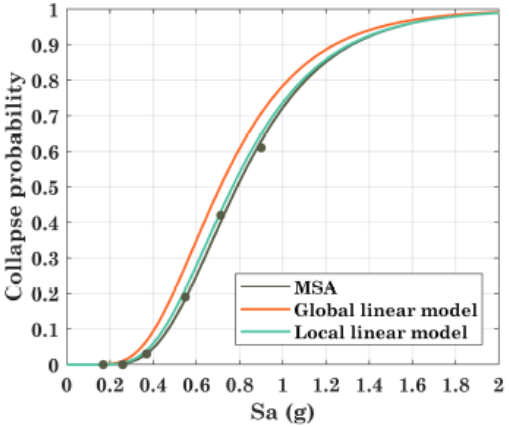
Median collapse capacity

GM parameters

Response Surface (log-linear)



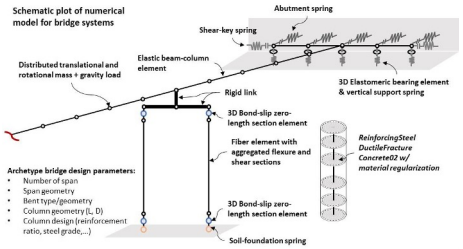
Raw & Adjusted Collapse



Validation w/Multi-Stripe Analysis (MSA)

Bridge Surrogate Models - PLoM

① Concrete bridge modeles

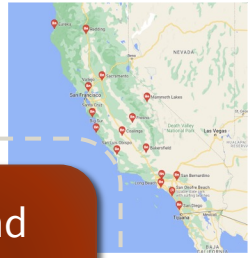


③ IDA *training data*

PLoM

② Site deaggregation

Ground motion selection



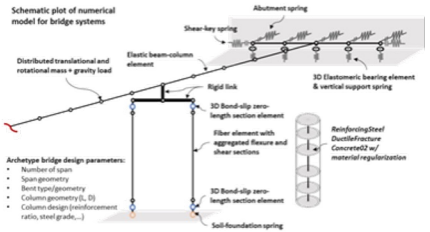
④ Multi-Stripe Analysis (MSA) *validation data*

Validate surrogate

⑤ Regional Analyses

PLoM: IDA Training Parameters and Data

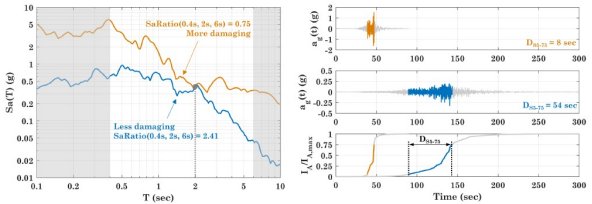
Structural Design & Modeling Parameters (X_S)



Model Parameters:
- Pier Slenderness (L/D)
- Axial Load Ratio (P/Po)
- Reinf. Ratio (As/Ag)
- Steel Fy

X_S

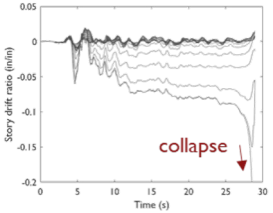
Site Specific Ground Motion Characteristics (X_{GM})



GM Parameters:
- Sa(T1)
- SaRatio
- Duration, $Ds_{5\text{-}75}$

X_{GM}

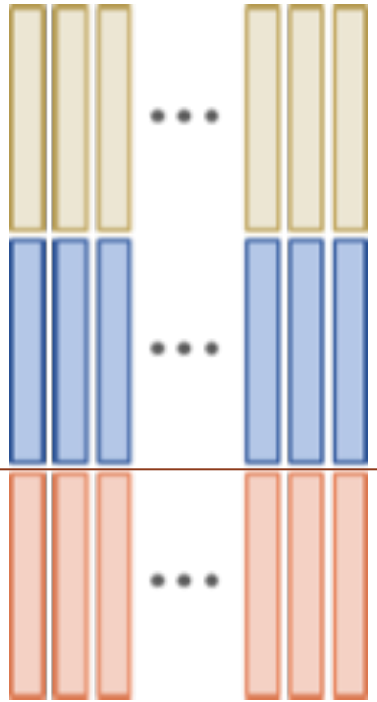
Structural Response & Damage Quantities (X_R)



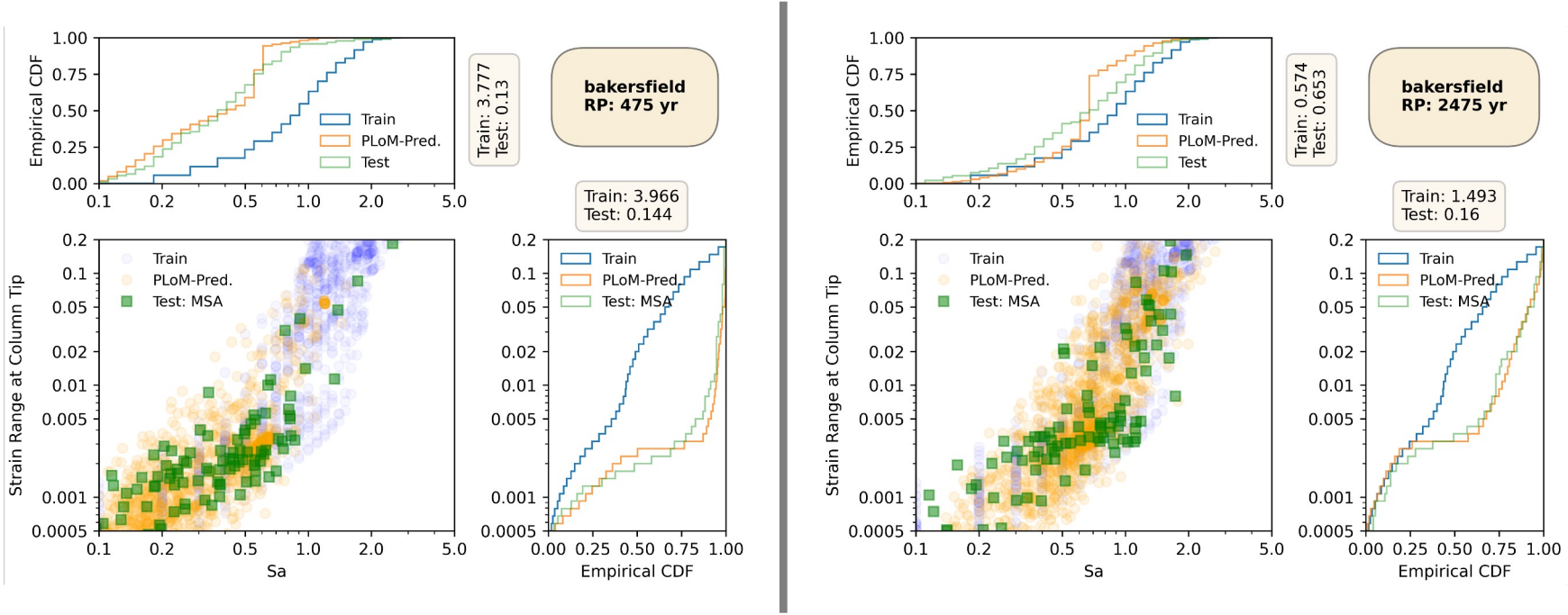
Response Quantities:
- Curvature (top/bot)
- Strain Range (top/bot)
- Fracture Index (top/bot)
- *Collapse*

X_R

# of IDA Simulations
(600 x ~20 = ~12,000)



Bridge Surrogate (PLoM) – Illustrative Results



Strain range at column tip vs. Sa

Calculated at Bakersfield SITE for TWO return periods (Sa, SaRatio, and Duration)

PLoM - Training/Calibration and Prediction

Train Data

1. Identify Input and Response Parameters (13 = $4X_S + 3X_{GM} + 6X_R$)
2. Grid Ground Motions (7x7)
3. Perform IDA (600 IDA realizations, n ~12,000 analyses)

PLoM Response Predictions

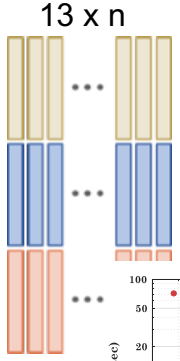
1. Constrain input variables (mean, sigma; 6 = $4X_S + 3X_{GM}$)
2. Run PLoM (***hyperparameters***, control parameters)

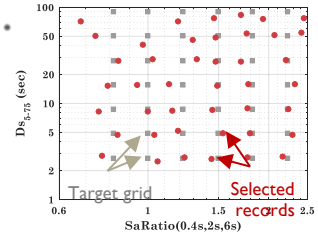
Calibrate PLoM Hyperparameters (β, ε)

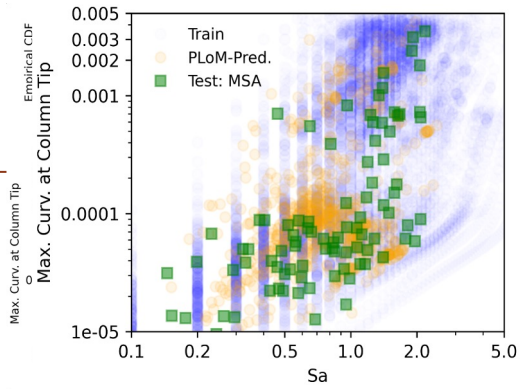
1. Assemble test data (selected set of MSA data)
2. Assume ***hyperparameters*** ***repeat / optimize***
3. Run PLoM and compare to test

Validation

1. Assemble validation data (comprehensive set of MSA data)
2. Run PLoM with calibrated hyperparameters
3. Compare to validation data



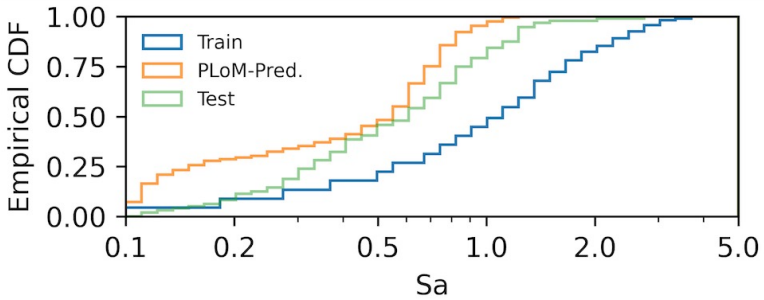




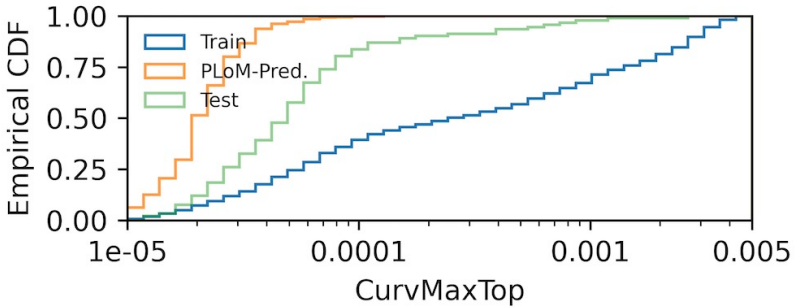
Importance of Hyperparameters

Poorly Fit Hyperparameters

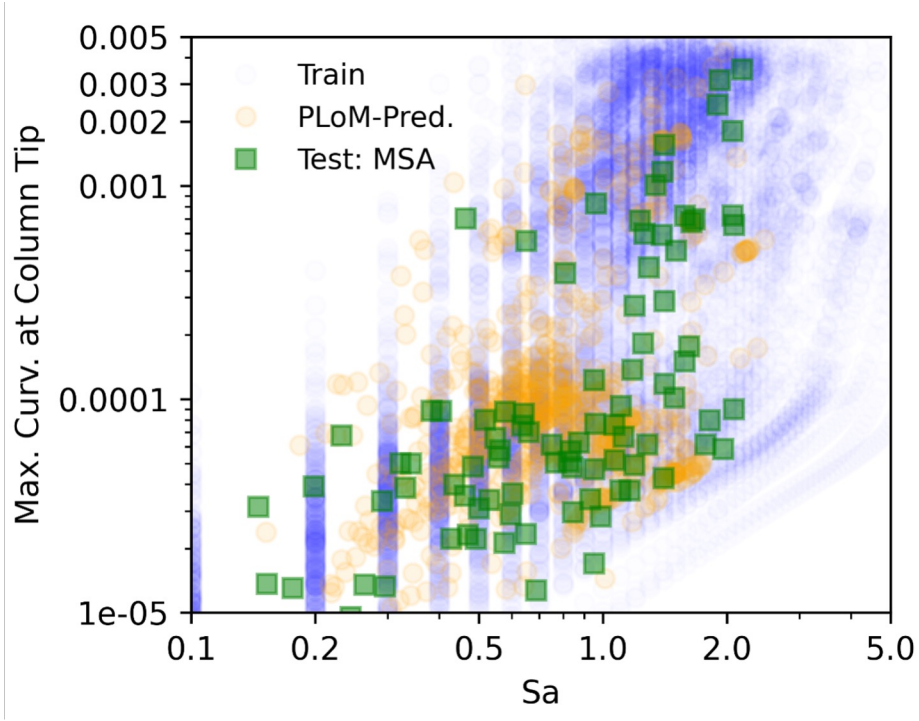
When hyperparameters are not tuned well, the input distributions do not match (example Sa):



When input distributions do not match well, the response distributions do not match well (example CurvMaxTop)



Optimized Hyperparameters



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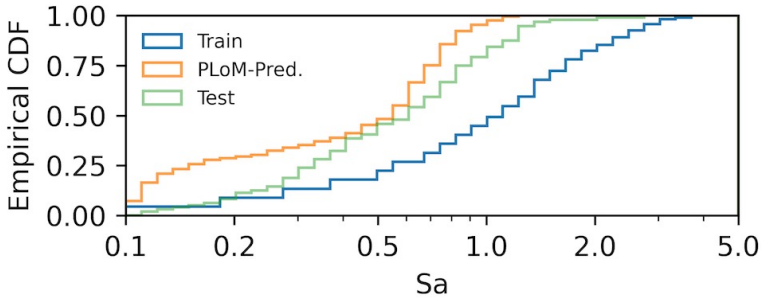
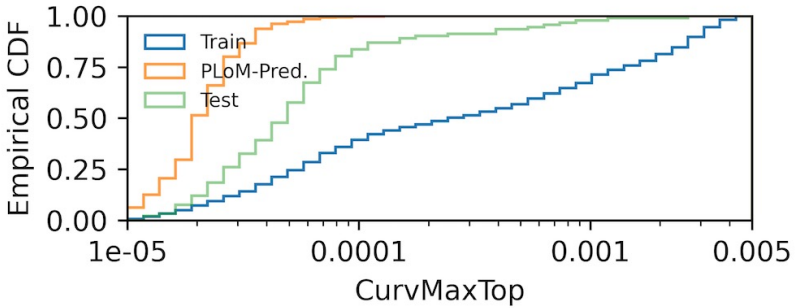
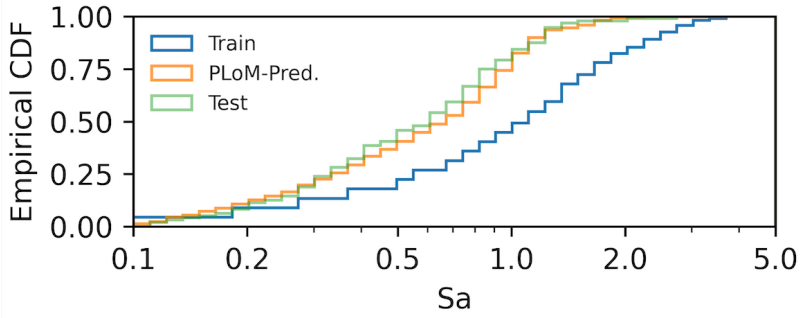


When input distributions do not match well, the response distributions do not match well (example CurvMaxTop)

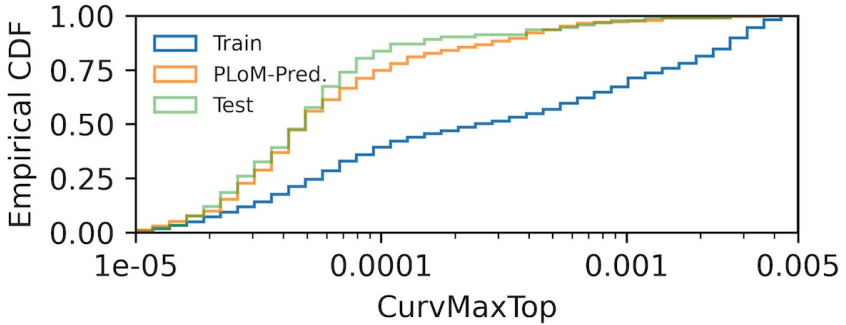


Optimized Hyperparameters

When hyperparameters are tuned well, the input distributions match (example Sa):



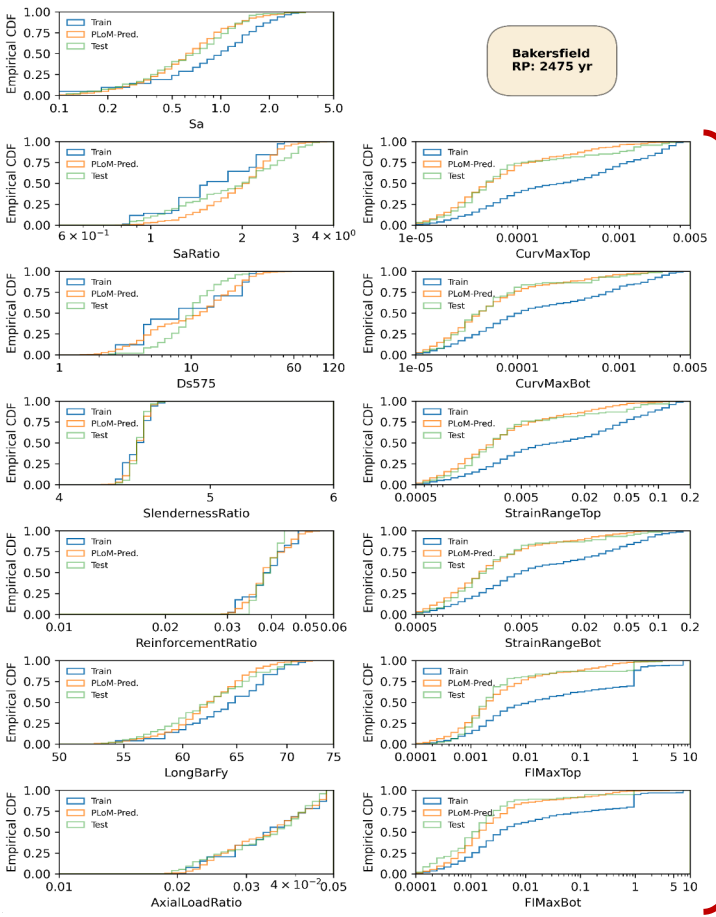
When input distributions match well, the response distributions match much better (example CurvMaxTop)



Validation Studies – Site & Bridge Specific Simulations

GM Parameters (X_{GM}):
- Sa(T1)
- SaRatio
- Duration, $Ds_{5\text{-}75}$

Model Parameters (X_S):
- Pier Slenderness (L/D)
- Axial Load Ratio (P/Po)
- Reinf. Ratio (As/Ag)
- Steel Fy



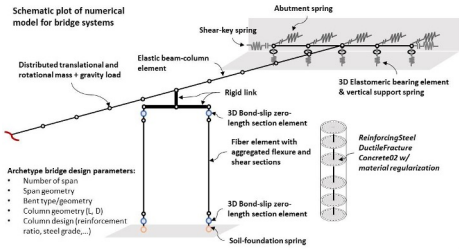
Response Quantities (X_R):
- Curvature (top/bot)
- Strain Range (top/bot)
- Fracture Index (top/bot)
- *Collapse*

Outline for Today

- **Overview of supporting SimCenter tools**
  - quoFEM, EE-UQ, R2D
- **Surrogate modeling of bridge performance (quoFEM, EE-UQ)**
  - Surrogate modelling methods: SAF-IDA, Gaussian Process, PLoM
  - Scope of design studies - archetype bridge models
  - Training and assessment of surrogate models
- **Regional simulation of bridges in highway network (R2D)**
  - Characterization of ground motion hazard
  - OpenSees vs Surrogate
- **Next Steps**

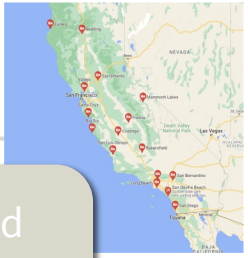
Bridge Surrogate Models - PLoM

① Concrete bridge modeler



② Site deaggregation

Ground motion selection



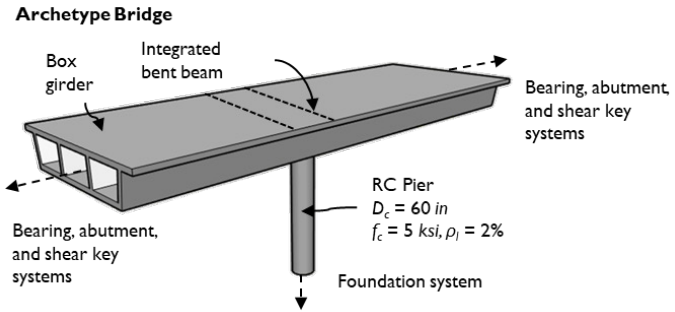
③ IDA Training set

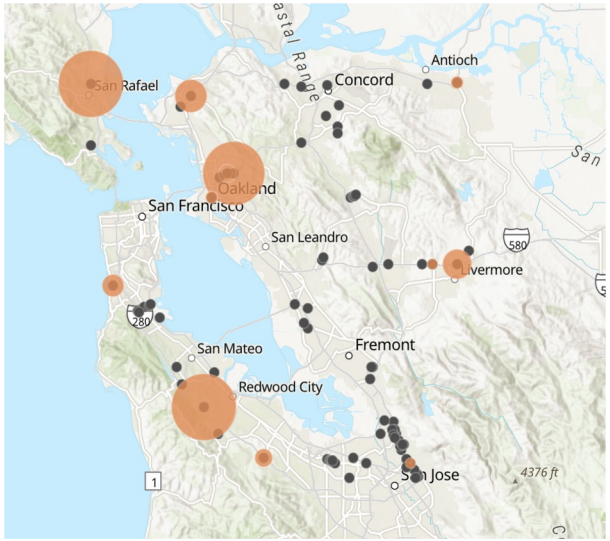
PLoM

④ MSA Test set

⑤ Regional Analyses

Trial Study – R2D





12 Bridges - from NBI database:

- Single Pier - 2 Span
- Built between 1970 and 1979
- Range of Vs_{30}

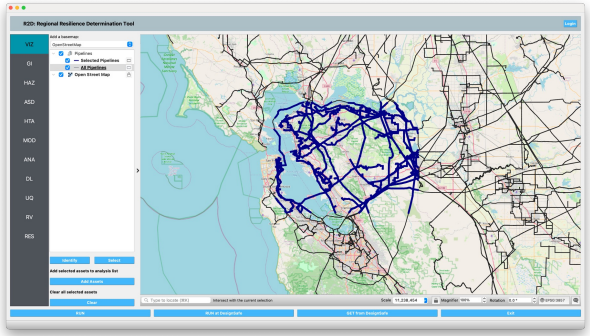
Haywired EQ Scenario:

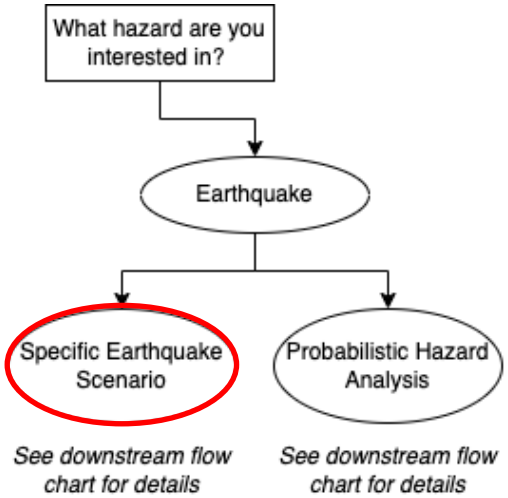
- M7, Hayward-Rodgers Creek

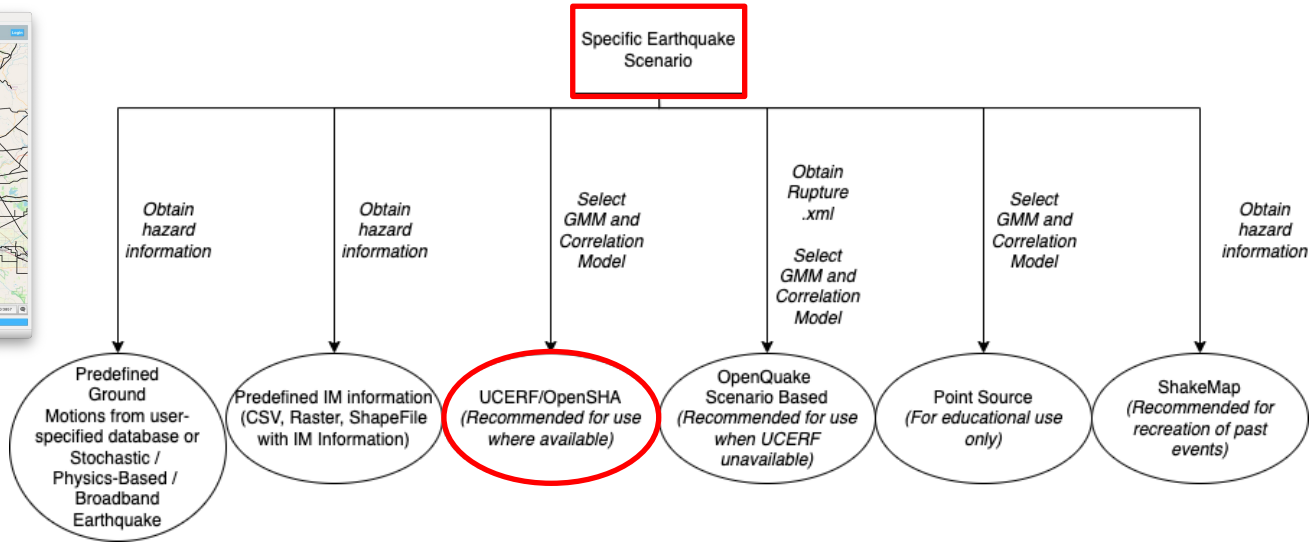
Response Simulations:

- OpenSees: NLRHA w/site specific GM's
- PLoM: site specific *Sa, SaRatio, Ds5-75*

R2D – Hazard Module



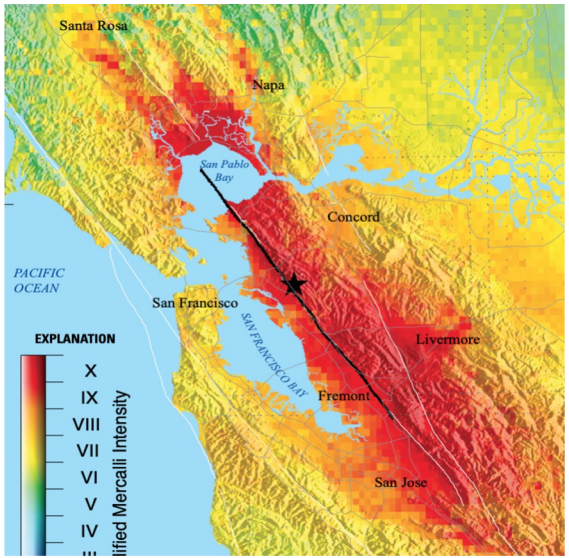




- EQ Scenario (one/more M,R realizations)
- Site Response Spectra (#realizations/scenario)
- Ground Motions (#GM/spectra realization)

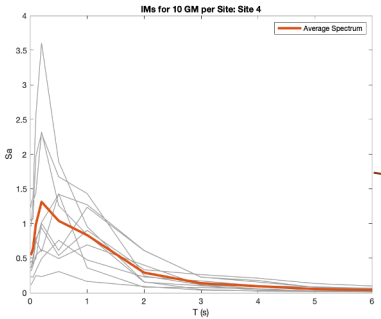
R2D - Earthquake Hazard Tool

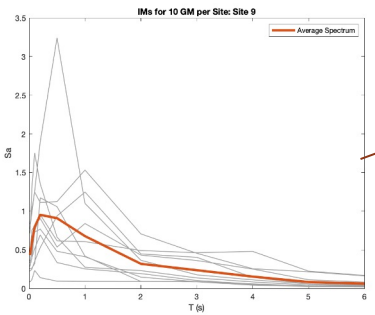
HayWired scenario was “Hayward-Rodgers Creek”

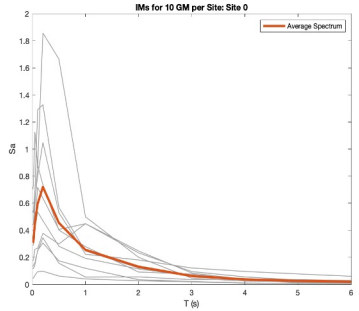


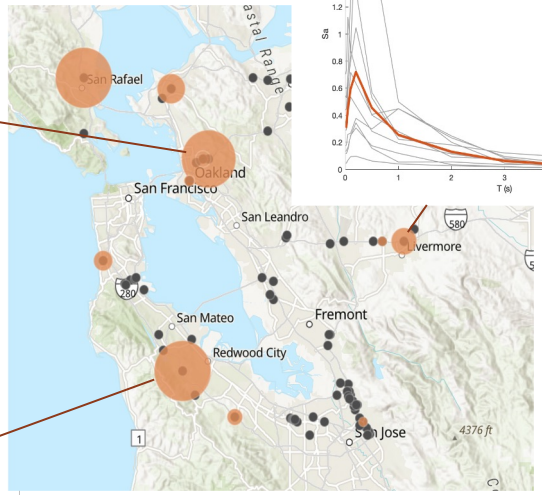
HN+HS in the UCERF2 catalogue

Magnitude 7.05 (Rupture 4, Source 28)







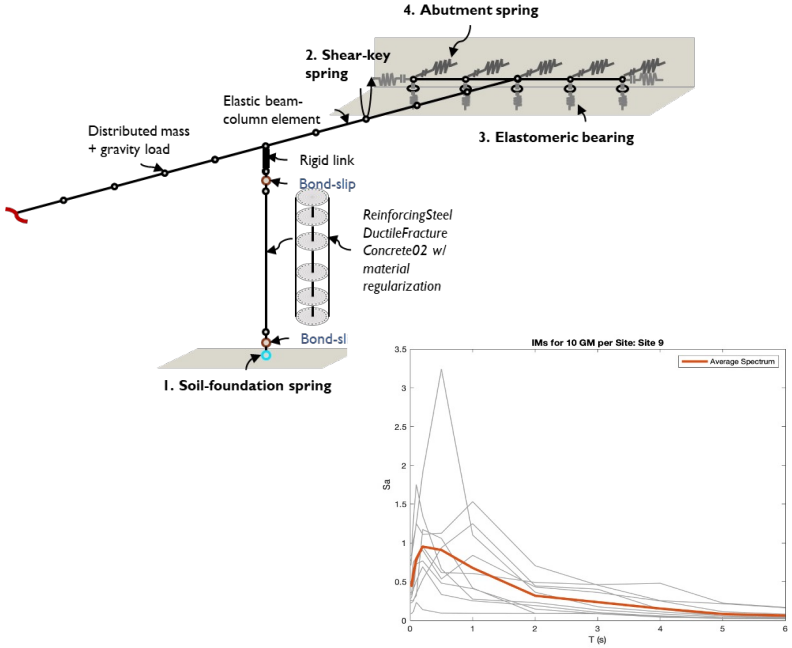


Ground Motion Spectra Realizations

Including correlations within and between EQ events

- *between periods (spectral shape)*
- *spatial between sites*

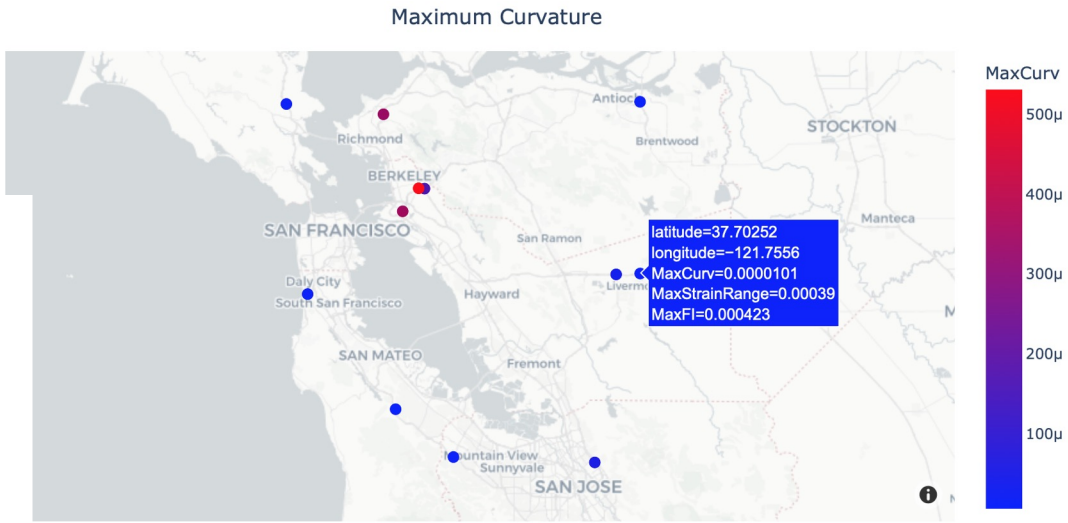
Trial Study – OpenSees Simulations



OpenSees NLRHA

X spectra realizations

Y ground motions/spectra



Bridge Response Data (Curvatures)

Summary and Next Steps

- In Progress
  - Training and validation of PLoM surrogate model (EE-UQ)
  - Integration of bridge models into regional analysis (R2D)
- Future – short to longer term
  - Seamless integration with bridge inventory data
  - Augment bridge inventory data (e.g., design features)
  - Exercise site/design specific OpenSees, SAF-IDA, PLoM, and GP(?)
  - Streamline surrogate modeling techniques and workflows
    - › *Researchers/Developers -- training/calibration of new models*
    - › *Application Users -- bridge models for transportation network analyses*