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Caltrans Risk-Based Seismic Design

Farzin Zareian

MLK Building, Pauley Ballroom, Berkeley, CA • August 24-25

2023 PEER Annual Meeting

UC BERKELEY • CALTECH • OSU • STANFORD • UC DAVIS • UC IRVINE • UCLA • UCSD • UNR • USC • UW

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ACKNOWLEDGEMENT

Performance-based seismic assessment of skewed bridges (PEER TSRP 2008, with UCLA)

Guidelines for Nonlinear Seismic Analysis of Ordinary Bridges: Version 2.0 (Caltrans 2011, with UCB and UCLA)

Guidelines for Ground Motion modeling for Performance-Based Earthquake Engineering of Ordinary Bridges (Caltrans 2017)

Probabilistic Damage Control Application: Implementation of Performance-Based Earthquake Engineering in Seismic Design of Highway Bridge Columns (Caltrans 2019)

Quantification of Variability in Performance Measures of Ordinary Bridges to Uncertainty in Seismic Loading Directionality and Its Implication in Engineering Practice. (PEER Lifelines 2012, with CSU-Chico)

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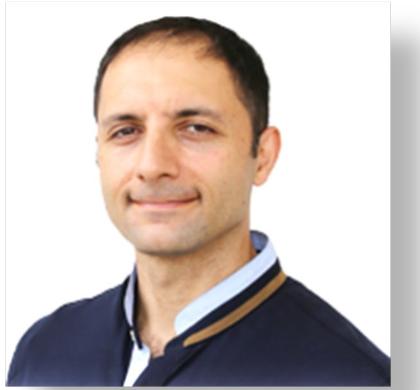
TEAM

Sharon Yen | Contract Manager

Prof. Saiid Saiidi and Prof. Norm Abrahamson | Project Advisory Board

Toorak Zokaie, Tony Yoon, Mark Mahan, Amir Malek, Sam Ataya, Christian Unanwa | PDCA Team



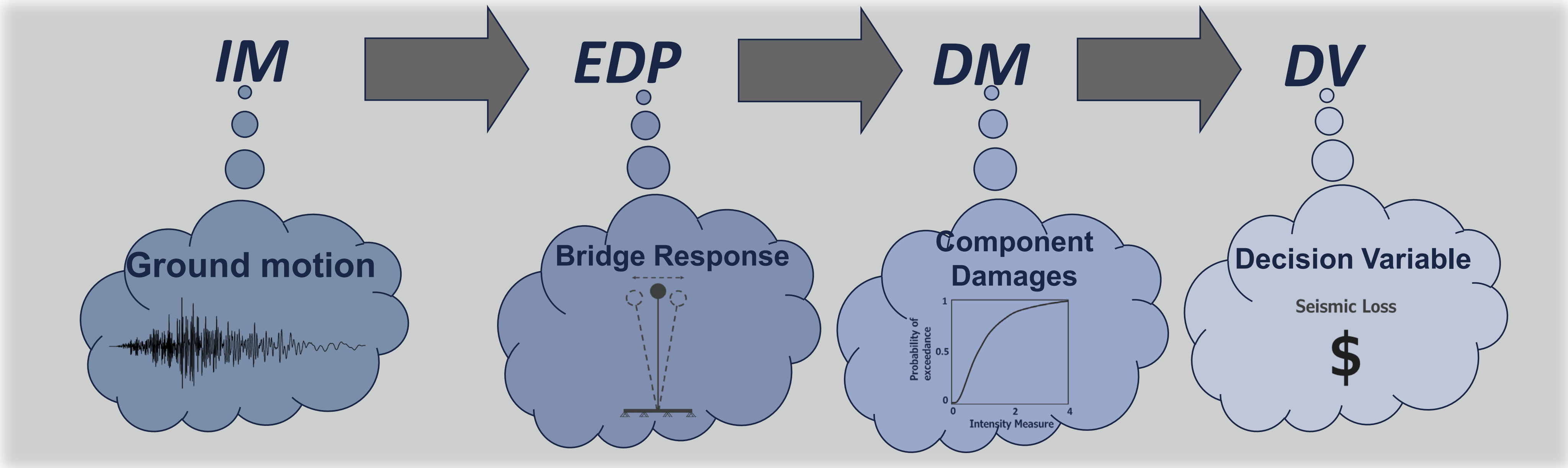
Farzin Zareian
Principal Investigator

Saurabh Singhal
Graduate Student Investigator

Vision

A data-driven framework for performance-based assessment and design of bridges in California where:

- ‼ Design captures variability in demand and capacity (location, sizing, etc.)
- ‼ The designer puts in minimal computational effort for analysis, i.e., NO need for NTHA



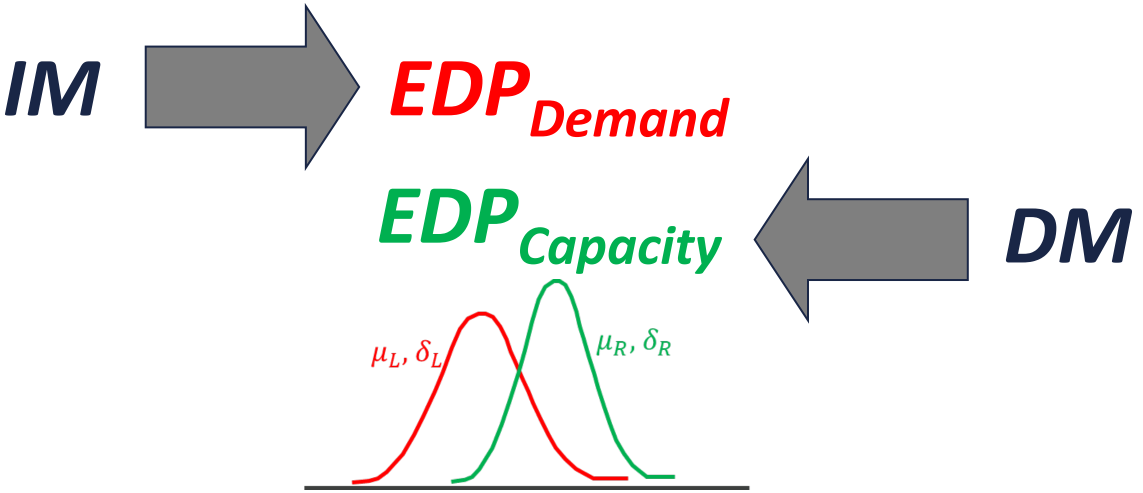
Solution

Caltrans Risk-Based Seismic Design

Probabilistic Damage Control Application: Implementation of Performance-Based Earthquake Engineering in Seismic Design of Highway Bridge Columns

Yeo Hoon Yoon, P.E.[1]; Sam Ataya, P.E.[2]; Mark Mahan, Ph.D., P.E., M.ASCE[3]; Amir Malek, Ph.D., P.E.[4]; M. Saiid Saiidi, Ph.D., P.E., F.ASCE[5]; and Toorak Zokaie, Ph.D., P.E., M.ASCE[6]

Seismic Demand vs. Seismic Capacity



$$\beta_i = \frac{ln\left(\frac{\mu_{Ri}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{Ri}^2+1}}\right)}{\sqrt{ln\left[(\delta_L^2+1)(\delta_{Ri}^2+1)\right]}}$$

Probability of exceedence

$$p_{fail} = 1 - \emptyset(\beta_i)$$

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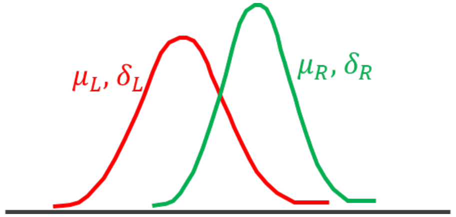
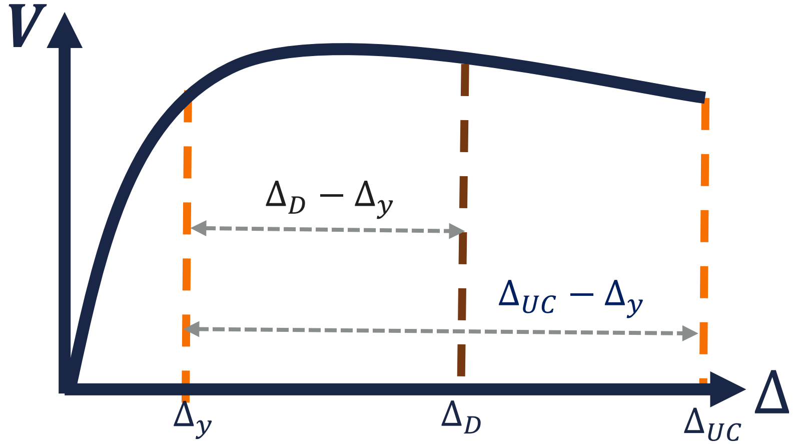
IM → **DI_L**

DI_R ← **DM**



Damage Index

$$DI = \frac{\Delta_D - \Delta_y}{\Delta_{UC} - \Delta_y}$$



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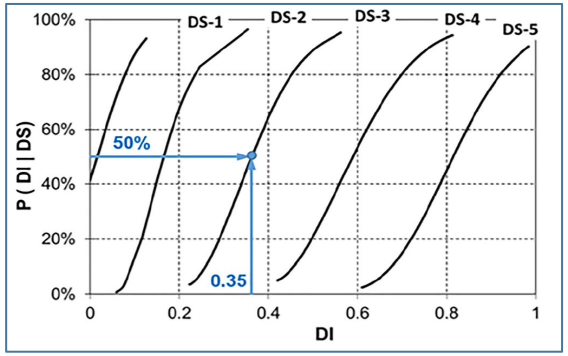
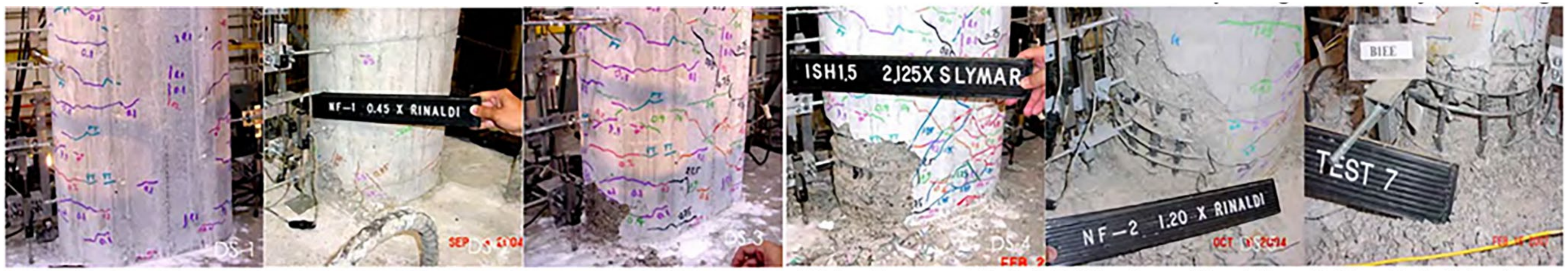
DI_R





DS1 – Surface Crack DS2 – First Spalling DS3 – Major Spalling DS4 – Exposed Reinf DS5 – Core Shedding DS6 – Reinf Rupture

Vosooghi, A., and M. Saiidi. 2010. Post-earthquake evaluation and emergency repair of damaged RC bridge columns using CFRP materials. CA Dept. of Transportation Research Rep. No. 59A0543. Reno, NV: Univ. of Nevada

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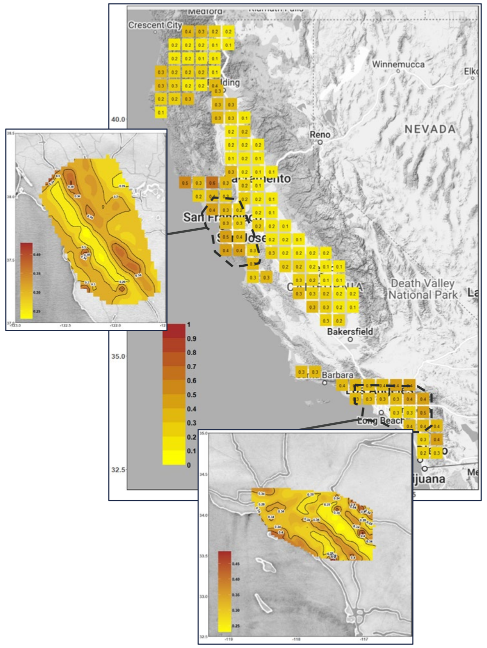
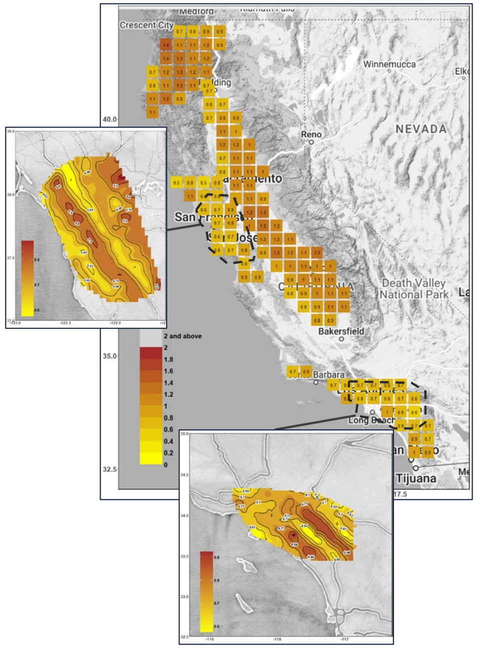


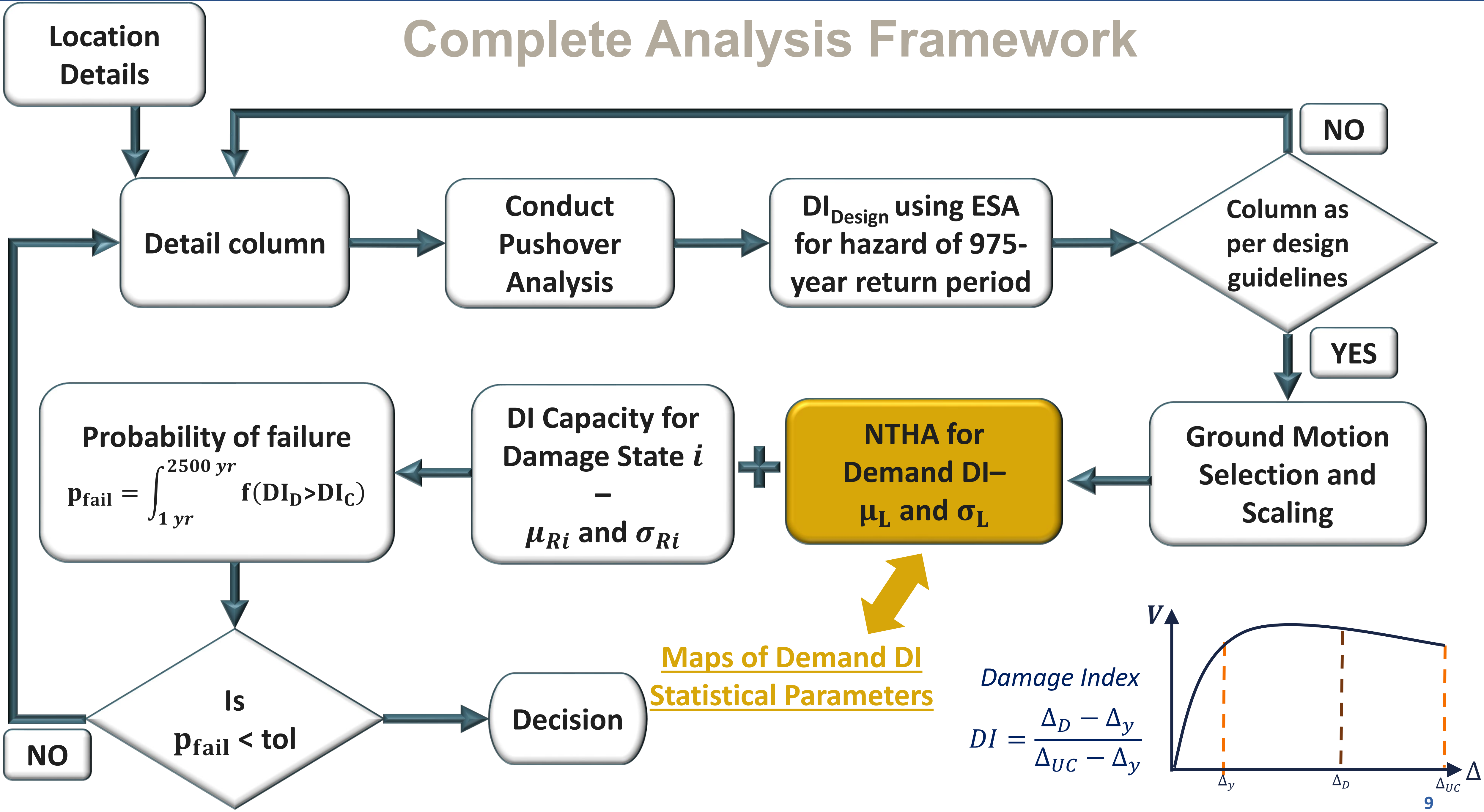
DI_L

Maps for μ_L, δ_L

???



Complete Analysis Framework



Do simulated and scaled GMs have secondary Intensity Measures (IM) that follow peer-reviewed models?

PGV	Abrahamson, N. and S. Bhasin (2020). "Conditional Ground-Motion Model for Peak Ground Velocity for Active Crustal Regions", Pacific Earthquake Engineering Research Center, October 2020, PEER report No. 2020/05.
AI	Abrahamson, C., M. Shi, and B. Yang (2016). Ground-motion prediction equations for Arias Intensity consistent with the NGA-West2 ground-motion models, PEER Rept. 2016/05
Duration	Abrahamson and Silva (1996). Description and validation of the stochastic ground motion model, Pacific Engineering and Analysis Report, Nov 1996
CAV	Macedo, Abarahamson, and Liu (2020). New Scenario-Based Cumulative Absolute Velocity Models for Shallow Crustal Tectonic Settings, BSSA (2021) 111 (1): 157–172

IM distribution from Model vs. IM distribution of GMs

Method to Obtain Secondary IM distributions

Secondary IM	Primary IM	Conditioning IM
CAV	PGA	$Sa(T_1)$
AI	PGA, Sa(1 sec)	$Sa(T_1)$
PGV	$Sa(T_{pgv})$	$Sa(T_1)$
D_{5-75}	PGA	$Sa(T_1)$
D_{5-95}	PGA	$Sa(T_1)$

*Lin, Ting, Stephen C. Harmsen, Jack W. Baker, and Nicolas Luco. "Conditional spectrum computation incorporating multiple causal earthquakes and ground-motion prediction models." *Bulletin of the Seismological Society of America* 103, no. 2A (2013): 1103-1116.

Scaling is done as per $Sa(T_1)$ (Conditioning IM)

↓

Primary IM conditioned on $Sa(T_1)$ using Conditional Spectrum*

↓

Distribution of the Secondary IM using models

- ❑ Preliminary analysis suggested that PGV is the only significant Secondary IM
- ❑ Use GMs with –
  - Mean PGV within 25%-75% confidence interval of model mean PGV
  - All PGV values fall between 5%-95% confidence interval

Ground Motion Simulation and Scaling

Razaeian et al. (2012) and Dabaghi et al. (2018)

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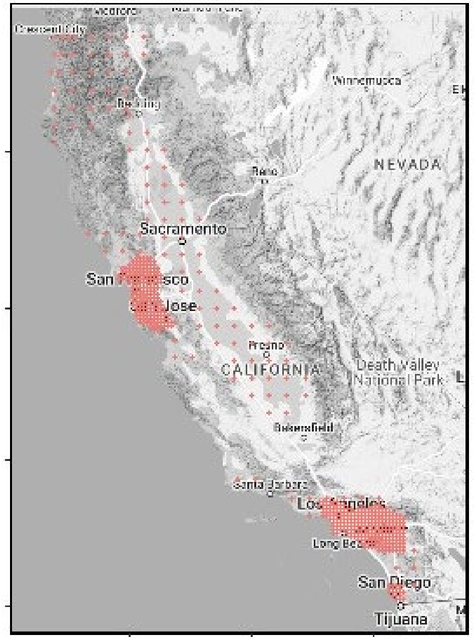
Data and Models

Site Class

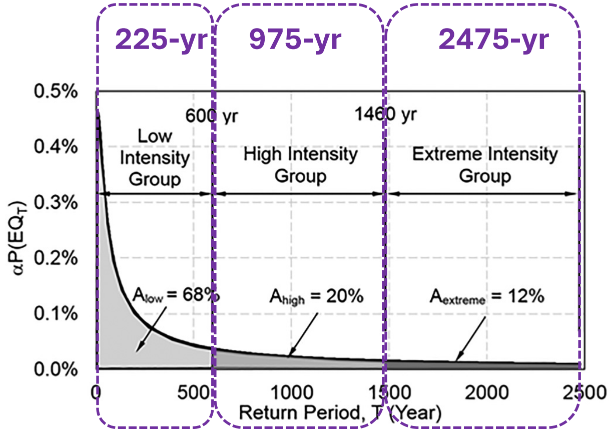
V_{S30} = 259 m/s (Site Class D)
V_{S30} = 537 m/s (Site Class C)



Bridge Column Geometric Parameters

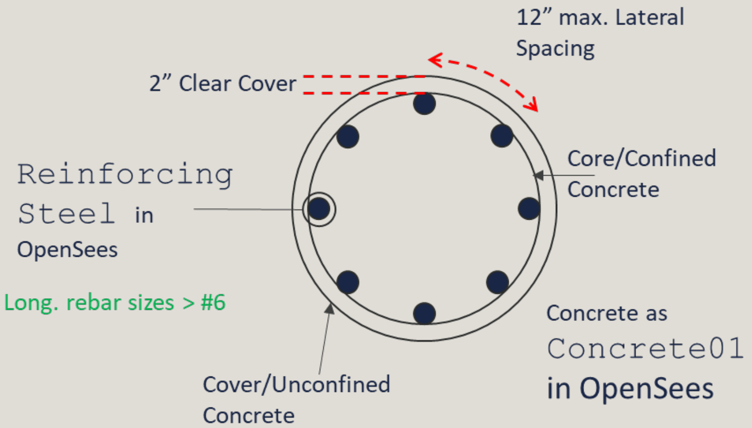
Parameter	Cases
Column Height (ft)	20, 30, 40, 50
Axial Force	$0.05f'_cA_g$, $0.10f'_cA_g$, $0.15f'_cA_g$
Long. Reinf. Ratio (%)	1.0, 1.75, 2.5
Diameter (ft)	5, 6, 7, 8
Hoop Rebar Sizes	#5, #6, #7, #8
Hoop Spacings (in)	3,4,5,6,7,8

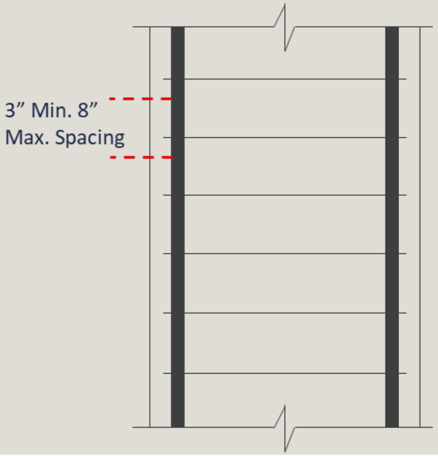
3 Representative Hazard Levels



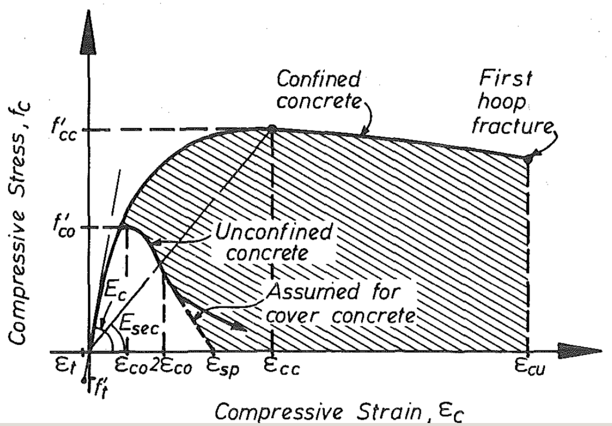
Bridge Column Model

All column designs with $DI_{ESA|975}$ between 0.2 and 0.4 were used for NTHA





Expected Unconfined Concrete Strength	5 ksi
Unconfined concrete compressive strain	0.005
Ultimate unconfined compressive strain	0.002
Expected Rebar Yield Strength	68 ksi
Expected Rebar Yield Strain	0.0023
Hoop Ultimate Tensile Strain of Steel, PDCA	0.18



***For generated hoop arrangement, confined concrete properties were estimated as per Mander's Model (1988)*

Data and Models

Site Class

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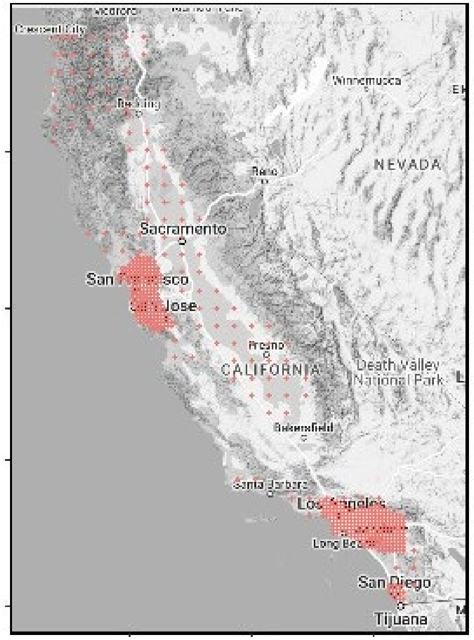
V_{S30} = 537 m/s (Site Class C)



Bridge Column Geometric Parameters

Parameter	Cases
Column Height (ft)	20, 30, 40, 50
Axial Force	$0.05f'_cA_g$, $0.10f'_cA_g$, $0.15f'_cA_g$
Long. Reinf. Ratio (%)	1.0, 1.75, 2.5
Diameter (ft)	5, 6, 7, 8
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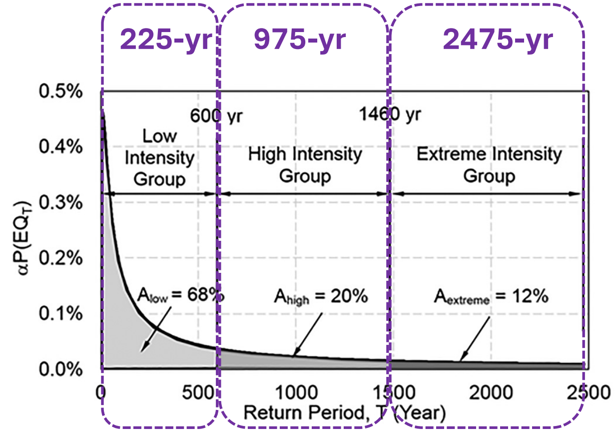
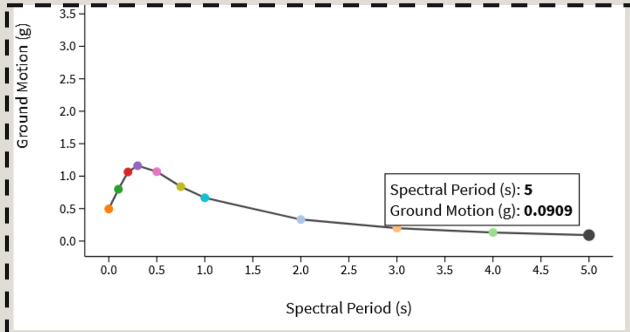
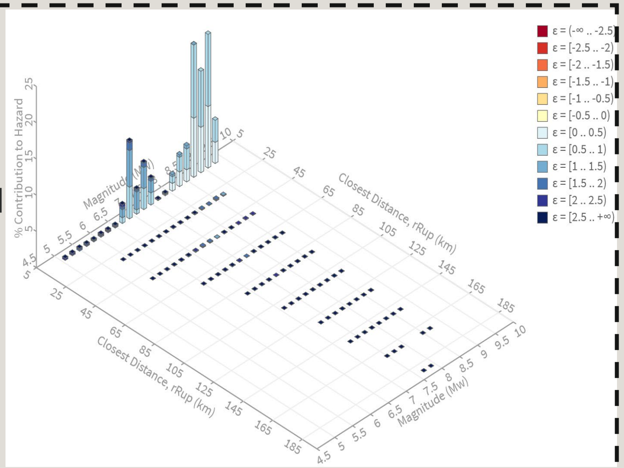
3 Representative Hazard Levels



Ground Motion Model

Site Class + **Hazard Level**





✓ *Uniform Hazard Curve and Hazard Deaggregation from USGS Unified Hazard Tool*

✓ *Range scaling between $T_n \pm 1$ sec (T_n = Natural Period of bridge) used for GM scaling*

51 Ground Motions

✓ *GM simulation algorithm by Razaeian et al. (2012) and Dabaghi et al. (2018)*

Post-Processing of Damage Indices

From NTHA → $DI = \{di_1, di_2, di_3, \ldots\ldots, di_n\}$ → **Post-Processing** **Why?**

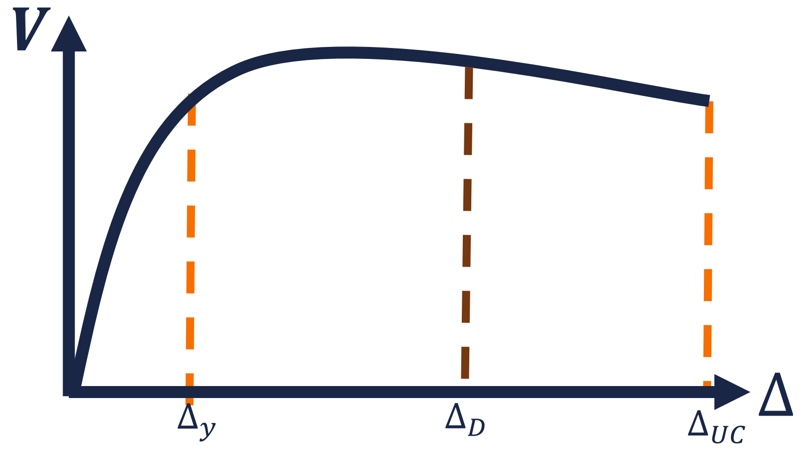
DI < 0 →
Demand less than Yield →
No Damage →
DI = 0

DI > 1 →
Demand more than Capacity →
Collapse →
DI = 1

DI is assumed to be lognormally distributed

Damage Index

$$DI = \frac{\Delta_D - \Delta_y}{\Delta_{UC} - \Delta_y}$$



Post-Processing of Damage Indices

From NTHA → $DI = \{di_1, di_2, di_3, \ldots\ldots, di_n\}$ → **Post-Processing**

No Clubbing

No post-processing of DI values from NTHA

$$\mu_L = mean(DI)$$
$$\sigma_L = std(DI)$$
$$\delta_L = \mu_L/\sigma_L$$

$$\beta_i = \frac{ln\left(\frac{\mu_{Ri}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{Ri}^2+1}}\right)}{\sqrt{ln[(\delta_L^2+1)(\delta_{Ri}^2+1)]}}$$

$$Pf = 1 - \emptyset(\beta_i)$$

Half Clubbing

DI > 1 is clubbed to 1

$$\mu_L = mean(DI)$$
$$\sigma_L = std(DI)$$
$$\delta_L = \mu_L/\sigma_L$$

$$\beta_i = \frac{ln\left(\frac{\mu_{Ri}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{Ri}^2+1}}\right)}{\sqrt{ln[(\delta_L^2+1)(\delta_{Ri}^2+1)]}}$$

$$Pf = 1 - \emptyset(\beta_i)$$

Clubbing

DI < 0 is clubbed to 0,
DI > 1 is clubbed to 1

$$\mu_L = mean(DI)$$
$$\sigma_L = std(DI)$$
$$\delta_L = \mu_L/\sigma_L$$

$$\beta_i = \frac{ln\left(\frac{\mu_{Ri}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{Ri}^2+1}}\right)}{\sqrt{ln[(\delta_L^2+1)(\delta_{Ri}^2+1)]}}$$

$$Pf = 1 - \emptyset(\beta_i)$$

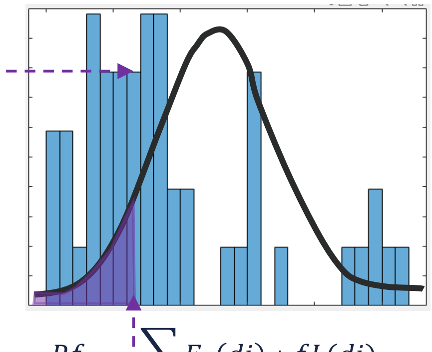
Numerical Integration Method

Tri-Part Probability of Failure Estimation

Part I : For values less than 0

$$P_1 = \frac{Number\ of\ values\ in\ DI\ less\ than\ 0}{n}$$

Part II : For values between 0 and 1



$$Pf_2 = \sum_{DI} F_R(di) * fL(di)$$

Capacity (Saiidi et al.) — Demand (Histogram)

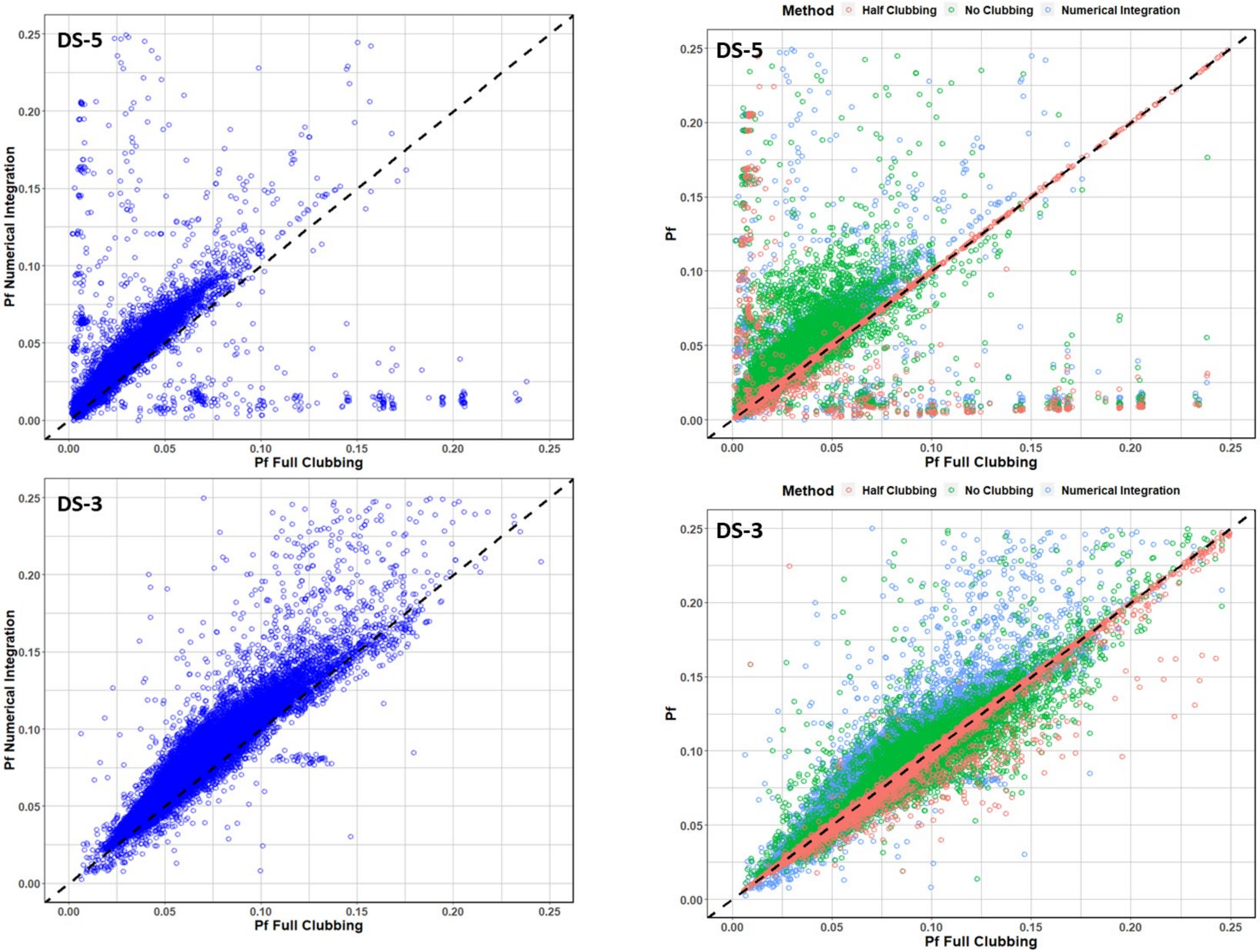
Part III : For values more than 1

$$P_3 = \frac{Number\ of\ values\ in\ DI\ more\ than\ 1}{n}$$

Probability of Failure

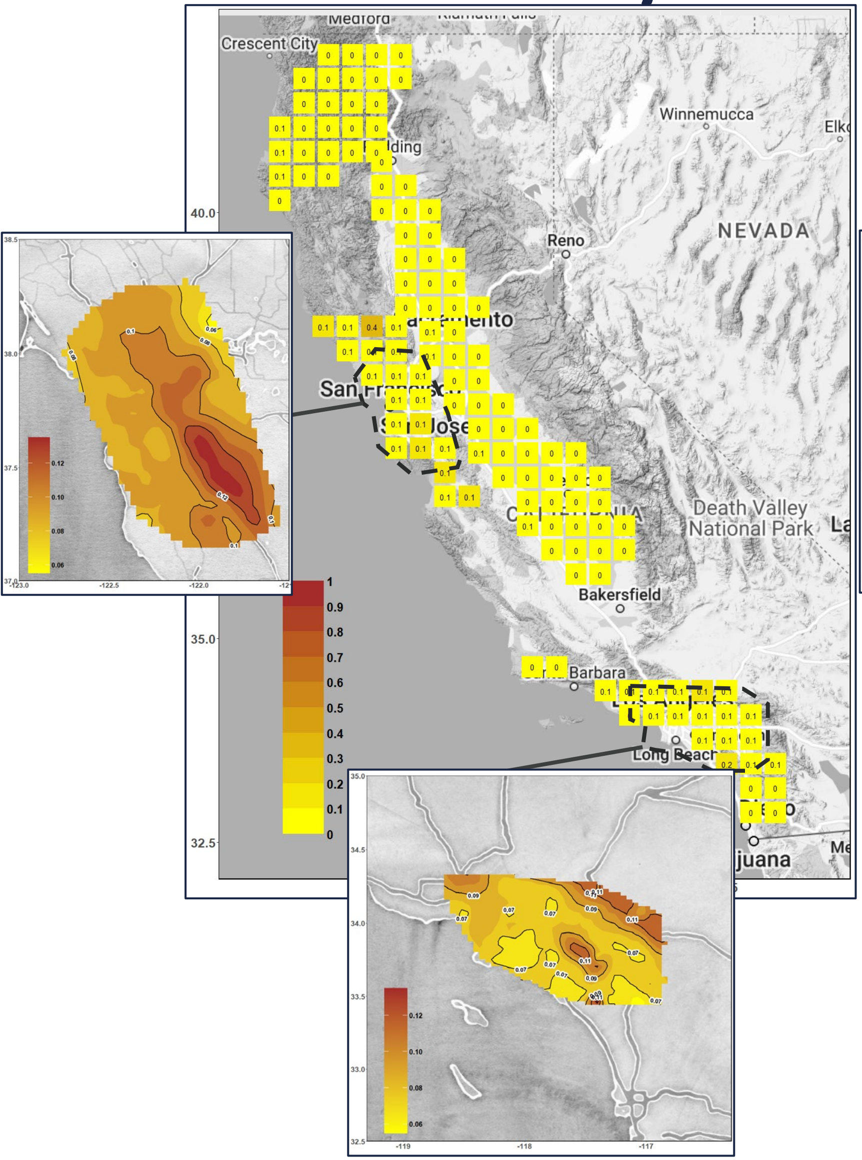
$$\boldsymbol{Pf = P_1 * 0 + (1 - P_1 - P_3) * Pf_2 + P_3 * 1}$$

Probability of Exceeding DM in 75 years

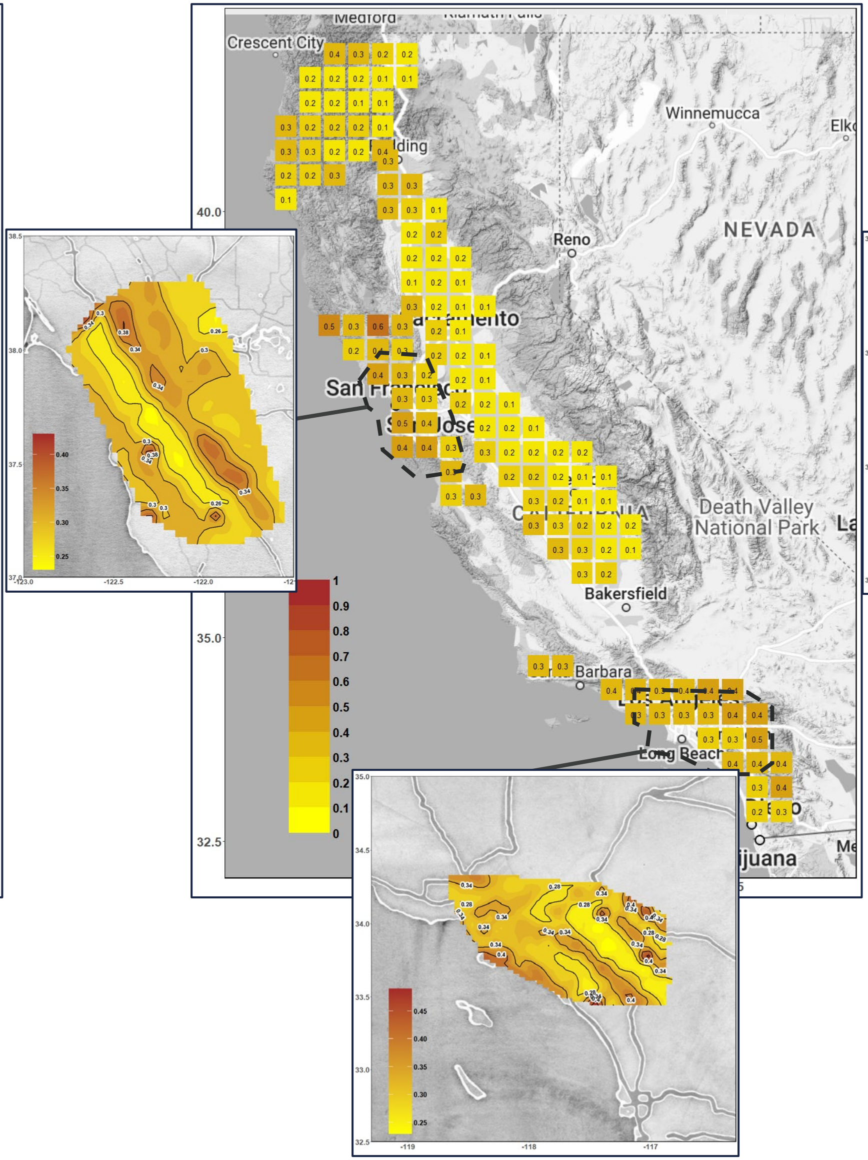


UCI Mean$_L$ Maps for V_{S30} = 259 m/s

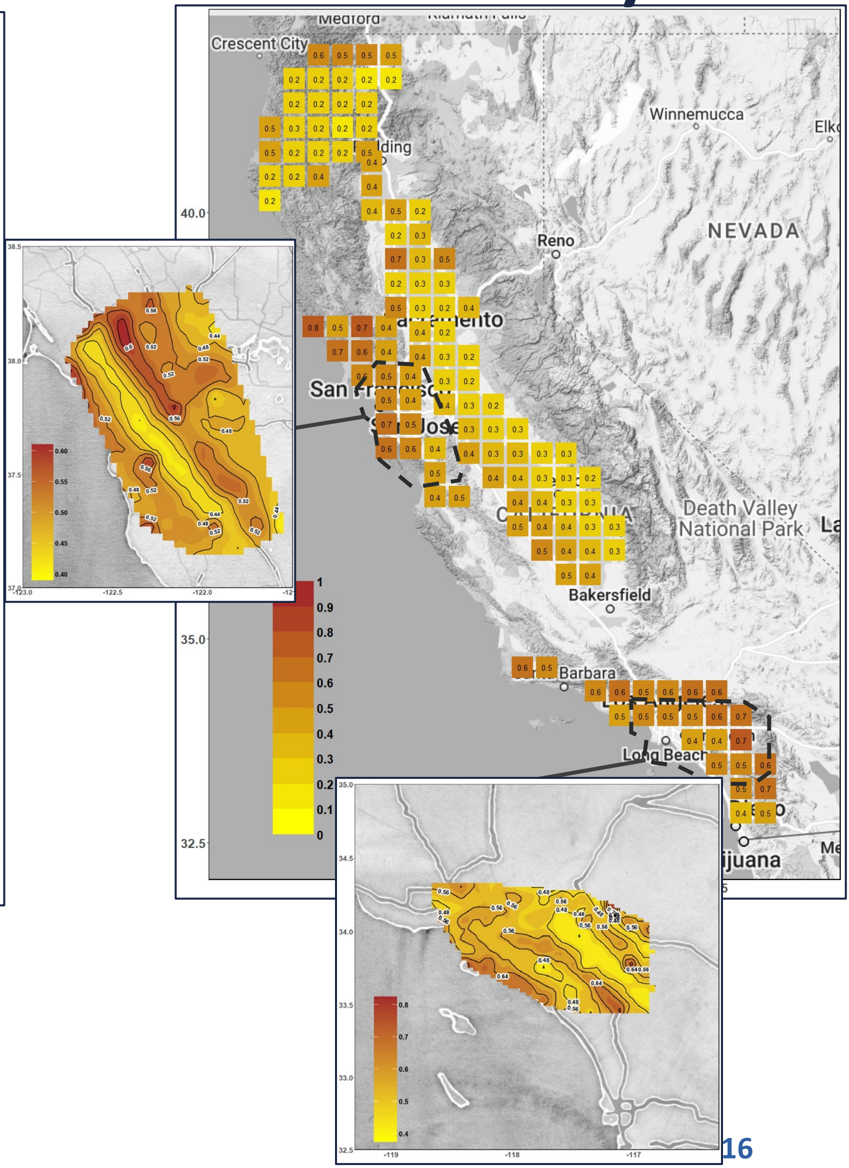
225-yr



975-yr

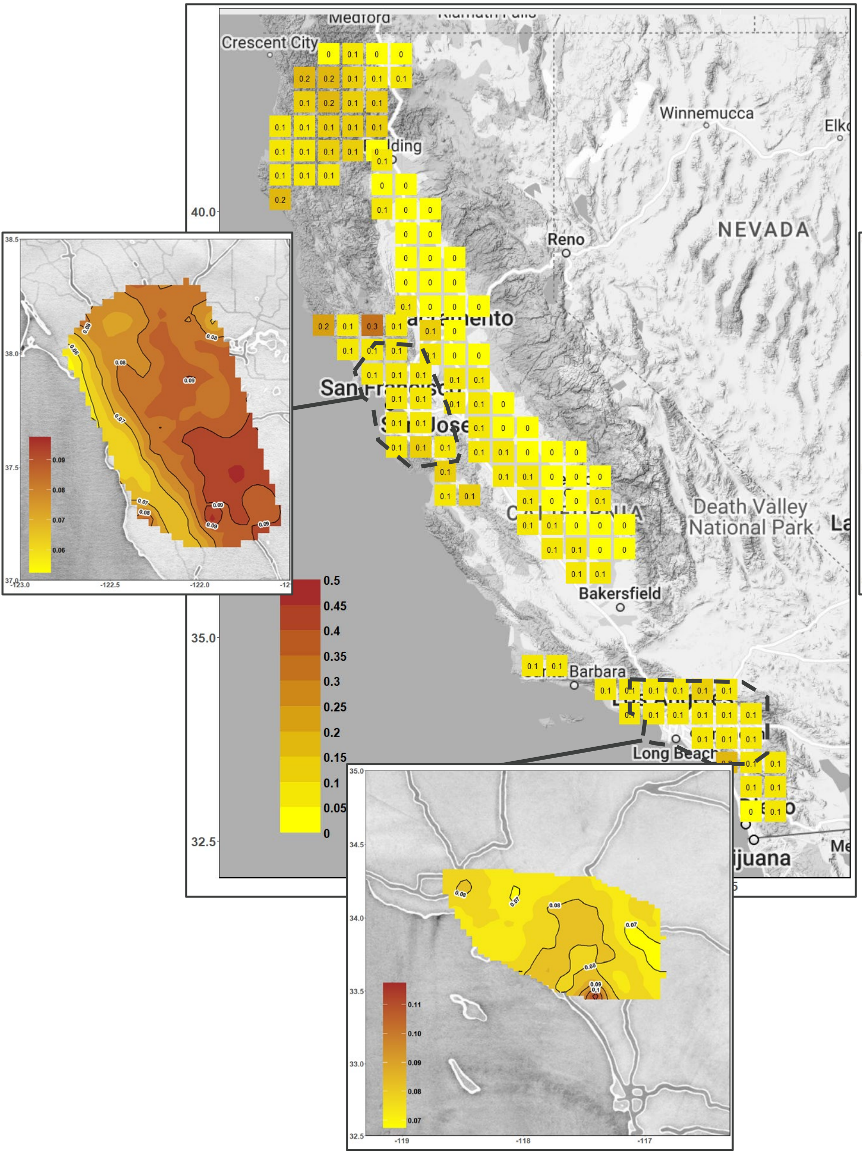


2475-yr

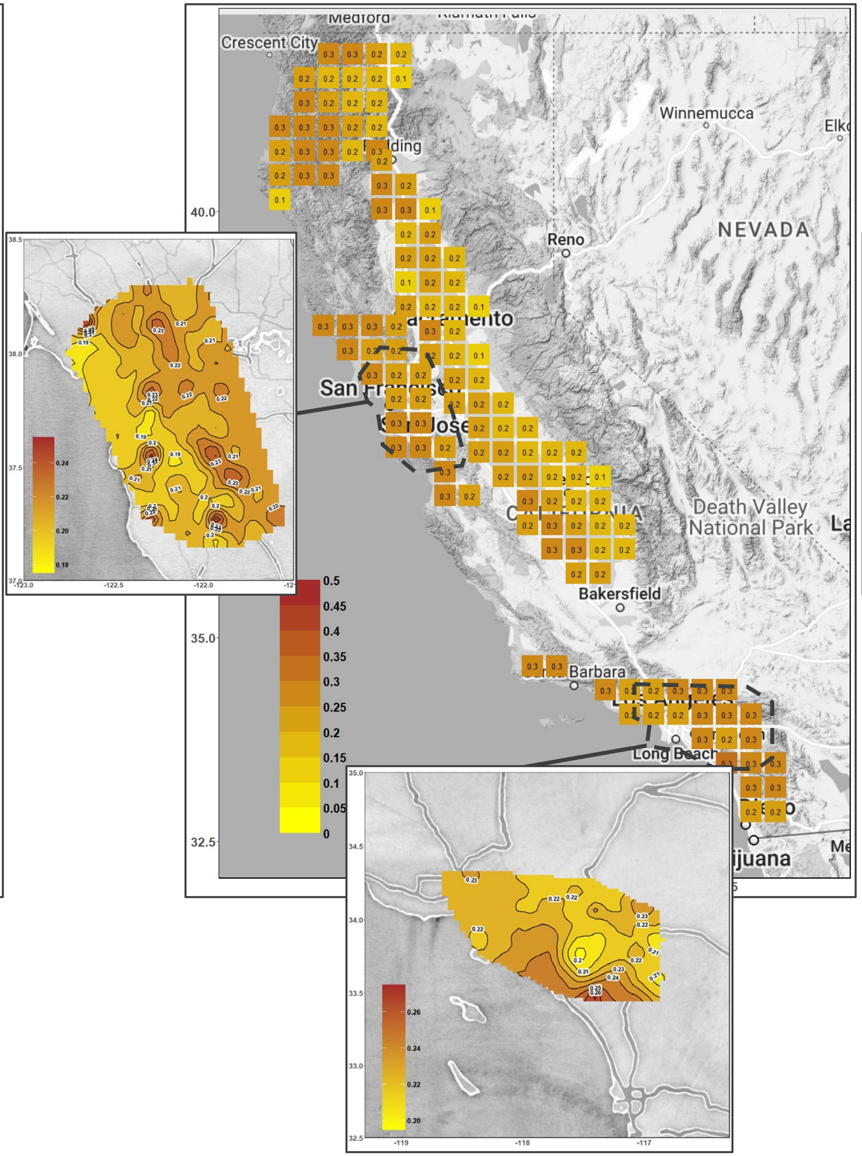


Sigma$_L$ Maps for V_{S30} = 259 m/s

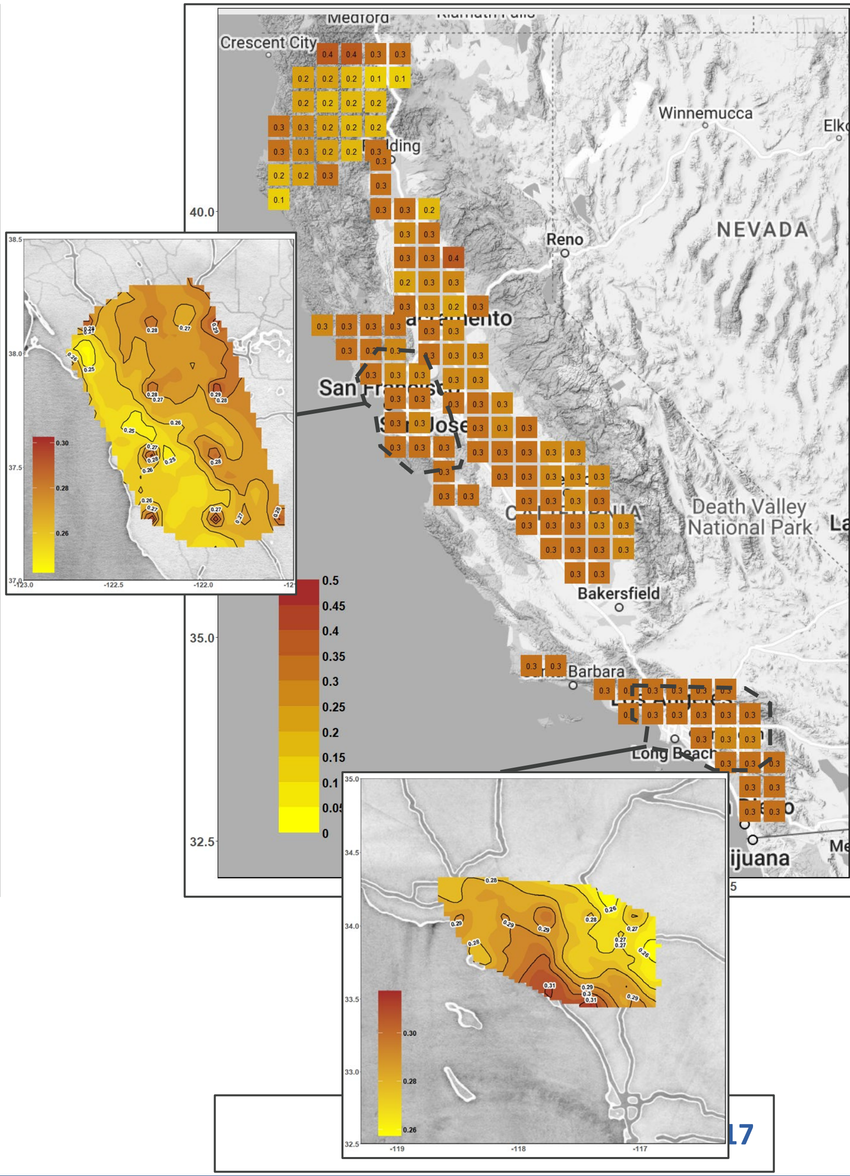
225-yr



975-yr

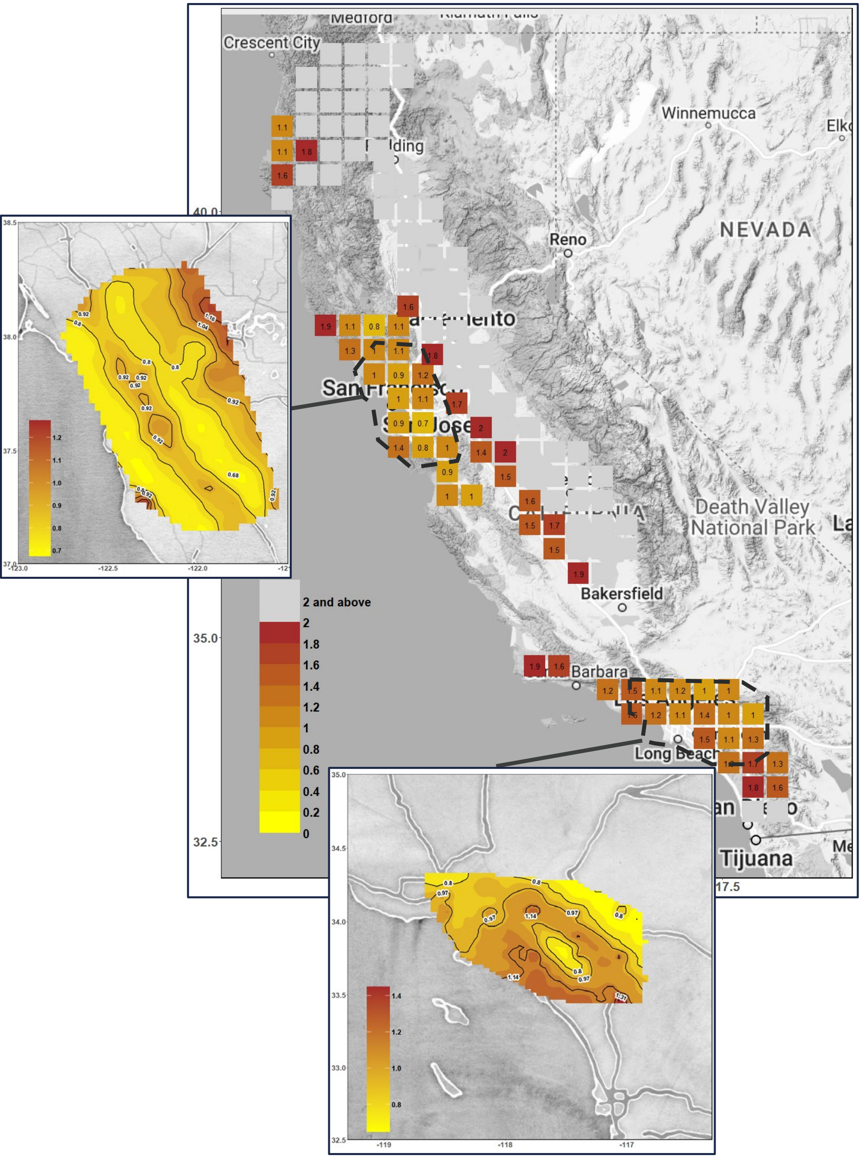


2475-yr

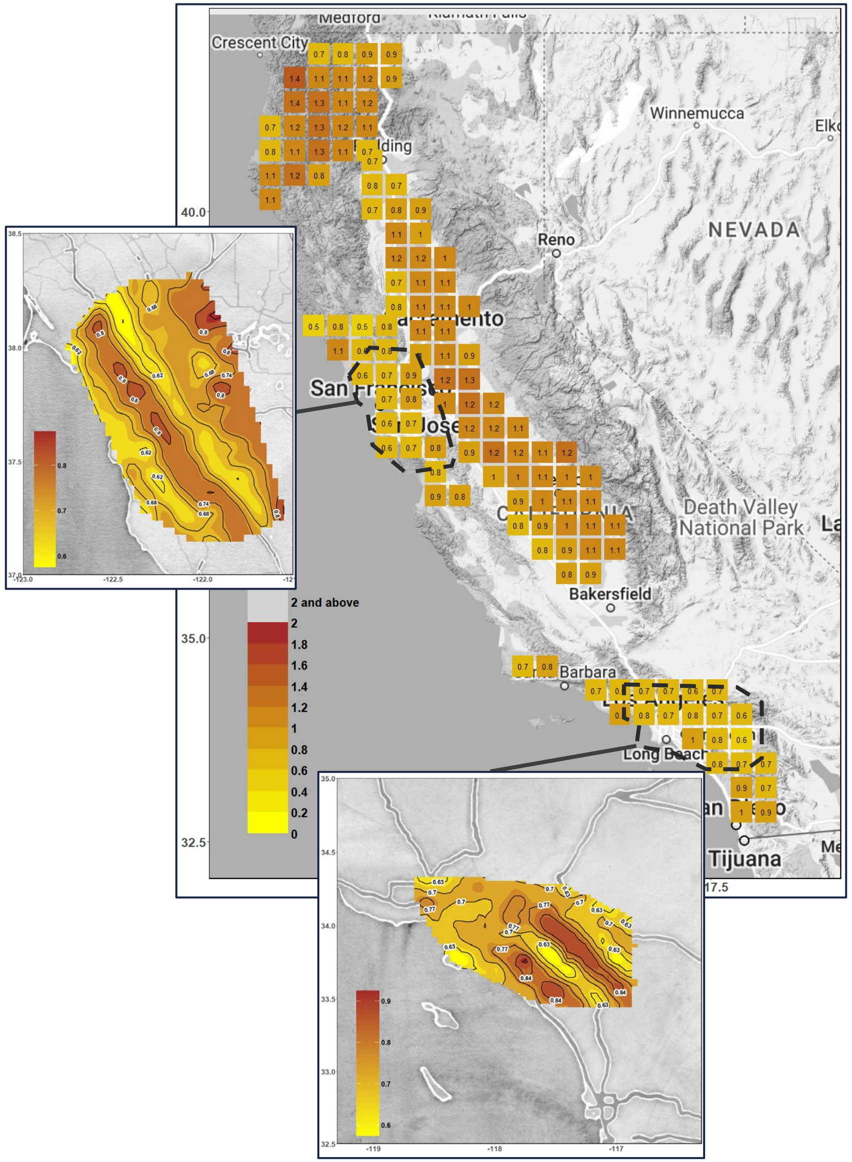


COV_L Maps for V_{S30} = 259 m/s

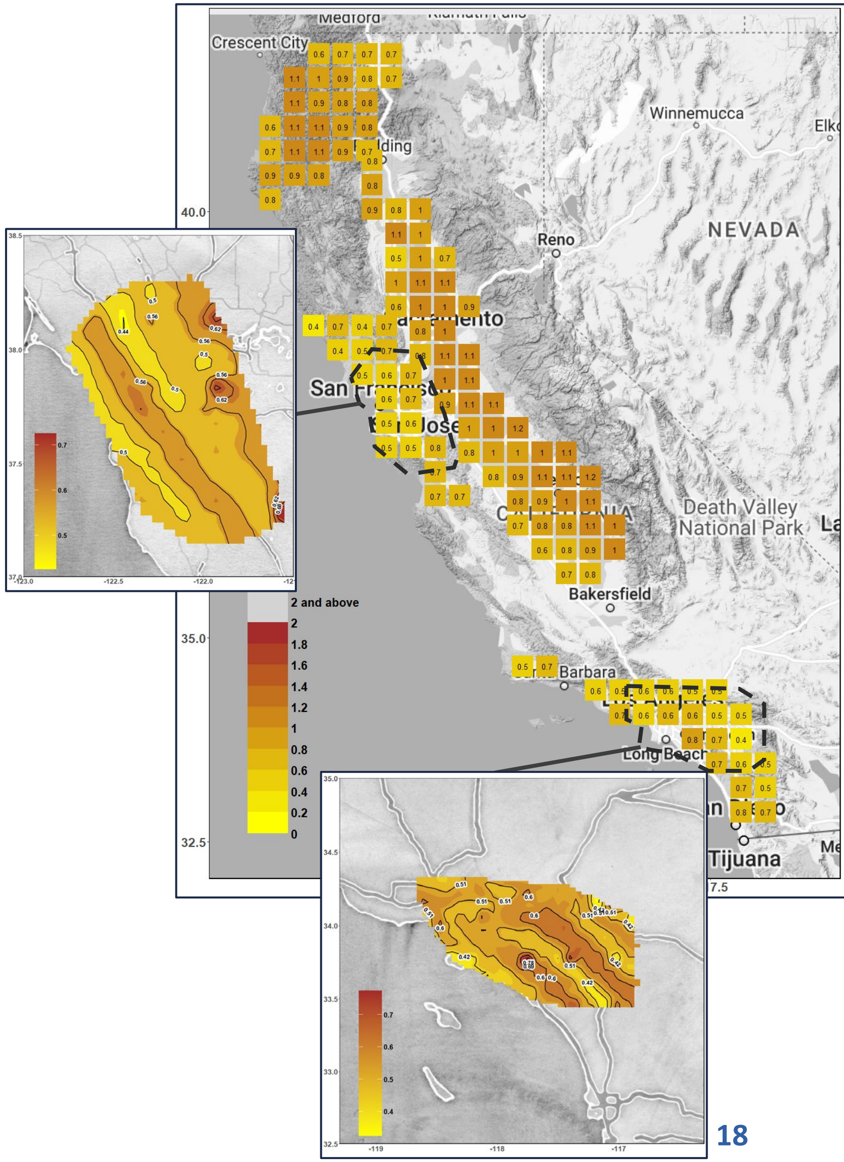
225-yr



975-yr

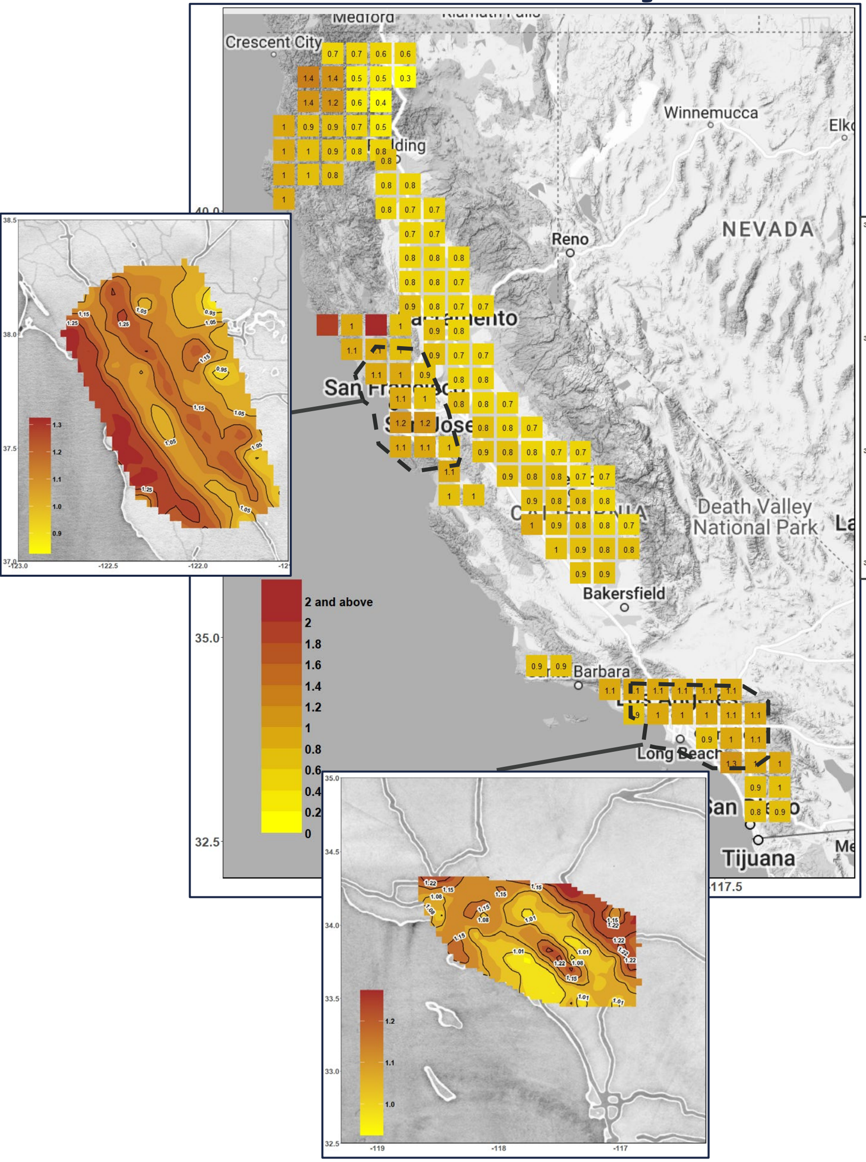


2475-yr

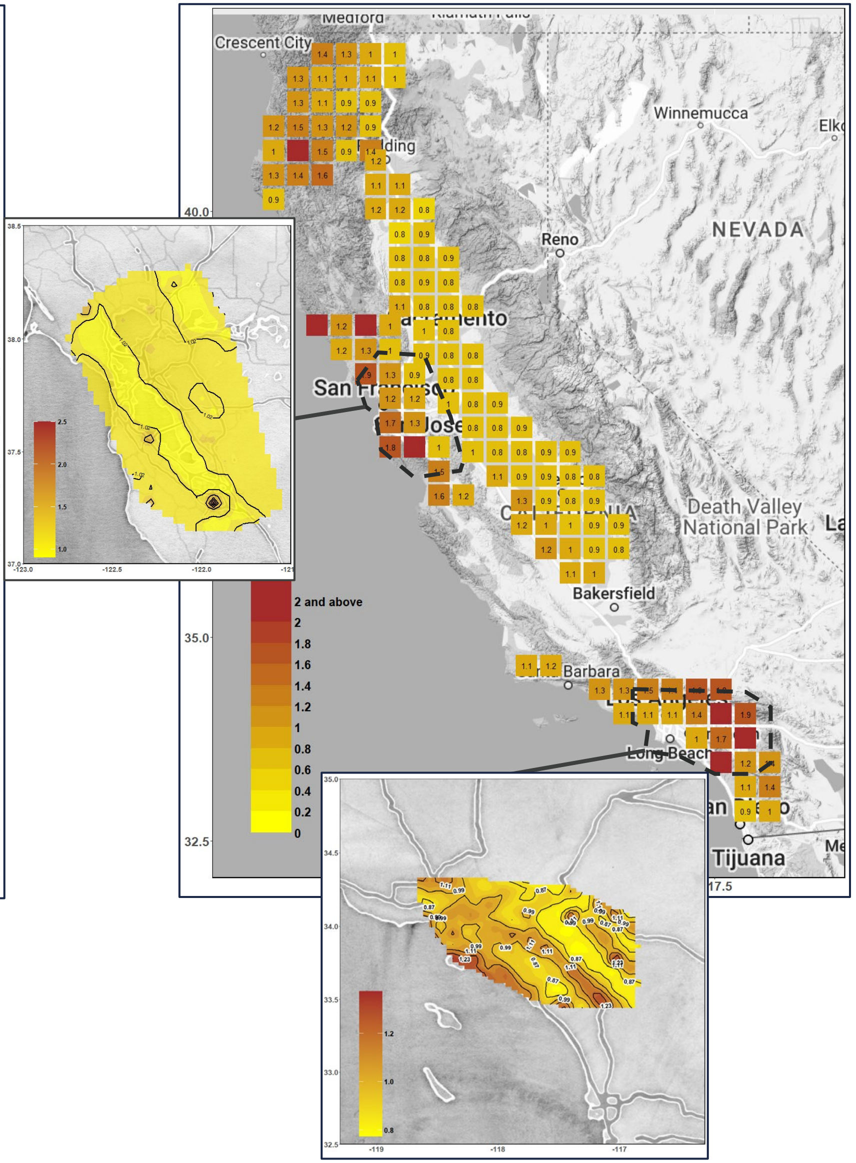


Nonlinear Displacement Amplification Factor for V_{S30} = 259 m/s

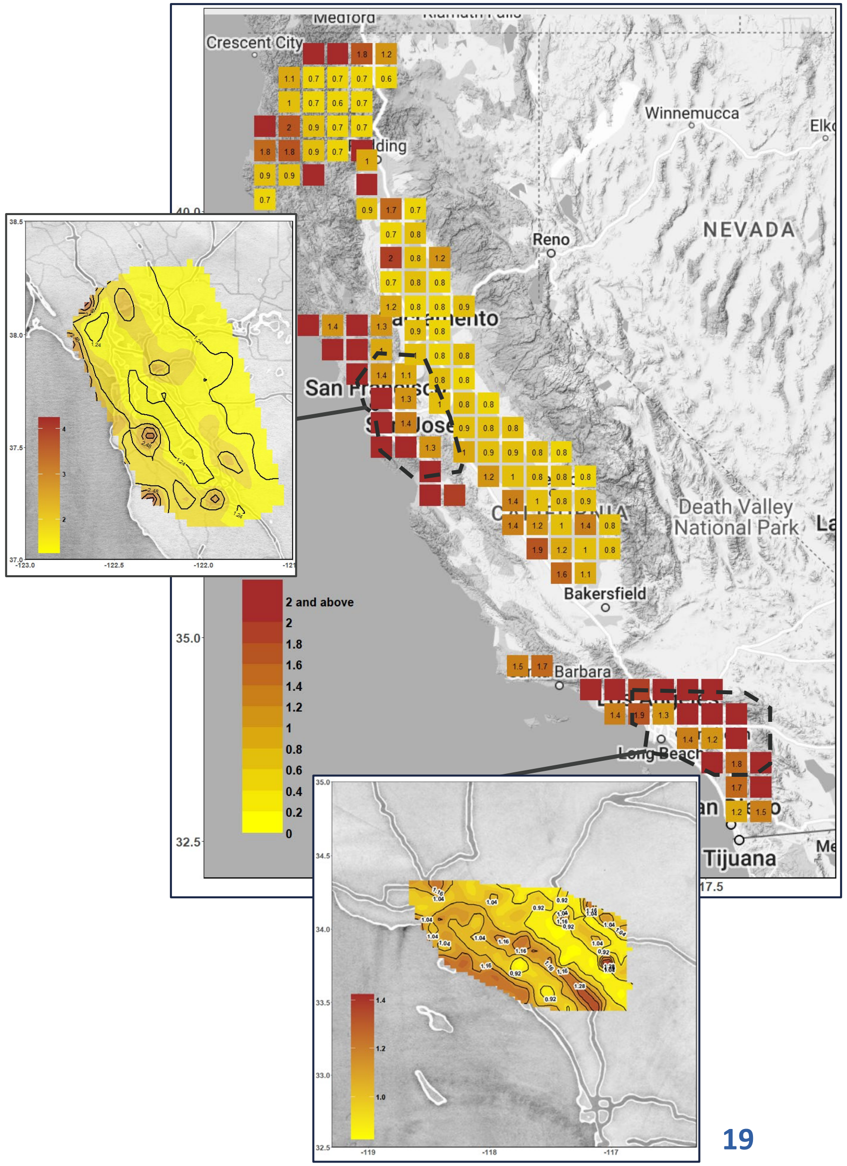
225-yr



975-yr

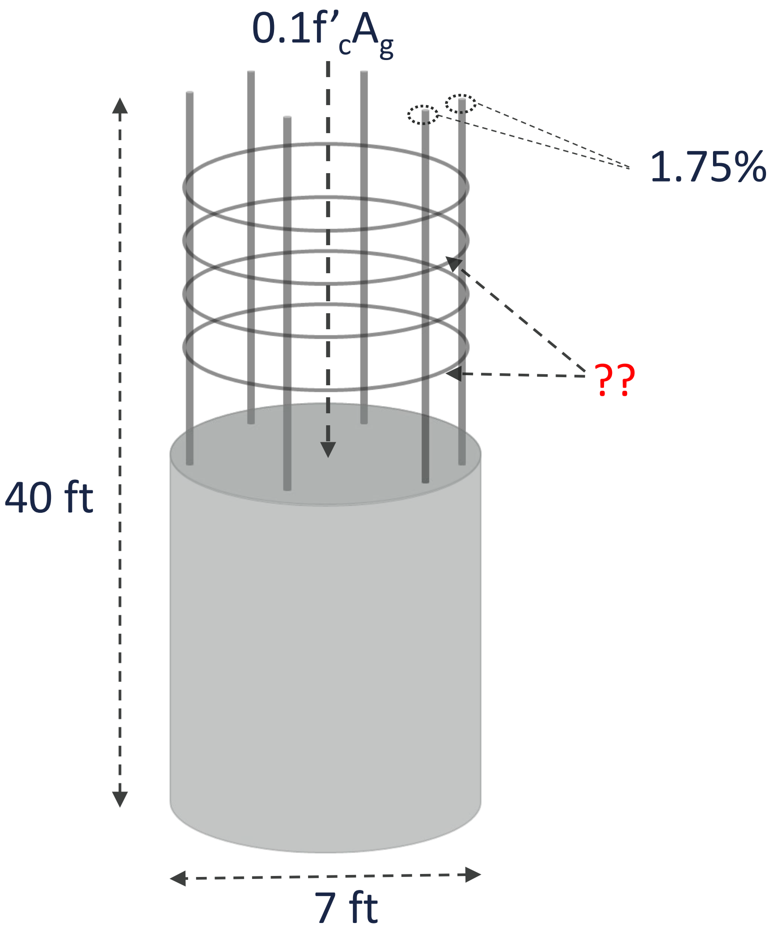


2475-yr



Example

Designer needs to determine suitable column transverse reinforcement for a bridge column in Downtown San Francisco with a targeted risk of <u>NOT</u> more than 1% probability of exceedance for Damage State 5 in its lifespan (75 years). (Assume site class D)



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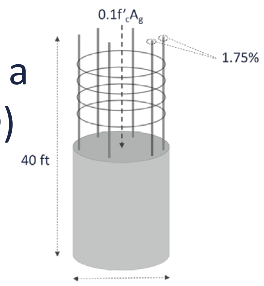

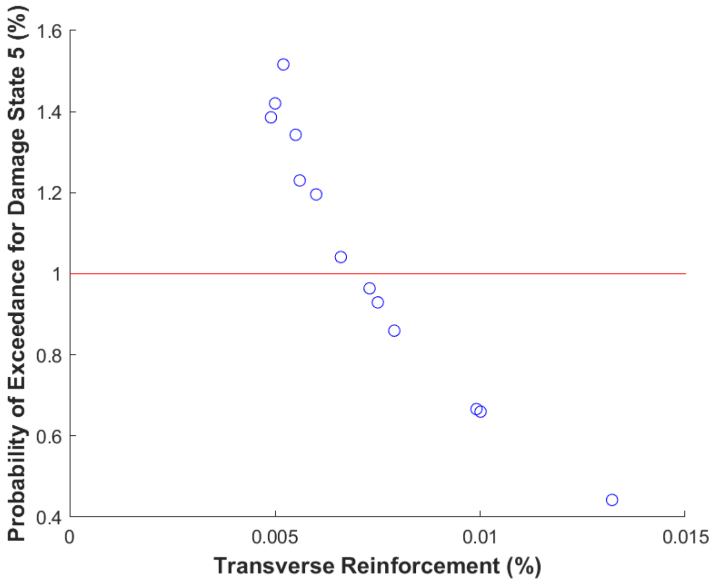

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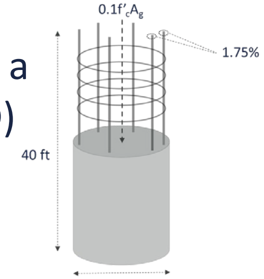
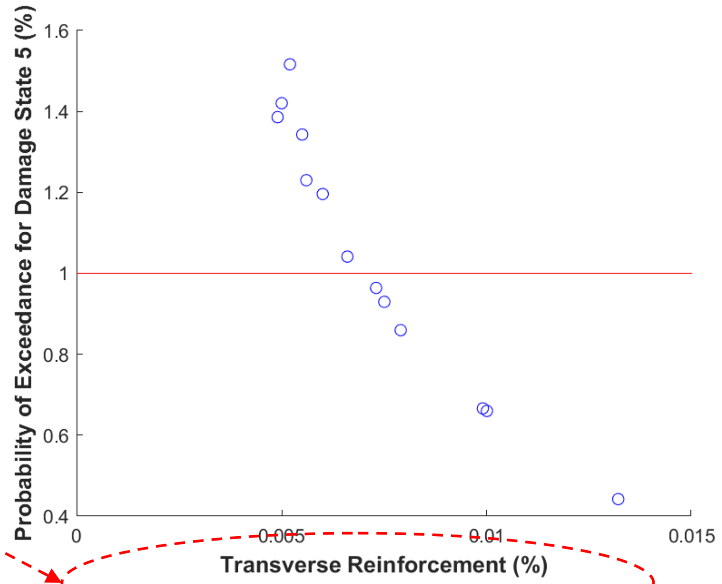


Hoop size (#)	Hoop Spacing (in)	Volumetric Transverse Reinforcement (%)	DI_{ESA}
5	3	0.0052	0.40
6	3	0.0073	0.33
6	4	0.0055	0.38
7	3	0.0100	0.29
7	4	0.0075	0.33
7	5	0.0060	0.36
7	6	0.0050	0.39
8	3	0.0132	0.25
8	4	0.0099	0.29
8	5	0.0079	0.32
8	6	0.0066	0.34
8	7	0.0056	0.36
8	8	0.0049	0.38



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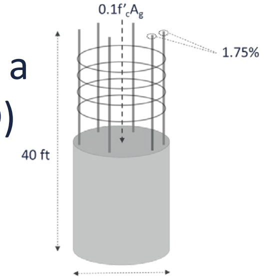

$$P(DS_i) = P(DS_5|GM_{225yr}) \times P(GM_{low}) + P(DS_5|GM_{975yr}) \times P(GM_{high}) + P(DS_5|GM_{2475yr}) \times P(GM_{extreme})$$

Where, $P(GM_{low}) = P(GM > GM_{1yr}) - P(GM > GM_{600yr})$

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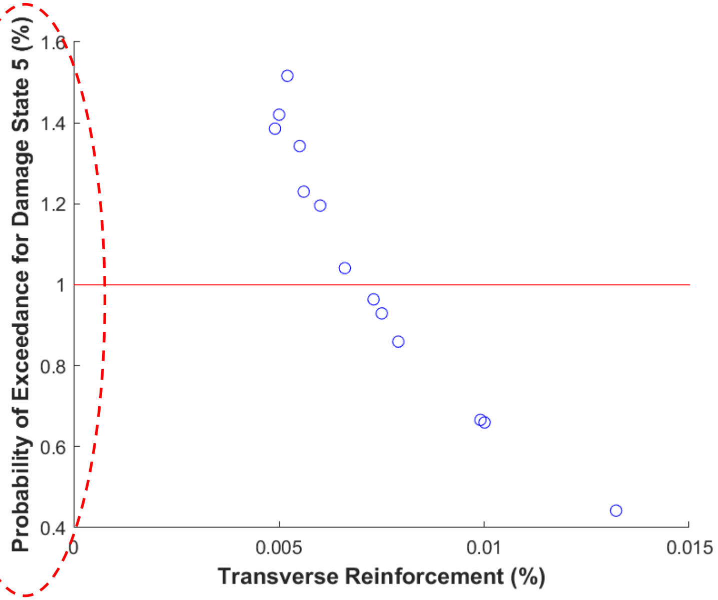
$P(GM_{extreme}) = P(GM > GM_{1725yr}) - P(GM > GM_{3000yr})$

Hoop size (#)	Hoop Spacing (in)	Volumetric Transverse Reinforcement (%)	DI_{ESA}
5	3	0.0052	0.40
6	3	0.0073	0.33
6	4	0.0055	0.38
7	3	0.0100	0.29
7	4	0.0075	0.33
7	5	0.0060	0.36
7	6	0.0050	0.39
8	3	0.0132	0.25
8	4	0.0099	0.29
8	5	0.0079	0.32
8	6	0.0066	0.34
8	7	0.0056	0.36
8	8	0.0049	0.38



Example

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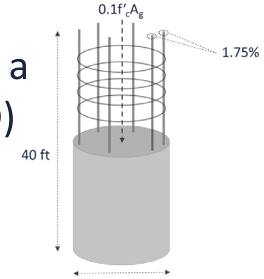

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$$P(DS_5|GM_{RP}) = 1 - \emptyset(\beta_5)\ ,where\ \beta_5 = \frac{ln\left(\frac{\mu_{R5}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{R5}^2+1}}\right)}{\sqrt{ln[(\delta_L^2+1)(\delta_{R5}^2+1)]}}$$

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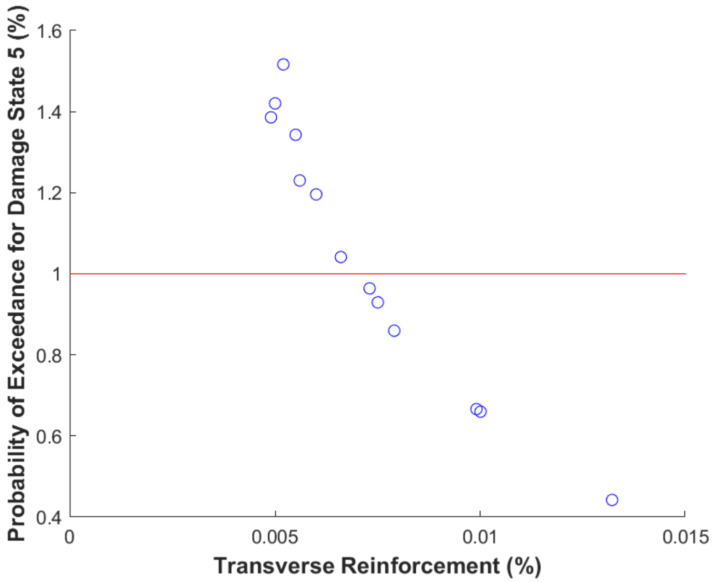

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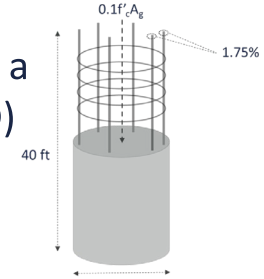

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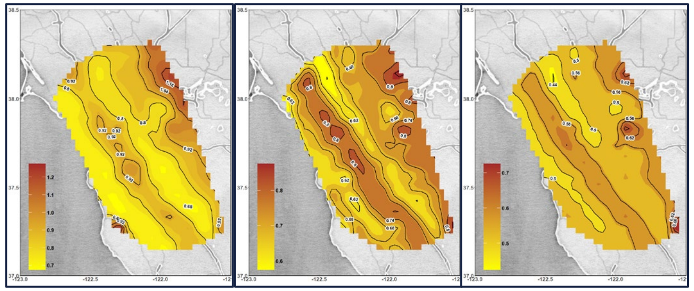
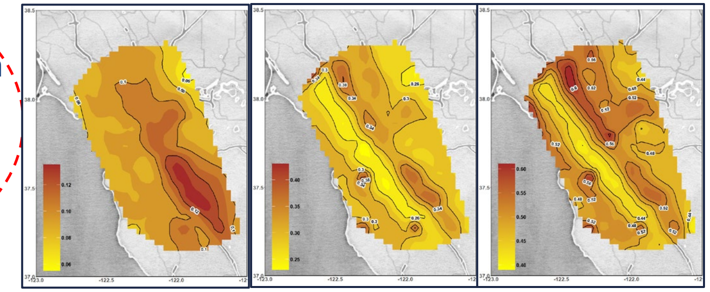
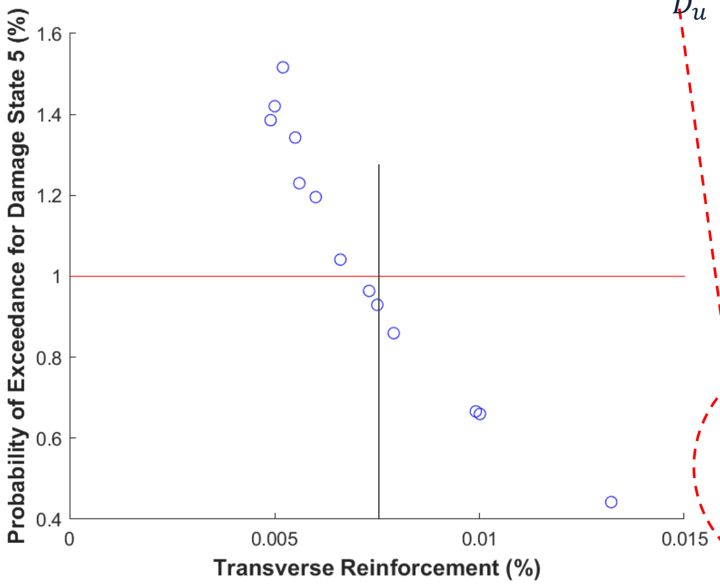
$$\mu_L = \frac{NLF \times D - D_y}{D_u - D_y}$$

COV$_L$ from maps for VS30 = 259 m/s



Amplification Factor from maps for VS30 = 259 m/s





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Summary

This study provides a comprehensive insight into statistical parameters (μ_L, δ_L) for Demand Damage Index across California, with the characteristics –

- ✓ Maps and auxiliary tools for estimation of μ_L, δ_L
- ✓ 25-mile grid across complete California and a 5-mile grid for Bay Area and Southern California
- ✓ Two site classes – C and D
- ✓ Examples to help engineers with design and assessment
- ✓ Insight into trends of demand DI statistical variation across California

Future Scope

- ❑ Analysis of full-scale bridges (single-bent, multiple-bent)
- ❑ Updating bridge fragility curves
- ❑ Response prediction equations

Thank You, Discussion

For further queries please feel free to reach at ZAREIAN@UCI.EDU or SINGHAL1@UCI.EDU