UCI

Statistical Variation of Seismic Damage Index (DI) of California Bridges

September 19, 2022

Saurabh Singhal, Farzin Zareian

PEER Researchers' Workshop
September 19-20, 2022

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)
- 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)
- 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)

UCI

Team

Farzin Zareian
(Principal Investigator)

Saurabh Singhal
(Graduate Student Investigator)

Sharon Yen (Contract Manager)

Prof. Saiid Saiidi and **Prof. Norm Abrahamson** (Project Advisory Board)

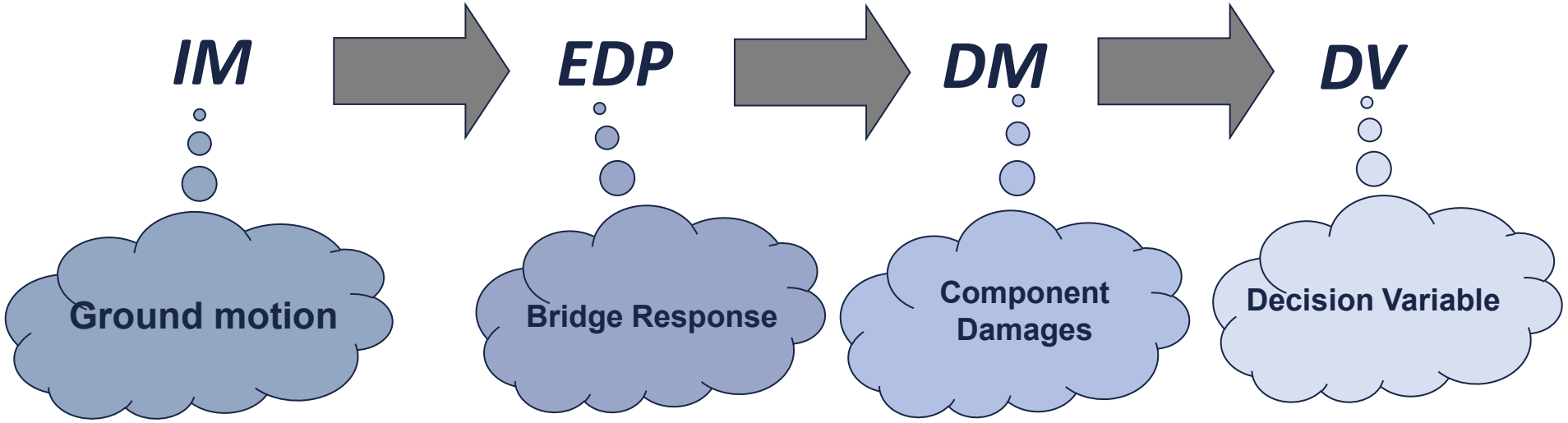
Toorak Zokaie, **Tony Yoon**, **Amir Malek**, **Sam Ataya** (PDCA Team)

Vision

The Problem at hand:

Create and implement a framework for performance-based assessment and design of bridges in California where:

- **Comprehensive**: captures the impact of all meaningful sources of variability
- **Simple**: does NOT need too many NTHA



Vision

Solution:

Probabilistic Damage Control Application (PDCA)

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 demands vs. capacity on a single bridge.

$IM \rightarrow EDP_{Demand}$

$EDP_{Capacity} \leftarrow DM$

Vision

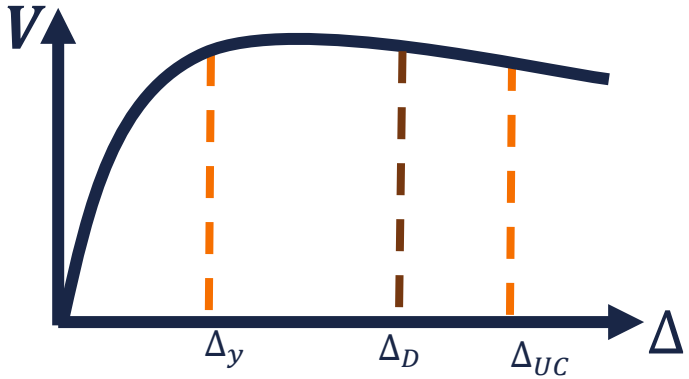
Solution:

Probabilistic Damage Control Application (PDCA)

Seismic demands vs. capacity on a single bridge.

IM → ***DI_{Demand}***

$DI_{Capacity}$ ← ***DM***



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

Vision

Solution:

Probabilistic Damage Control Application (PDCA)

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

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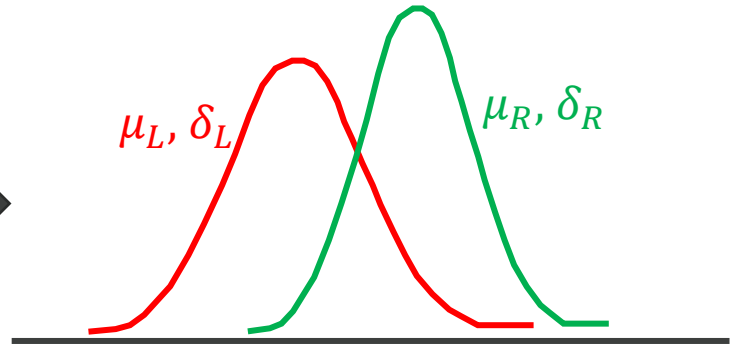
$$Damage\ Index, DI = \frac{\Delta_D - \Delta_y}{\Delta_{UC} - \Delta_y}$$

Seismic demands vs. capacity on a single bridge.

DI_{Demand}

vs.

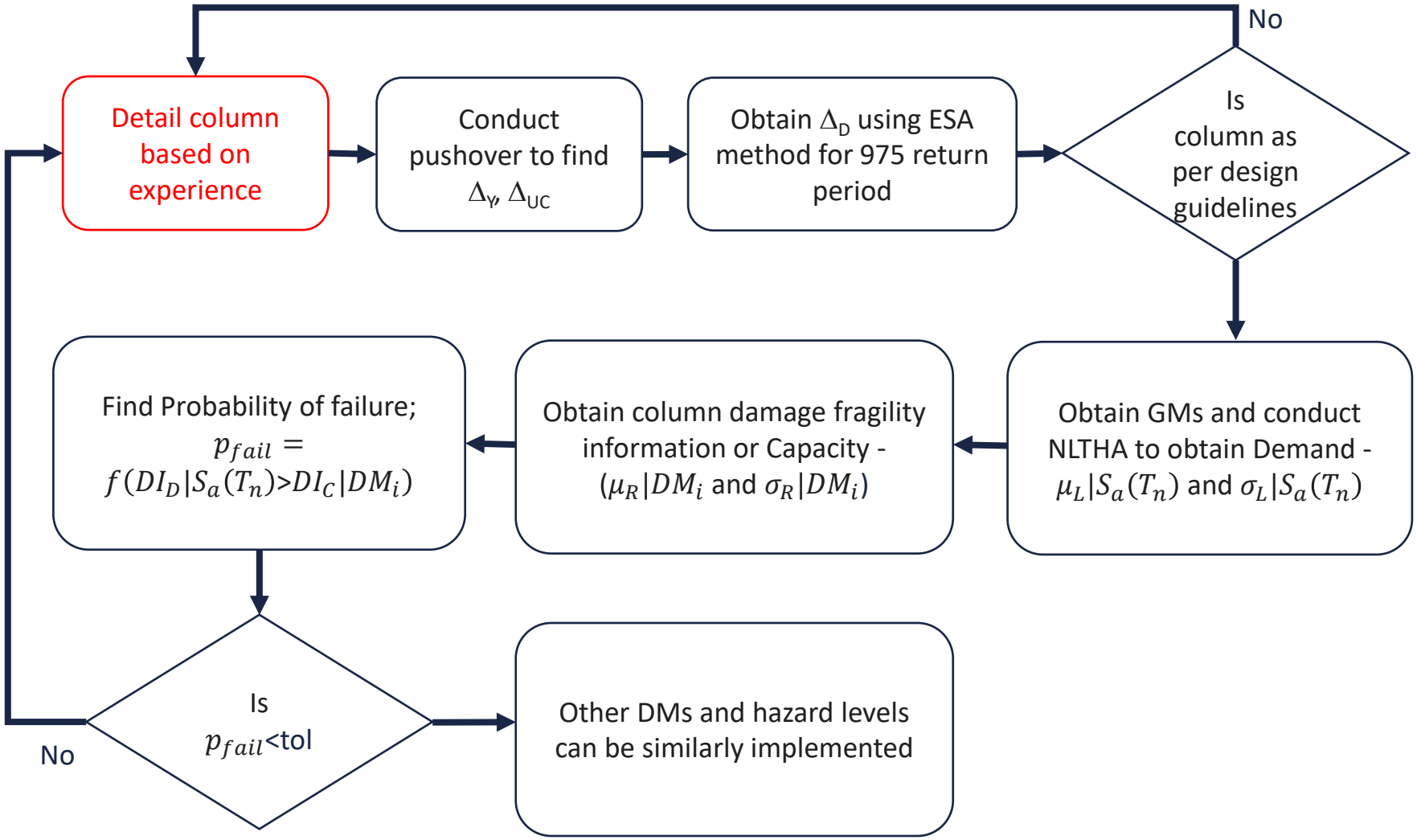
$DI_{Capacity}$

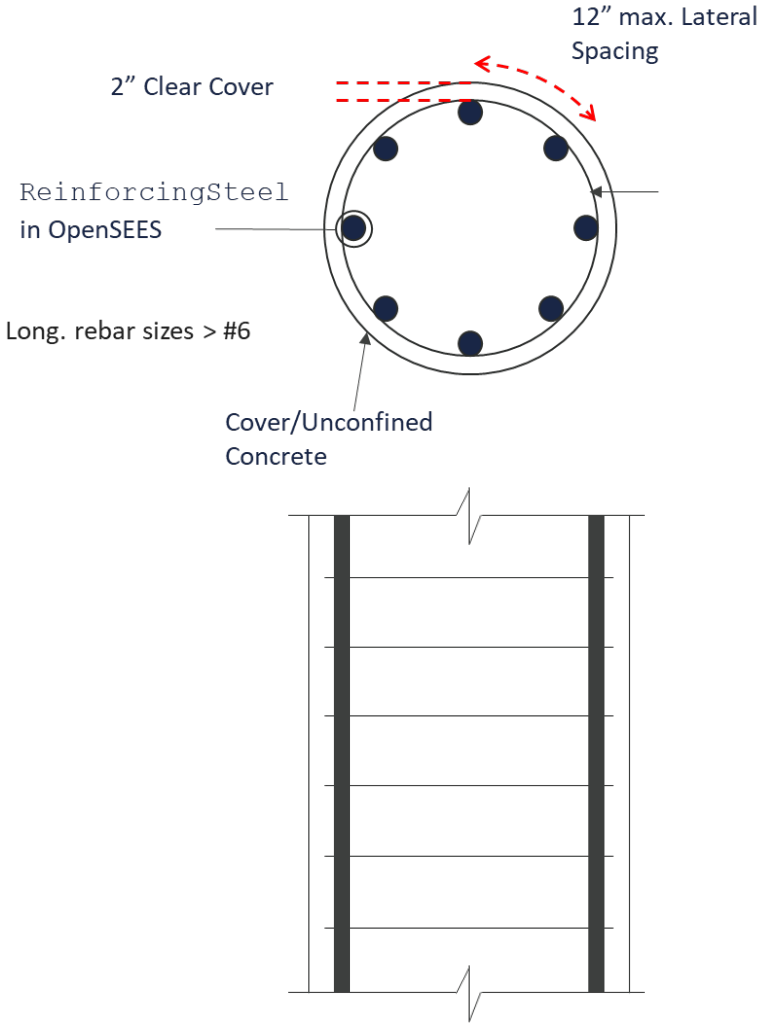


$$\beta_i = \frac{\ln\left(\frac{\mu_{Ri}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{Ri}^2+1}}\right)}{\sqrt{\ln\left[\left(\delta_{Ri}^2+1\right)\left(\delta_L^2+1\right)\right]}}$$

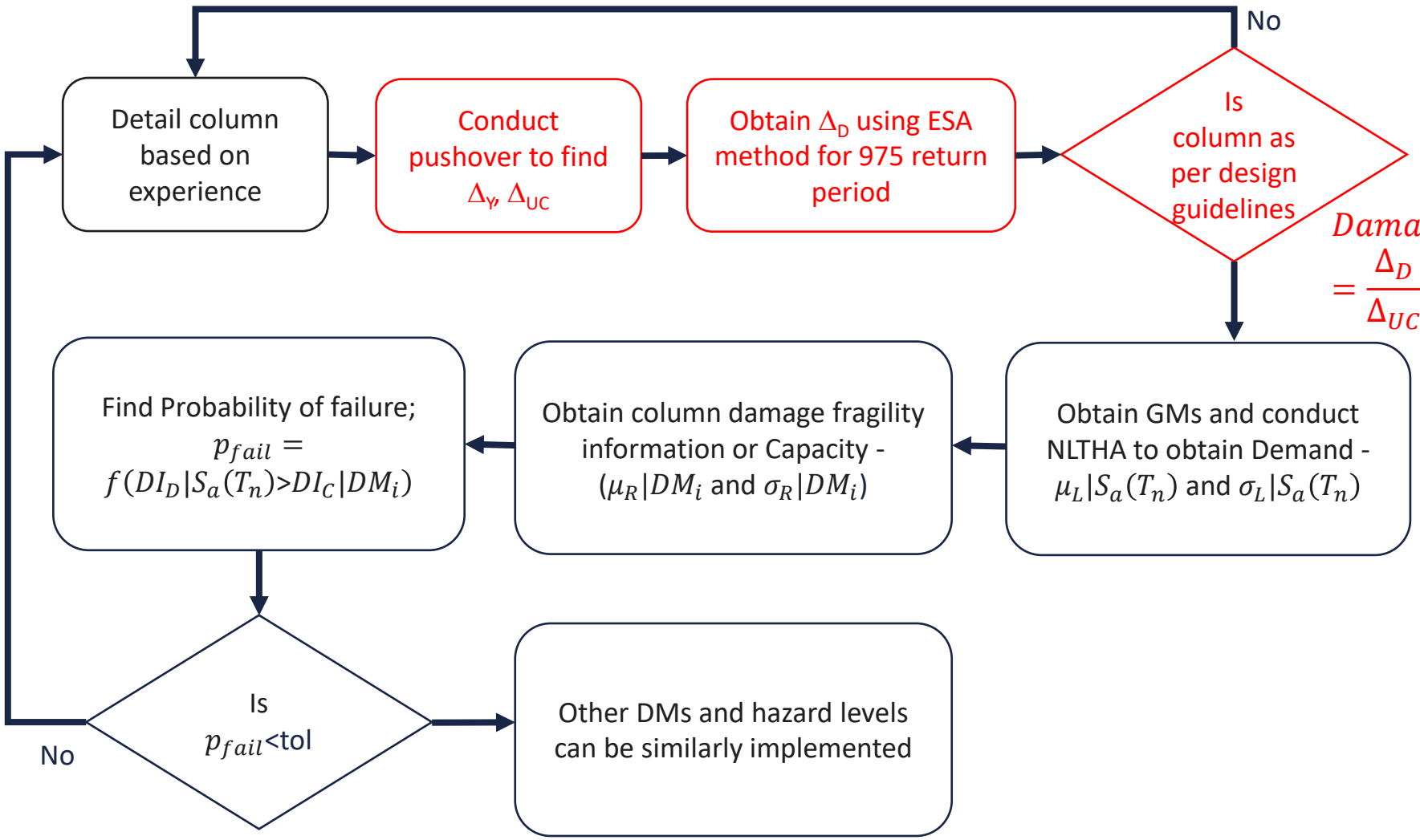
$$Probability\ of\ exceedence, p_{fail} = 1 - \Phi(\beta_i)$$

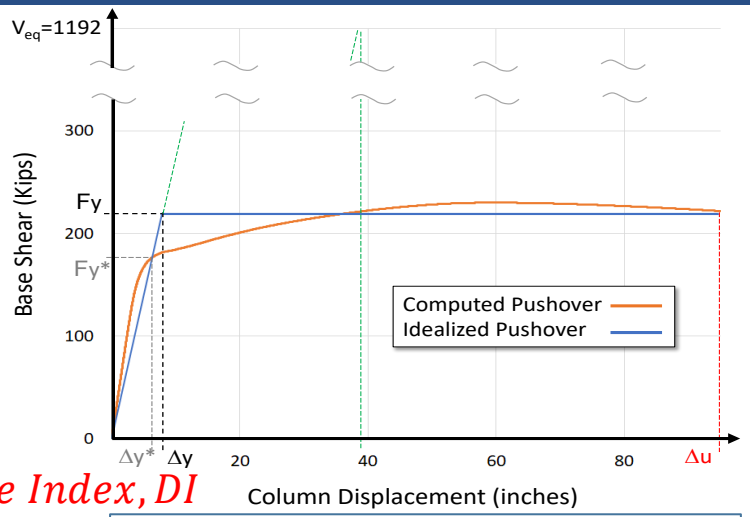
PDCA Framework



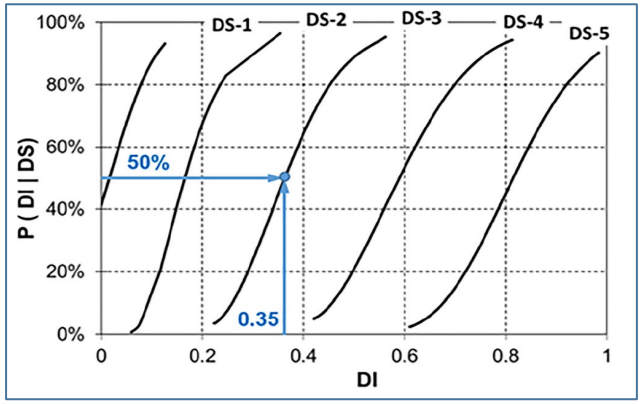


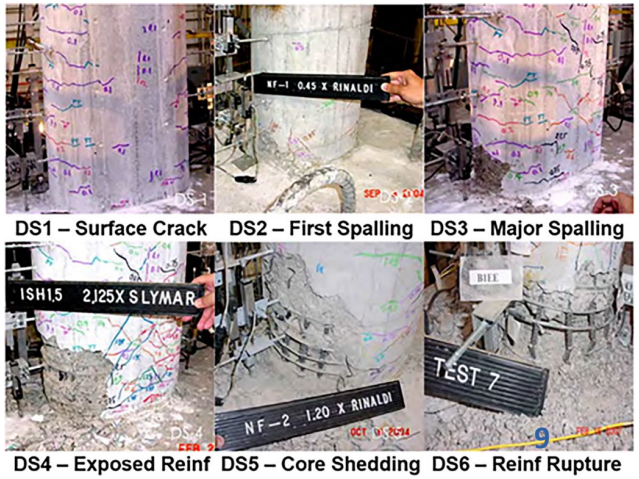
PDCA Framework





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

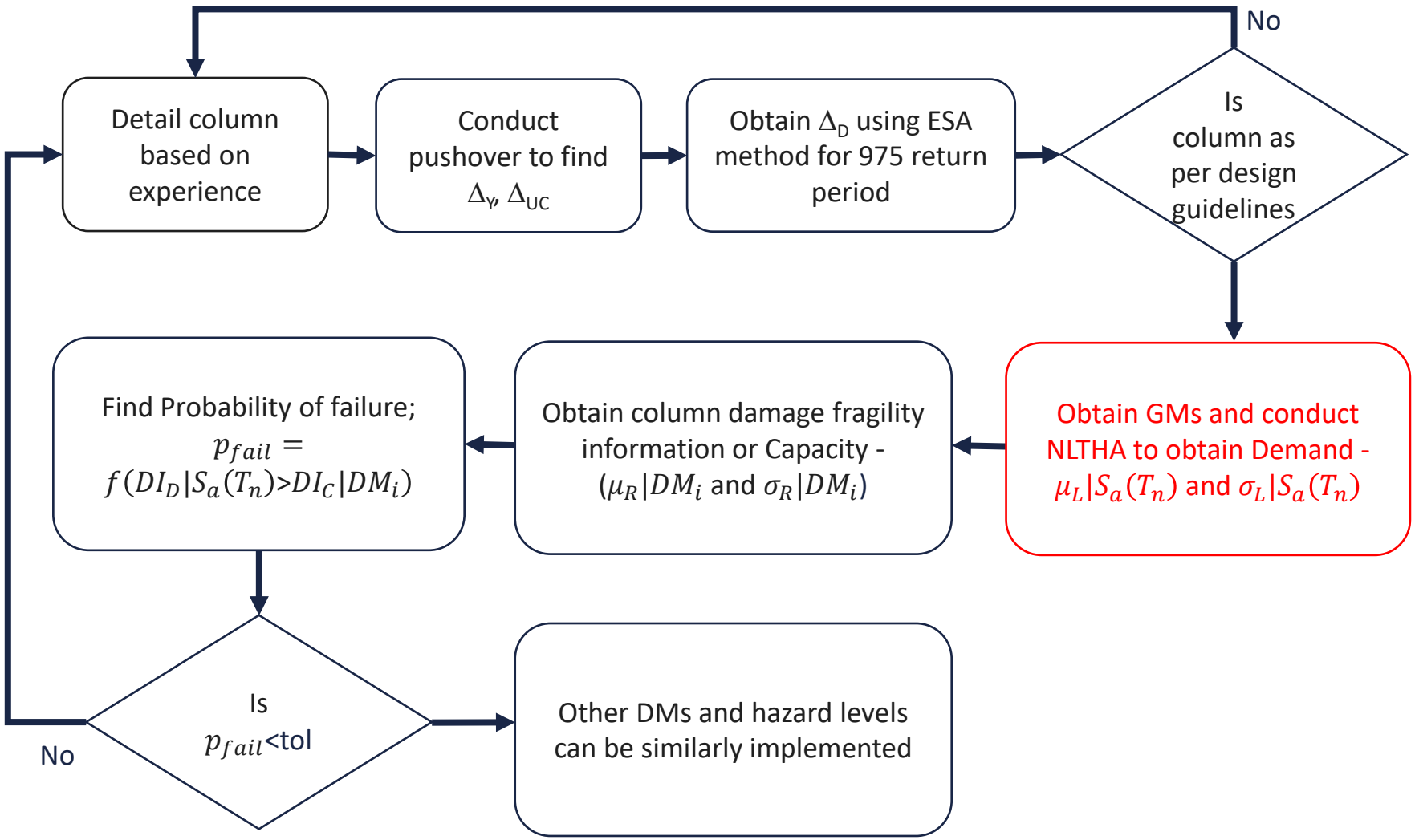


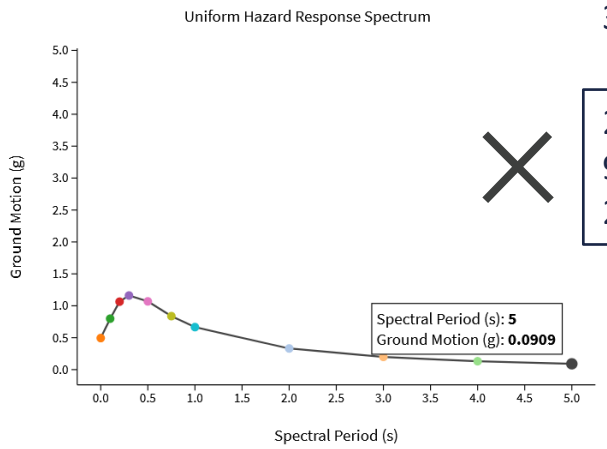


DS1 – Surface Crack DS2 – First Spalling DS3 – Major Spalling

DS4 – Exposed Reinf DS5 – Core Shedding DS6 – Reinf Rupture

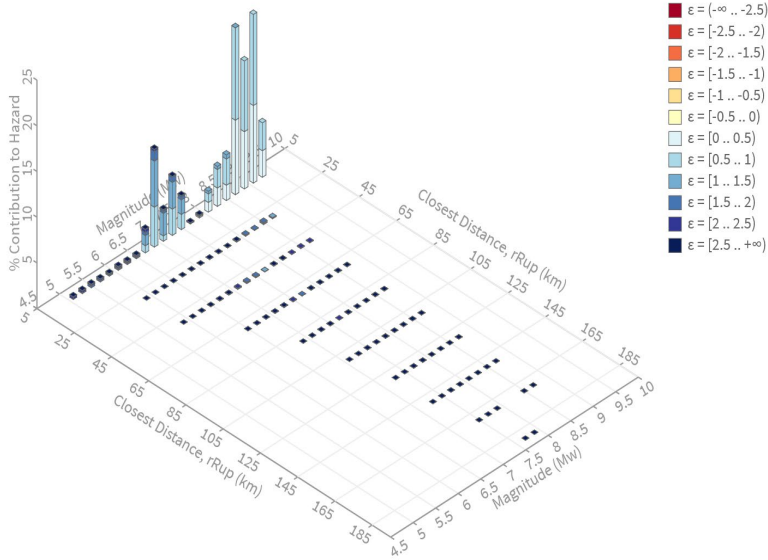
PDCA Framework





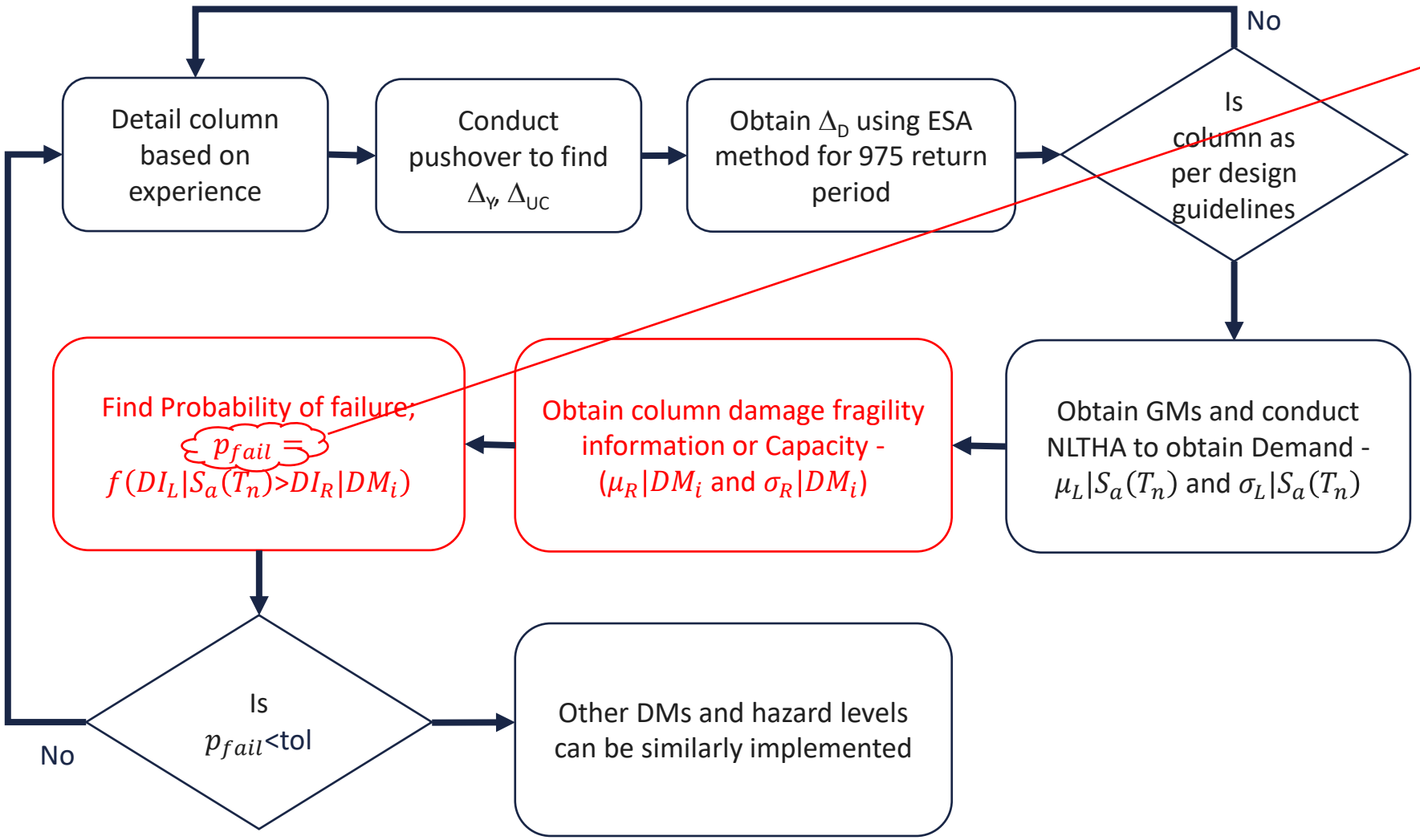
3 Hazard Levels

225-year
975-year
2475-year



- Uniform Hazard Curve and Hazard Deaggregation from USGS Hazard Tool
- Top scenarios from deaggregation used in binning
- GM simulation algorithm by Razaeian et al. (2012) and Dabaghi et al. (2018)

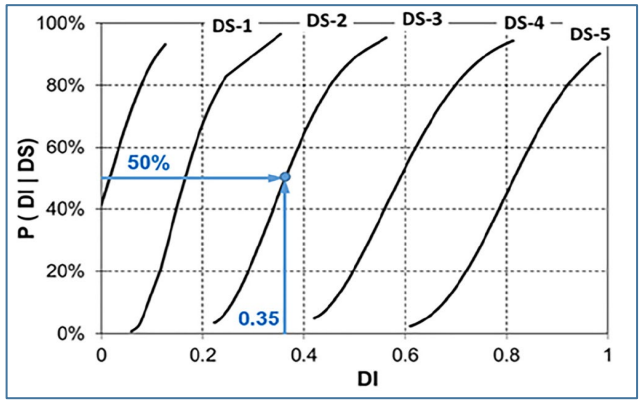
PDCA Framework



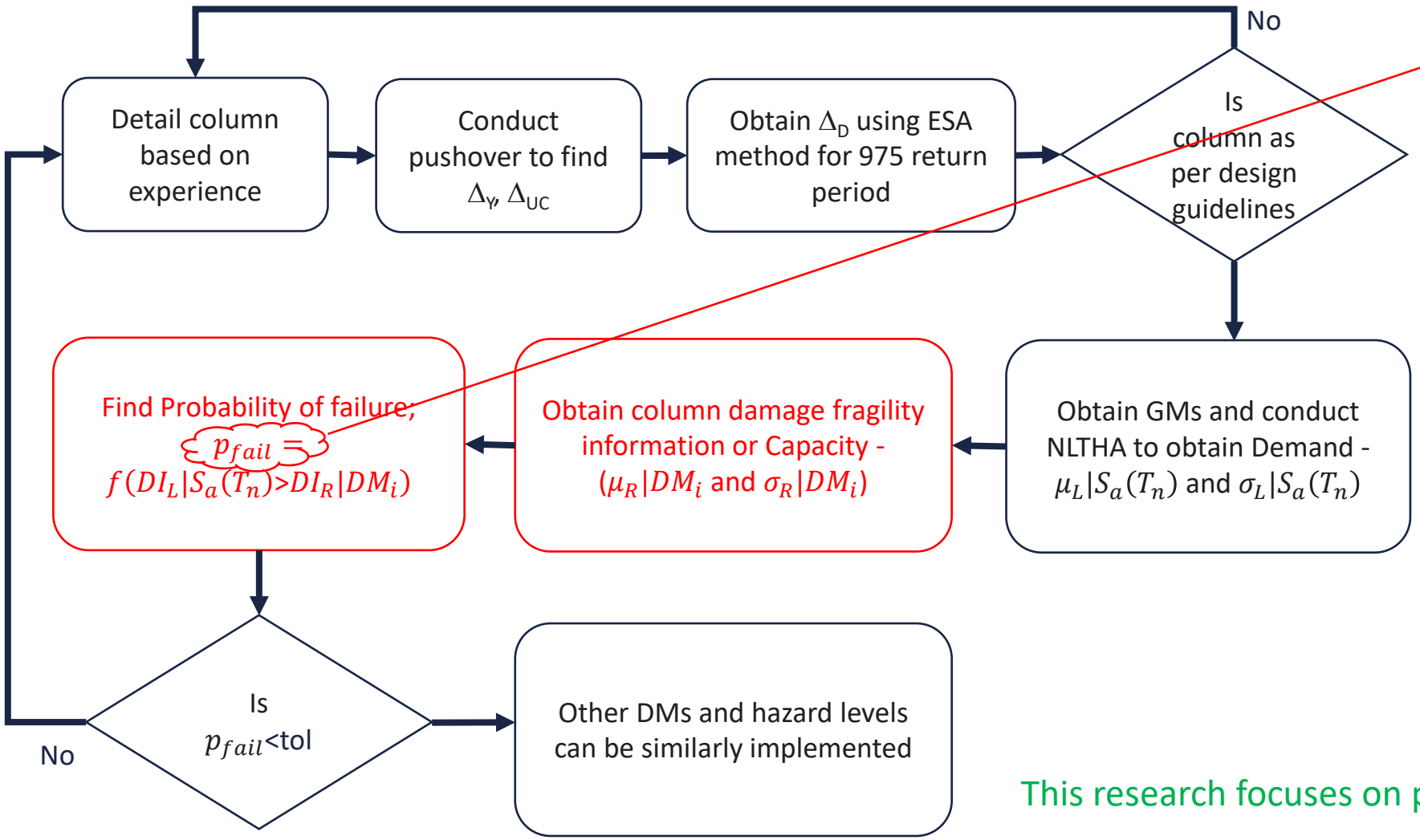
$$Probability\ of\ exceedence, p_{fail} = 1 - \Phi(\beta_i)$$

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

$\mu_{Ri}, \delta_{Ri} \rightarrow Mean\ and\ COV\ of\ DI\ capacity,$
$from\ Saini\ and\ Saiidi's\ work$



PDCA Framework



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$\mu_L, \delta_L \rightarrow Mean\ and\ COV\ of\ DI\ demand$

Can demand mean (μ_L) be determined by the designer using approaches such as ESA?

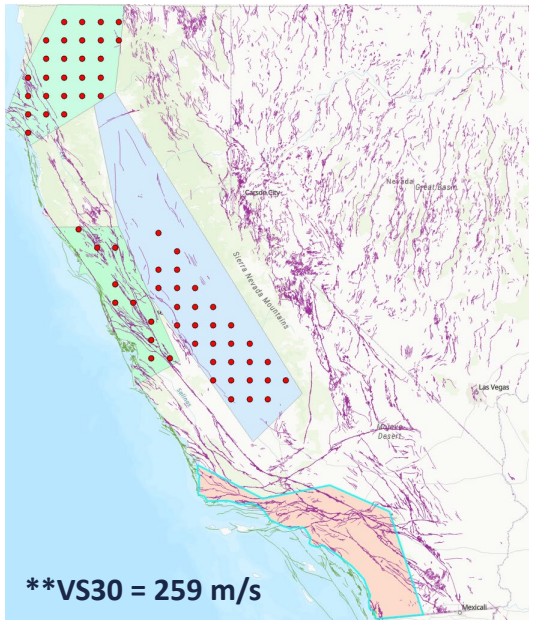
Can we develop predefined demand COV (δ_L)?

This research focuses on producing δ_L maps across California

+

μ_L transformation from ESA to NTHA

Approach and Methods



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Bridge Geometric Parameters

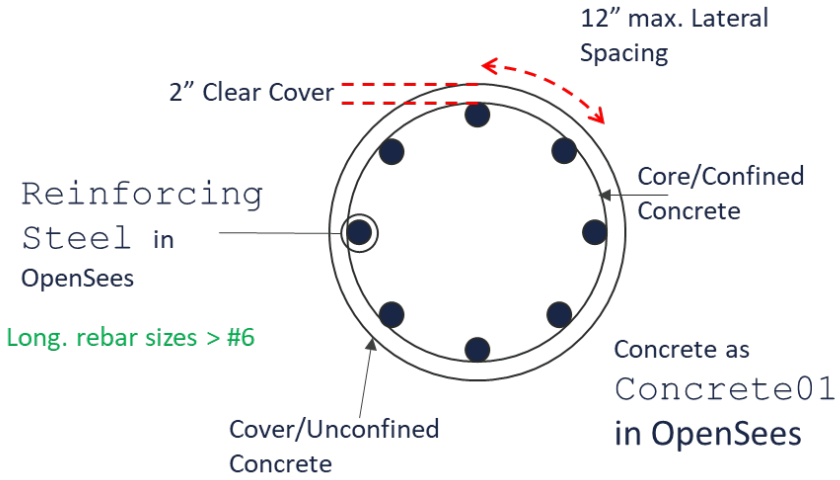
Parameter	Cases
Column Height (ft)	20, 30, 40, 50
Axial Force	$0.05f'_cA_g$, $0.10f'_cA_g$, $0.15f'_cA_g$
Reinf. Ratio (%)	1.0, 1.75, 2.5
Diameter (ft)	5, 6, 7, 8
Hoop Rebar Sizes	#5, #6, #7, #8
Hoop Spacings (in)	3,4,5,6,7,8

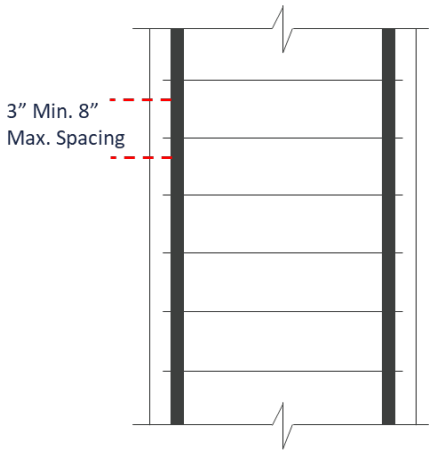
×

3 Hazard Levels

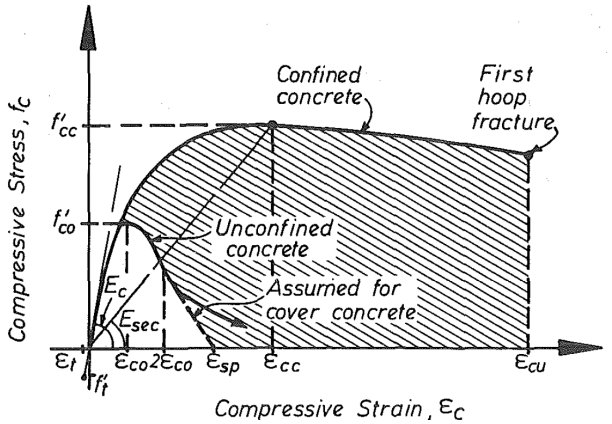
225-year
975-year
2475-year

Column Model Properties





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 for Distributions of DI

Design Group
PC23 | PC34 | PC24

Location
67 Locations across CA

VS30
259

Scaling Type
RS

Hazard
225 | 975 | 2475

Designed Columns
$\{CID_1\}$
$\{CID_2\}$
…
$\{CID_N\}$

Parameter	Cases
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51 Ground Motions

3,126,614 DI Estimates

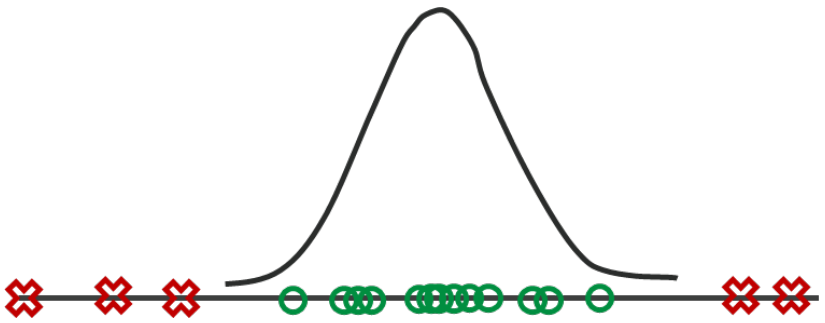
~2.5 years of analyses

GLOSSARY

PC23 : Designs with DI Design (DI_{ESA}) between 0.2 and 0.3 – Recovery Bridges as per Caltrans criteria	**225** : 225-yrs return period	**259** : VS30 = 259 m/s	**RS** : Range Scaling	**CID** : Designed Column ID
PC34 : Designs with DI Design (DI_{ESA}) between 0.3 and 0.4 – Ordinary Bridges as per Caltrans criteria	**975** : 975-yrs return period			
PC24 : Designs with DI Design (DI_{ESA}) between 0.2 and 0.4	**2475** : 2475-yrs return period			

GMSS Validation

- Does simulated GMs using Razaeian et al. (2012) and Dabaghi et al. (2018) have secondary Intensity Measures (IM) that follow peer-reviewed models?
- Secondary IMs:
  - Arias Intensity (AI)
  - Cumulative Average Velocity (CAV)
  - Peak Ground Velocity (PGV)
  - Significant Duration 5-75 (D5-75)
  - Significant Duration 5-95 (D5-95)



- Secondary IM models follow are conditional ground motion models by Abrahamson et al.:

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

GMSS Validation

Secondary IM	Primary IM	Conditioning IM for the Primary IM
CAV	PGA	$Sa(T_1)$
AI	PGA, Sa(1 sec)	$Sa(T_1)$
PGV	$Sa(T_{pgv})$	$Sa(T_1)$
D5-75	PGA	$Sa(T_1)$
D5-95	PGA	$Sa(T_1)$

- Secondary IM model from Abrahamson et al.
- Conditional IM model from Lin et al. on Conditional Spectrum*
- Conditioning IM model from Abrahamson & Silva GMPE (2014)

*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.

$Sa(T_1)$ is the Sa value at the natural time period of the structure. Scaling is done as per $Sa(T_1)$

↓

Obtain the distribution of Primary IM conditioned on $Sa(T_1)$ using Conditional Spectrum*

↓

Obtain the distribution of the Secondary IM conditioned on the Primary IM using conditional models

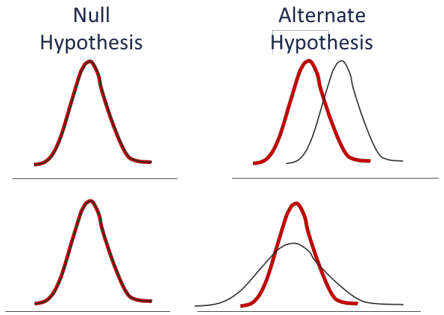
↓

Check statistics of Secondary IMs against the distribution of Secondary IMs

GMSS Validation

Three tests are performed to check distribution of each secondary IM:

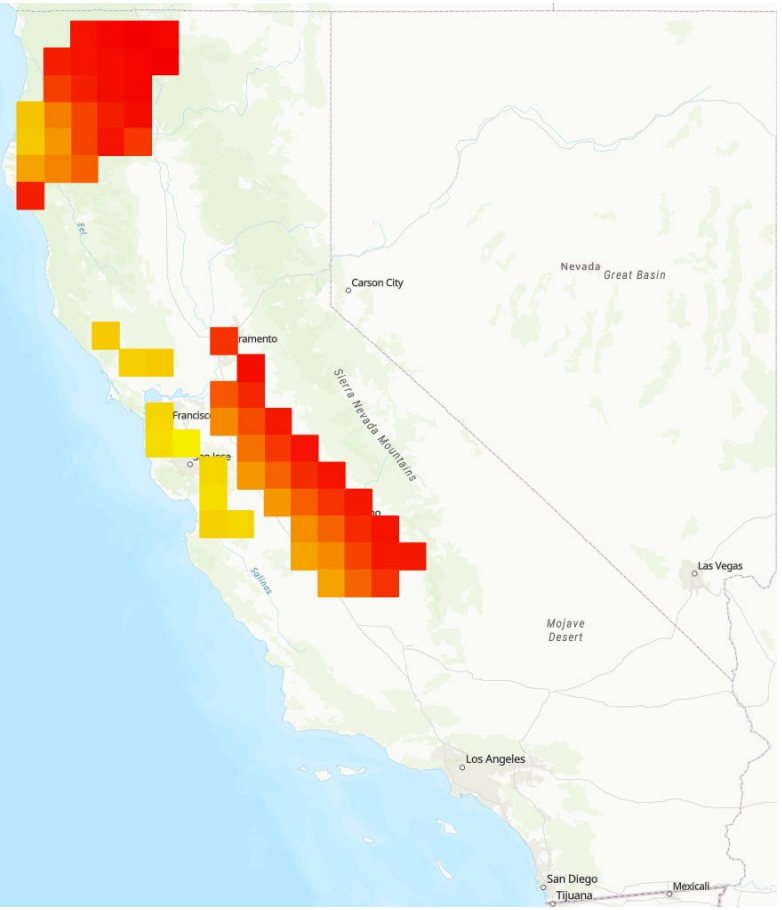
1. **Shapiro_Wilk test**: If distribution is normal
2. **Test of Mean**: to check if distribution mean matches computed mean from conditional model
3. **Test of Variance**: to check if distribution variance matches computed mean from conditional model

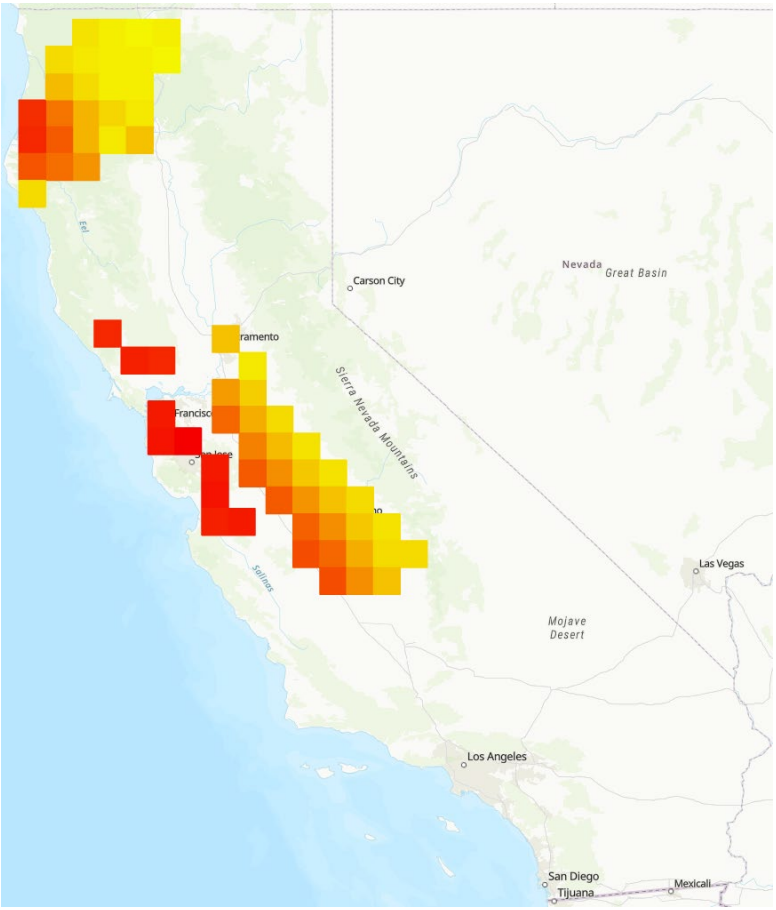


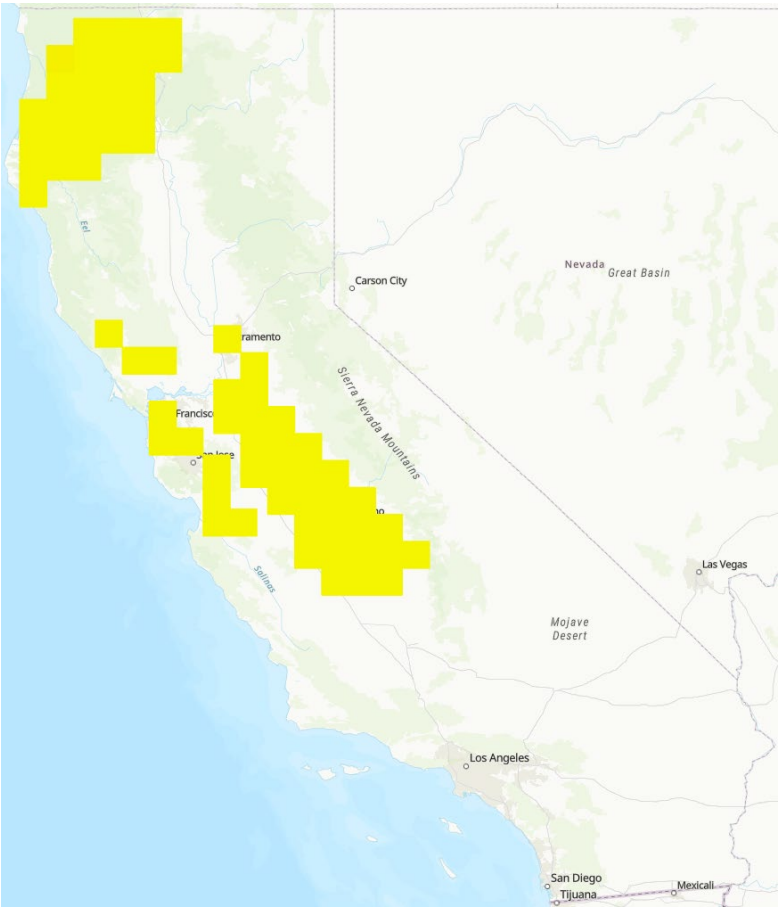
- PGV is the only significant secondary IM for column response assessment.
- The mismatch between the distribution of PGV from the simulated GMs and peer-reviewed models is rendered unimportant as PGV values of the simulated GMs significantly cover the 5-95% range of peer-reviewed PGV models.
- Use GMs with mean PGV for the set fall between 25%-75% confidence interval of the mean distribution from peer-reviewed models, and all PGV values fall between 5%-95% band.

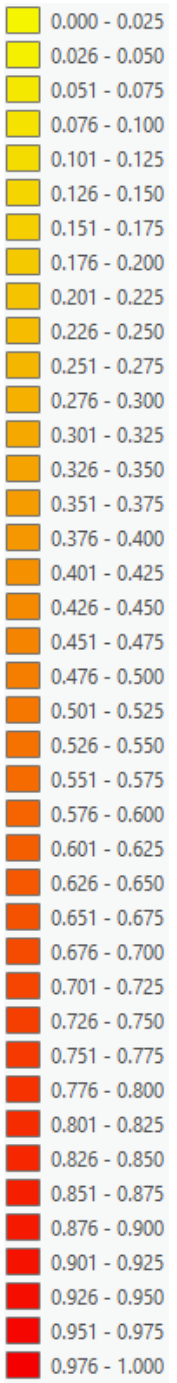
Demand DI Distribution – 225 Yrs

PC24









Fraction of $DI_L < 0$

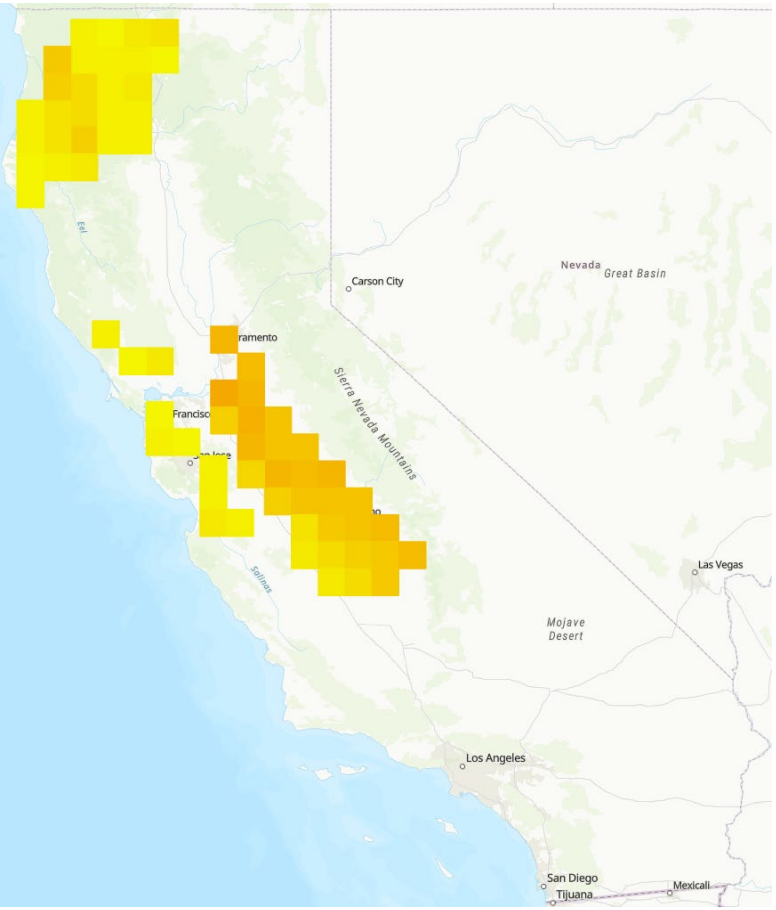
$$DI = \frac{\Delta_D - \Delta_y}{\Delta_{UC} - \Delta_y}$$

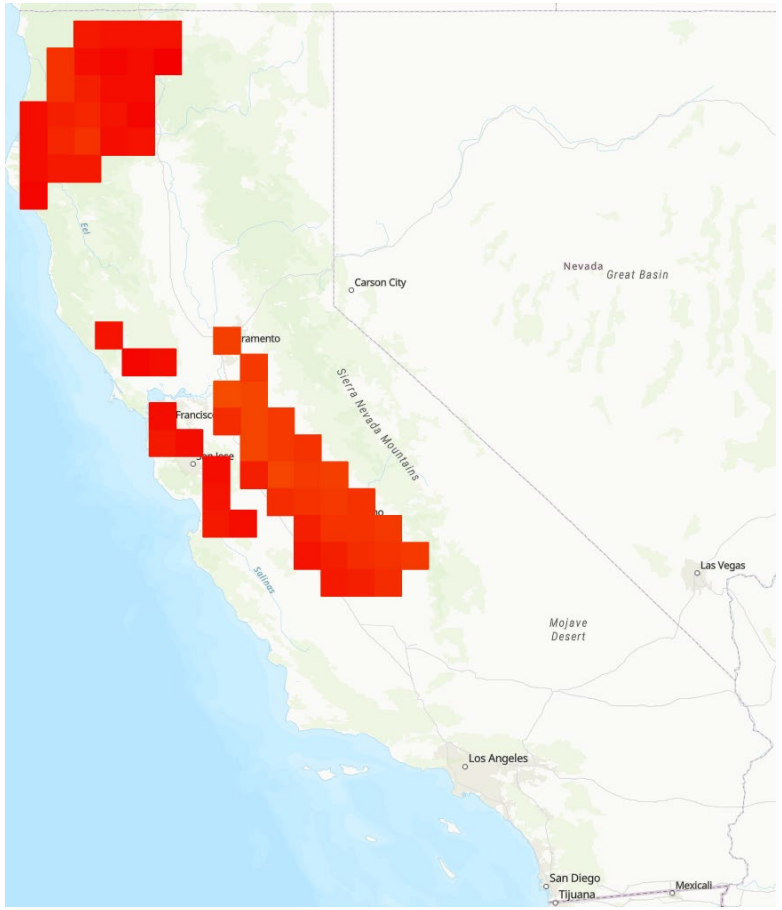
Fraction of DI_L between 0 and 1

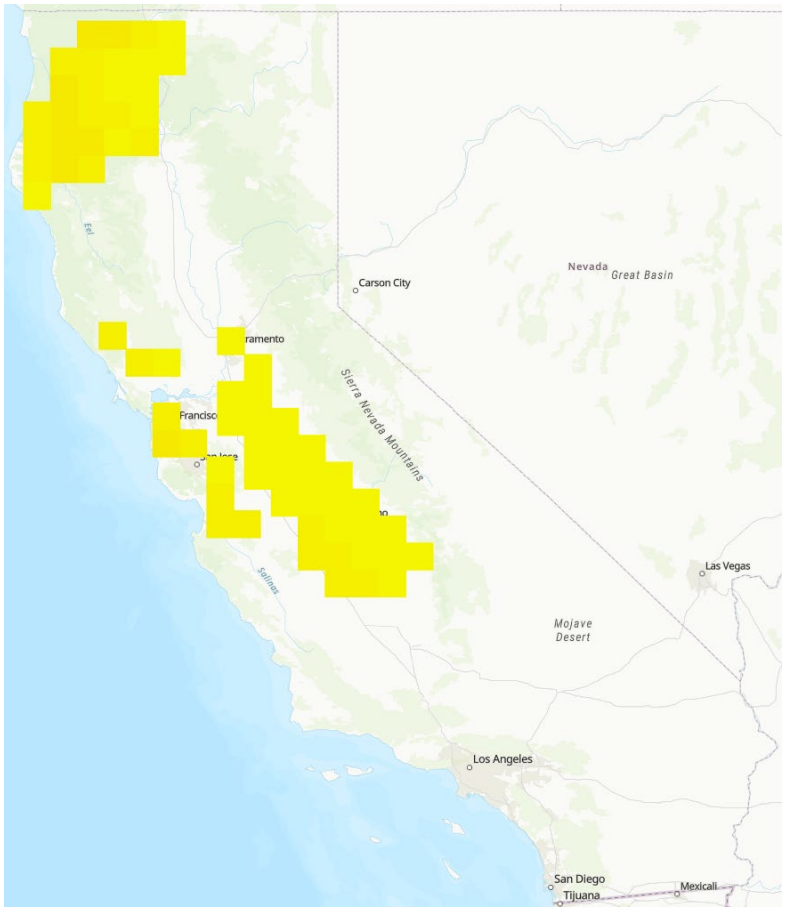
Fraction of $DI_L > 1$

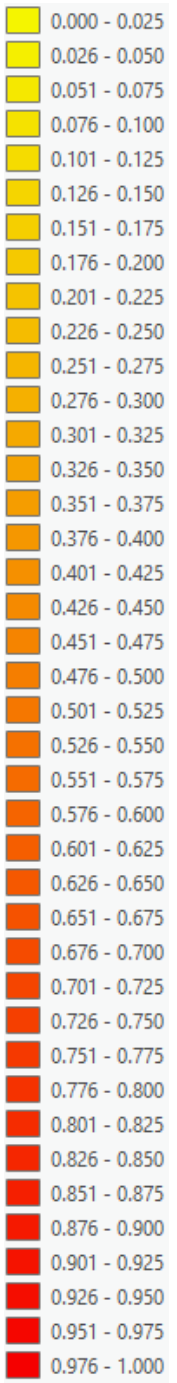
Demand DI Distribution – 975 Yrs

PC24









Fraction of $DI_L < 0$

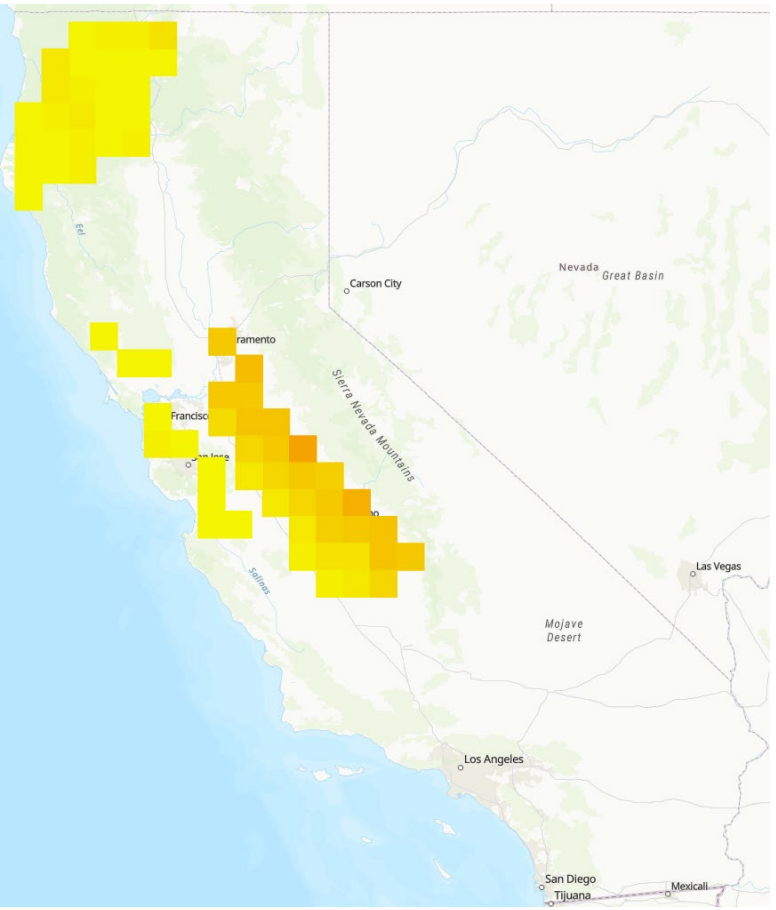
$$DI = \frac{\Delta_D - \Delta_y}{\Delta_{UC} - \Delta_y}$$

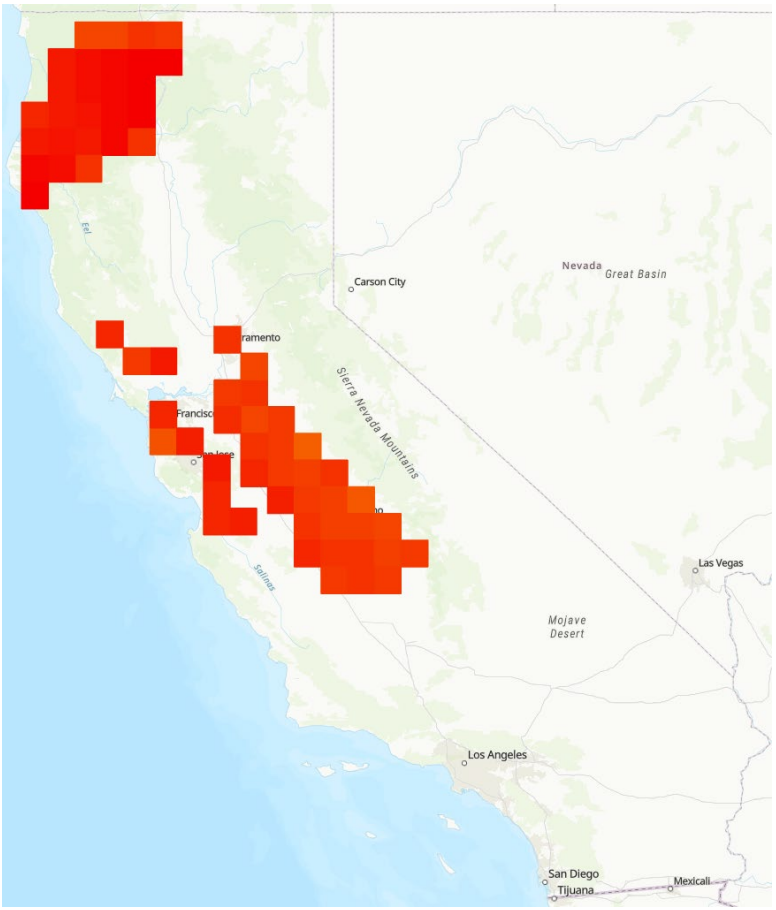
Fraction of DI_L between 0 and 1

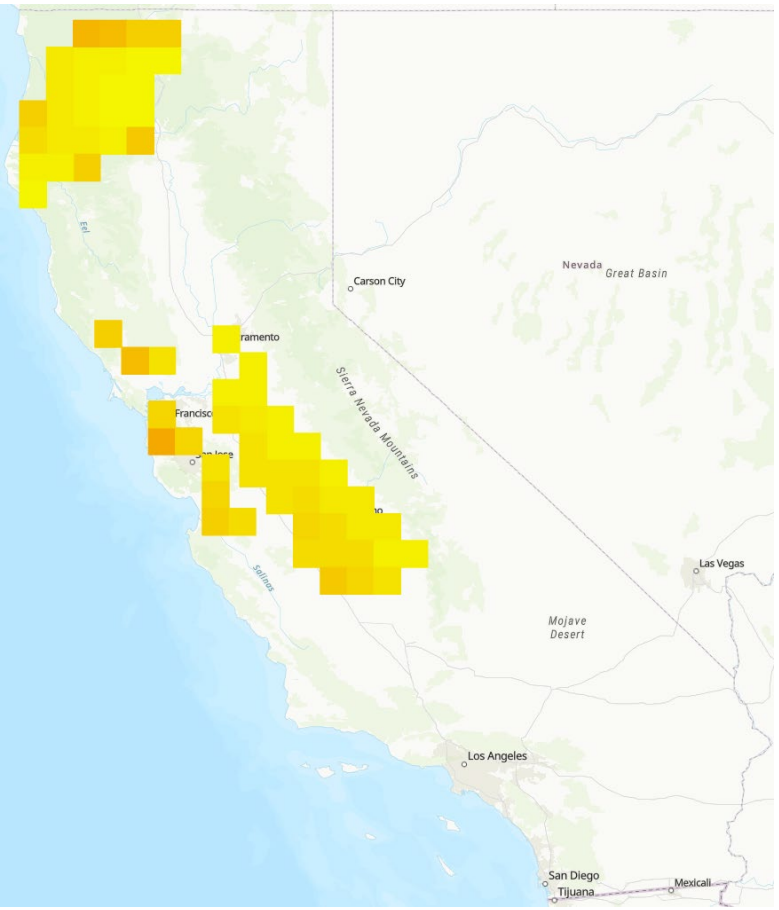
Fraction of $DI_L > 1$

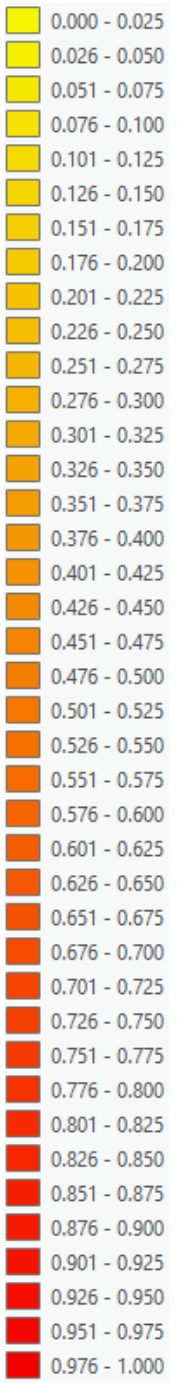
Demand DI Distribution – 2475 Yrs

PC24









Fraction of $DI_L < 0$

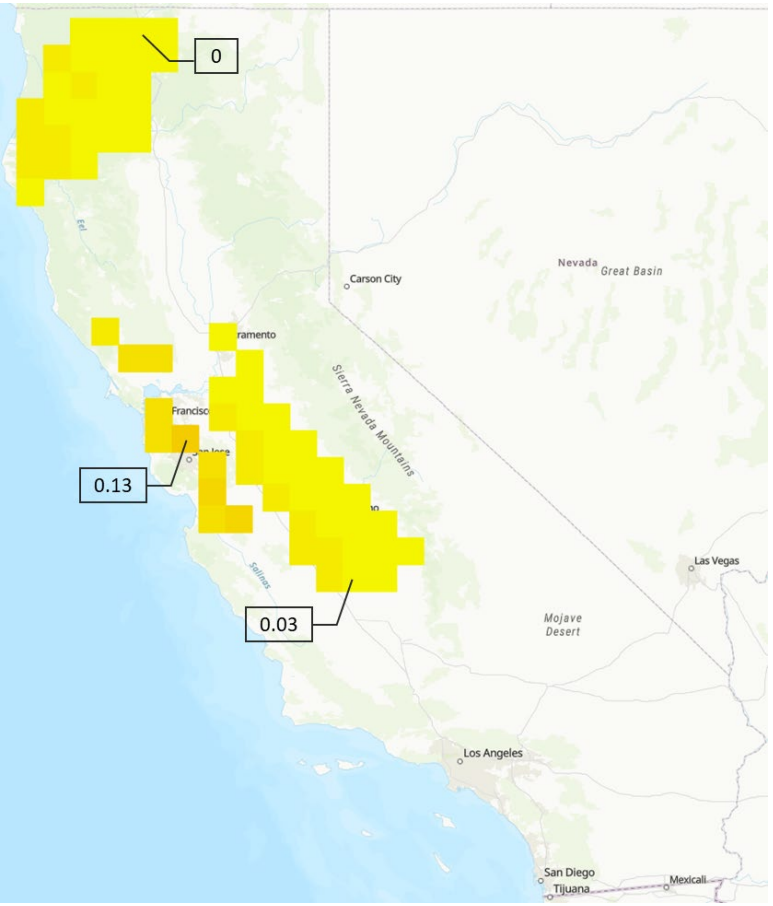
$$DI = \frac{\Delta_D - \Delta_y}{\Delta_{UC} - \Delta_y}$$

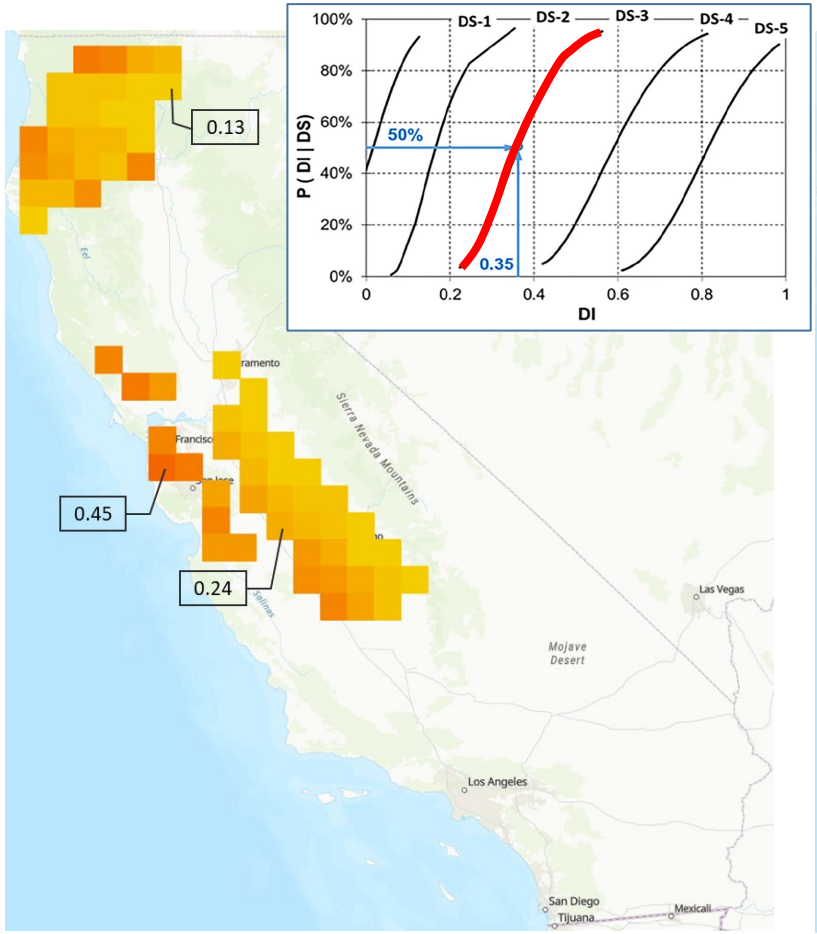
Fraction of DI_L between 0 and 1

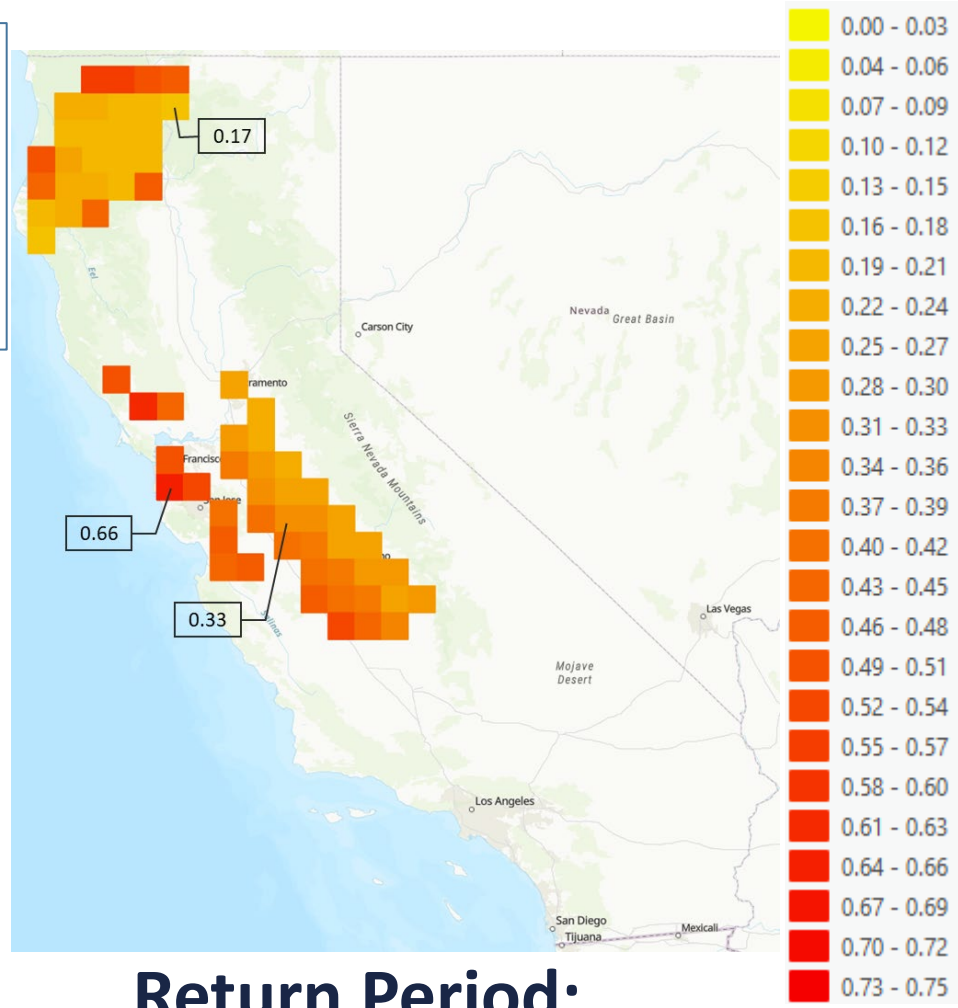
Fraction of $DI_L > 1$

Mean of Demand DI (μ_L)

PC24







Return Period: 225 years

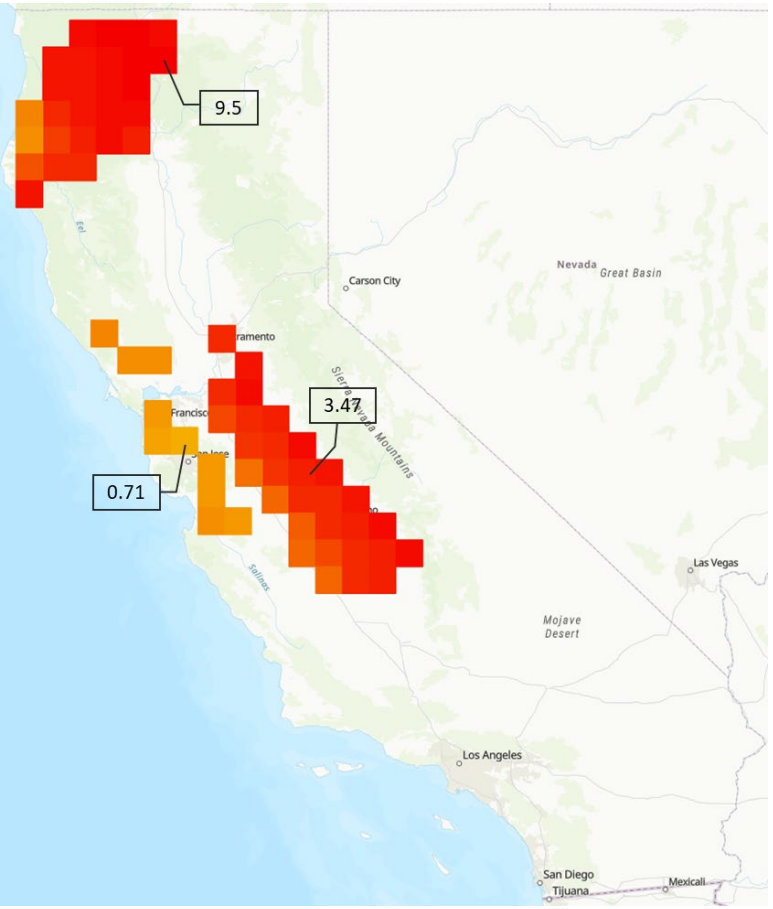
Return Period: 975 years

Return Period: 2475 years

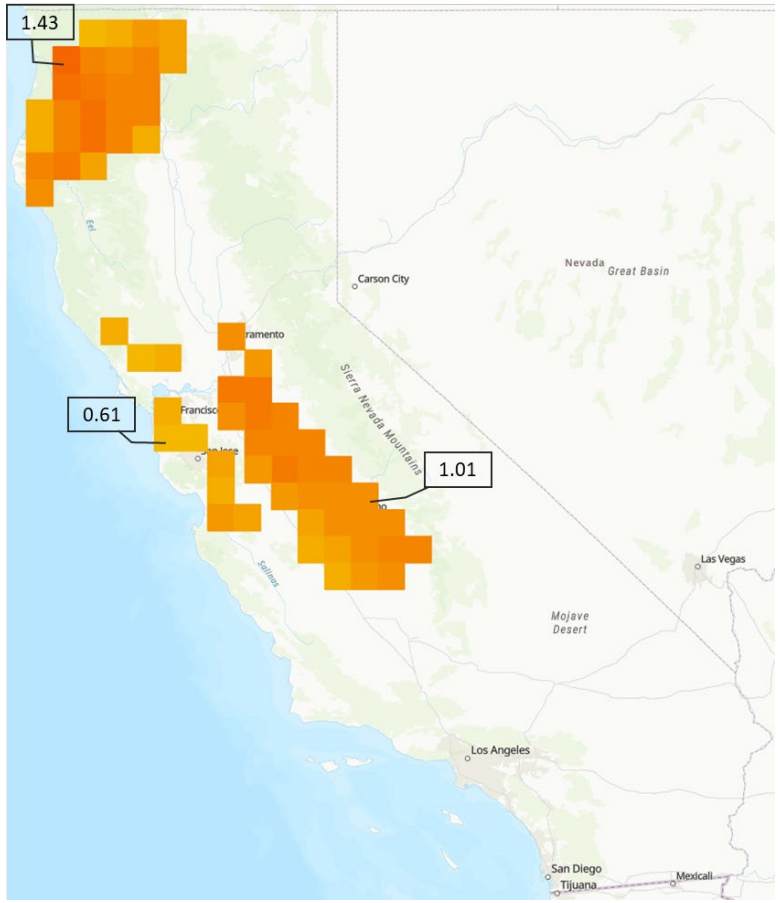
$$DI = \frac{\Delta_D - \Delta_y}{\Delta_{UC} - \Delta_y}$$

COV of Demand DI (δ_L)

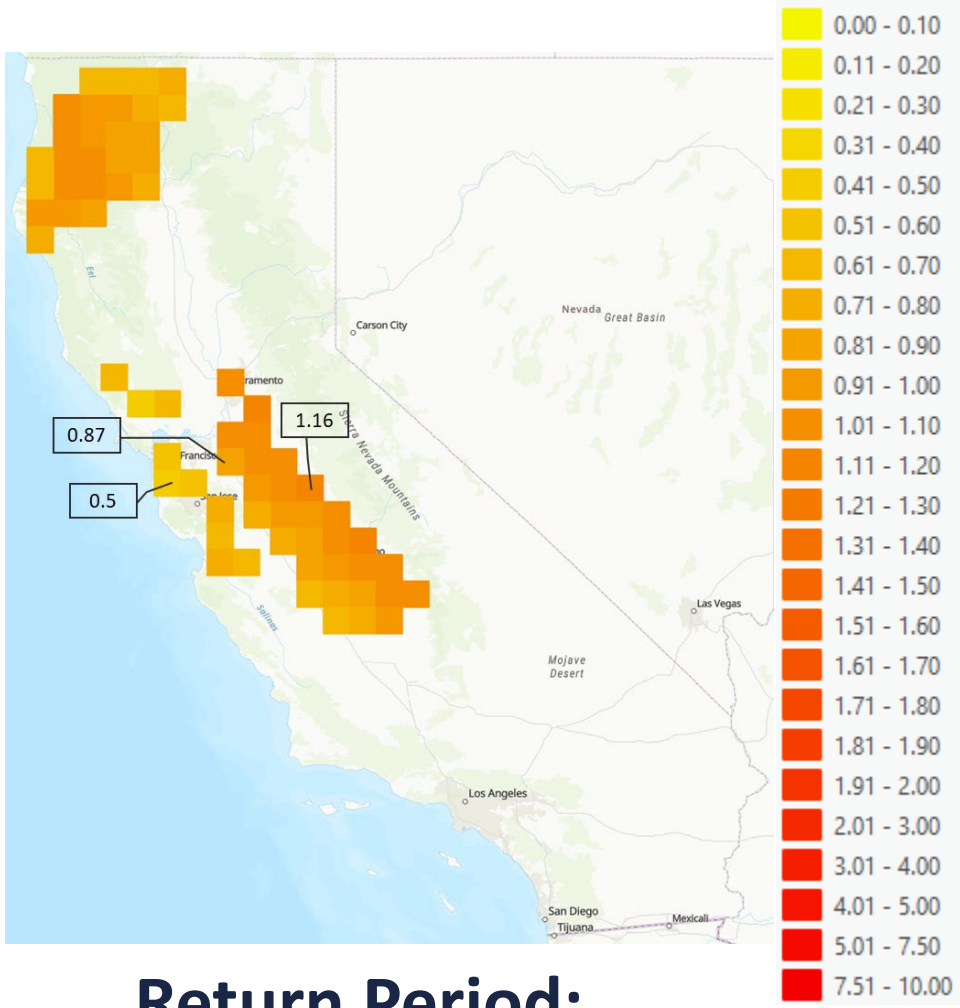
PC24



Return Period: 225 years

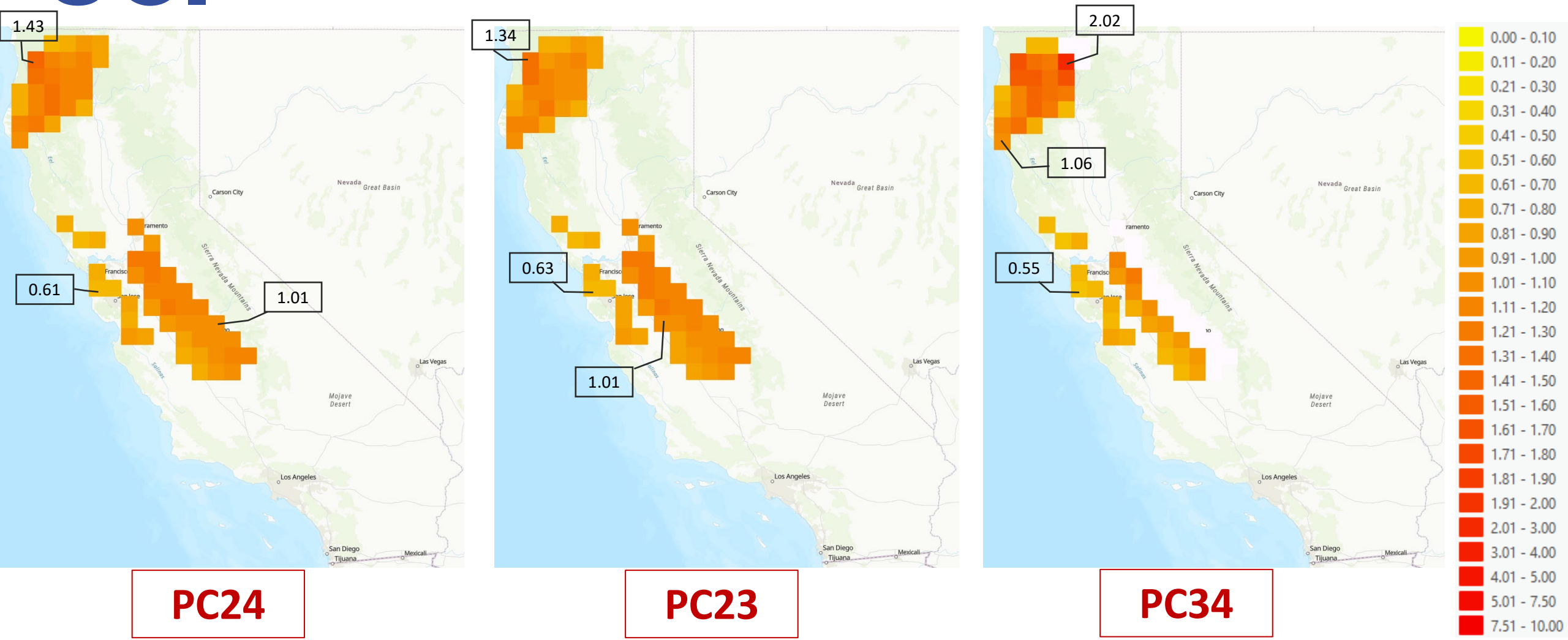


Return Period: 975 years



Return Period: 2475 years

COV of Demand DI (δ_L) by Design Groups – 975 Yrs



PC24

PDCA Group with DI Design between 0.2 and 0.4

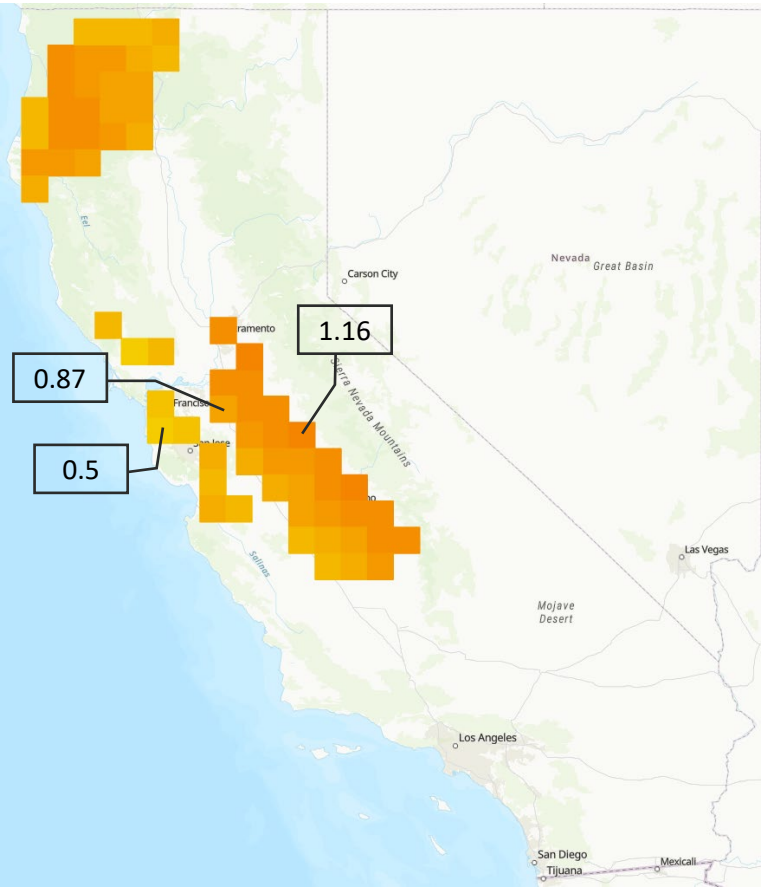
PC23

PDCA Group with DI Design between 0.2 and 0.3 or Recovery Bridges

PC34

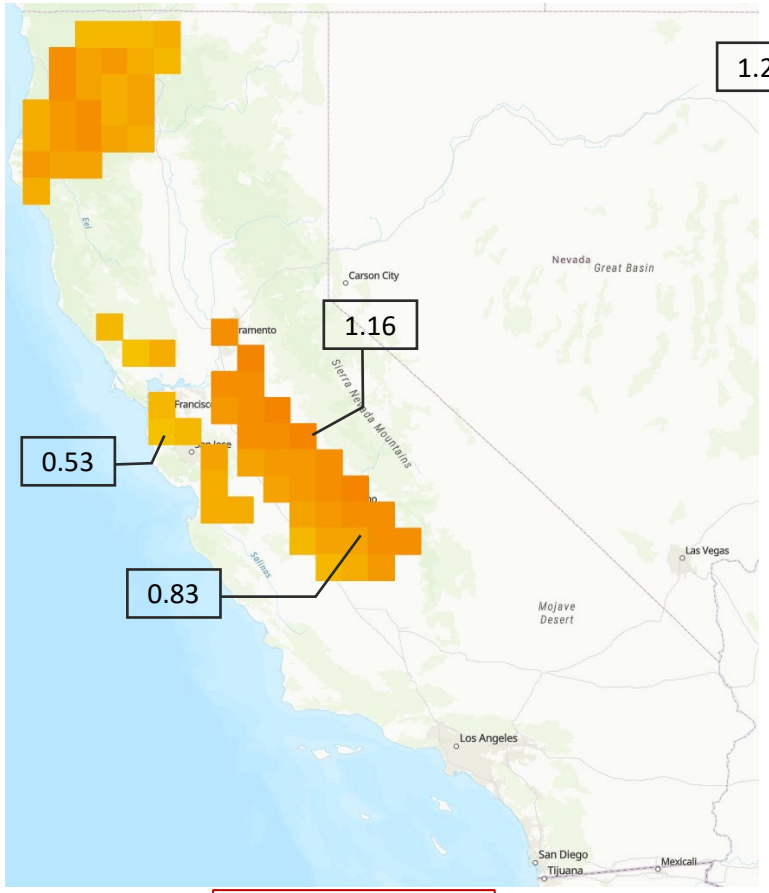
PDCA Group with DI Design between 0.3 and 0.4 or Ordinary Bridges

COV of Demand DI (δ_L) by Design Groups – 2475 Yrs



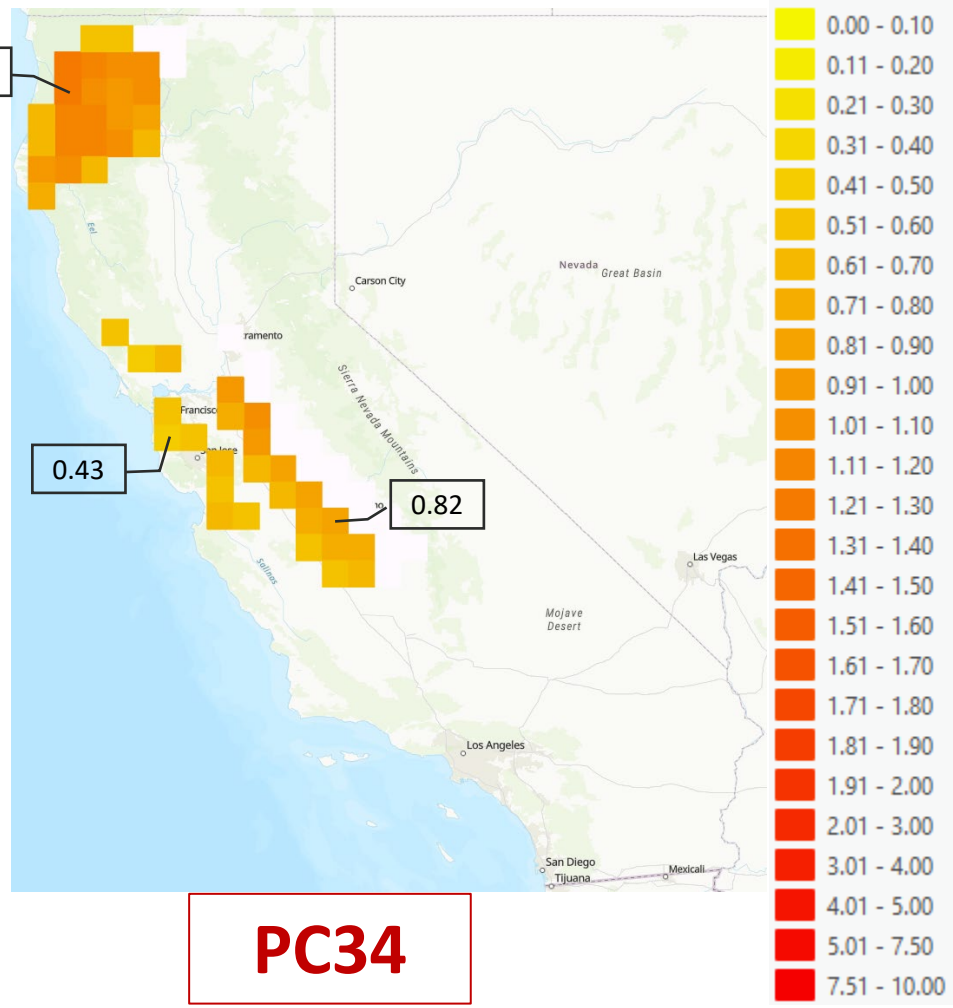
PC24

PDCA Group with DI Design between 0.2 and 0.4



PC23

PDCA Group with DI Design between 0.2 and 0.3 or Recovery Bridges

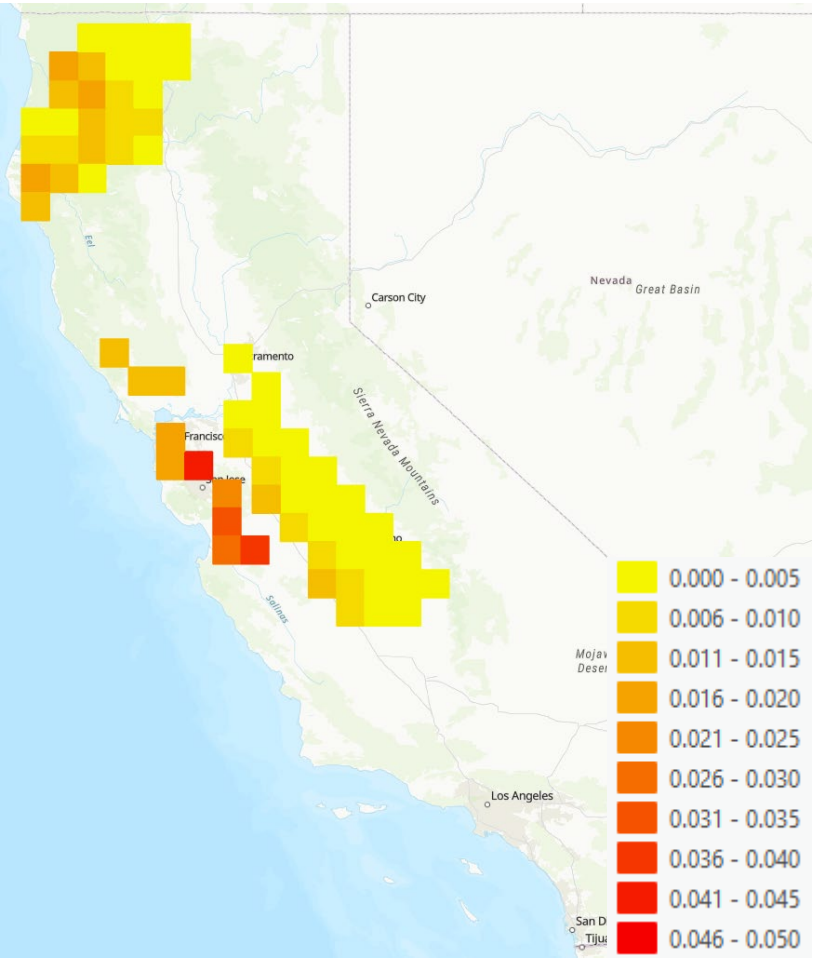


PC34

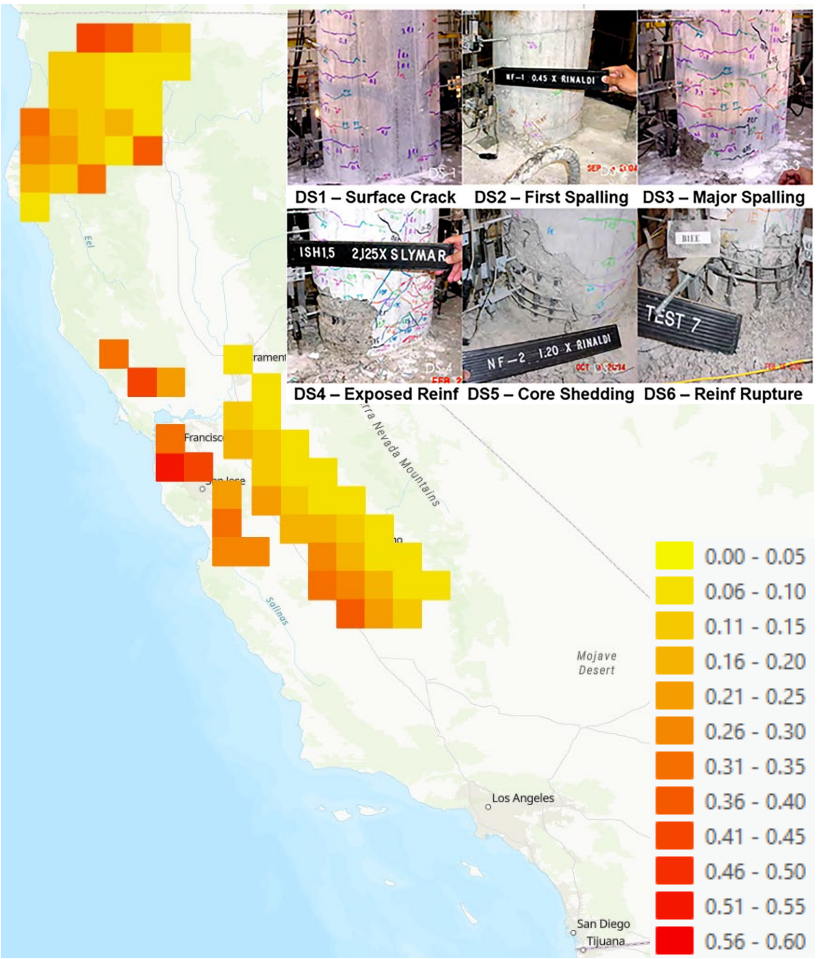
PDCA Group with DI Design between 0.3 and 0.4 or Ordinary Bridges

Probability of Exceedance for Damage State 3

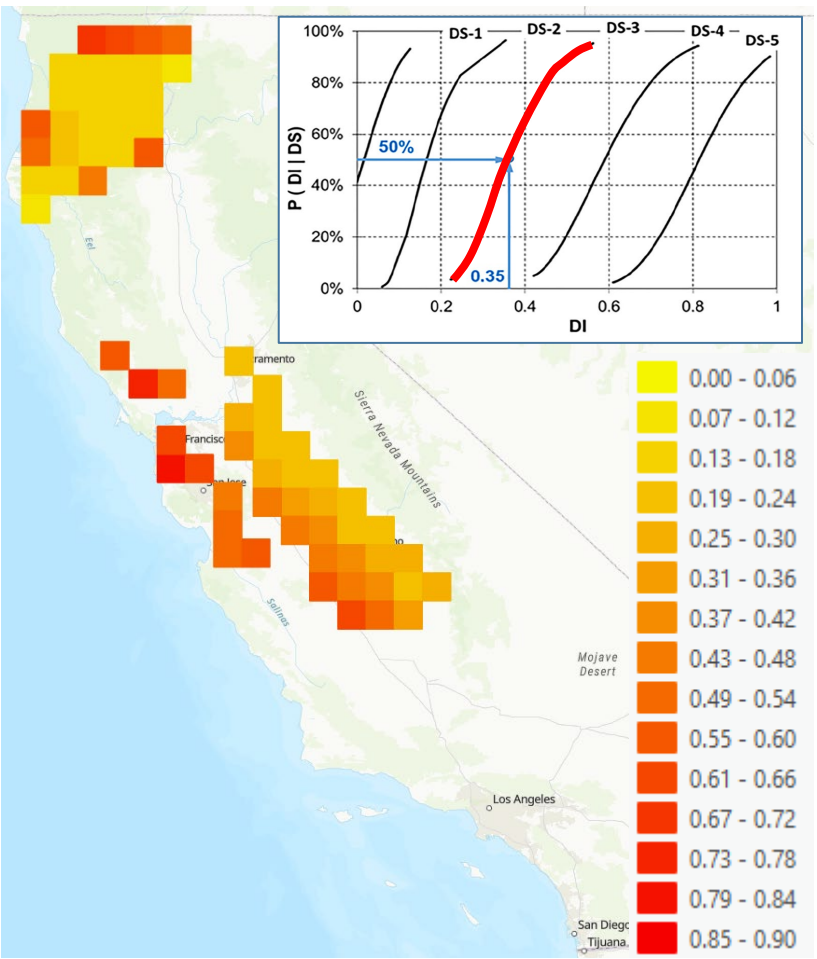
PC24



Return Period: 225 years

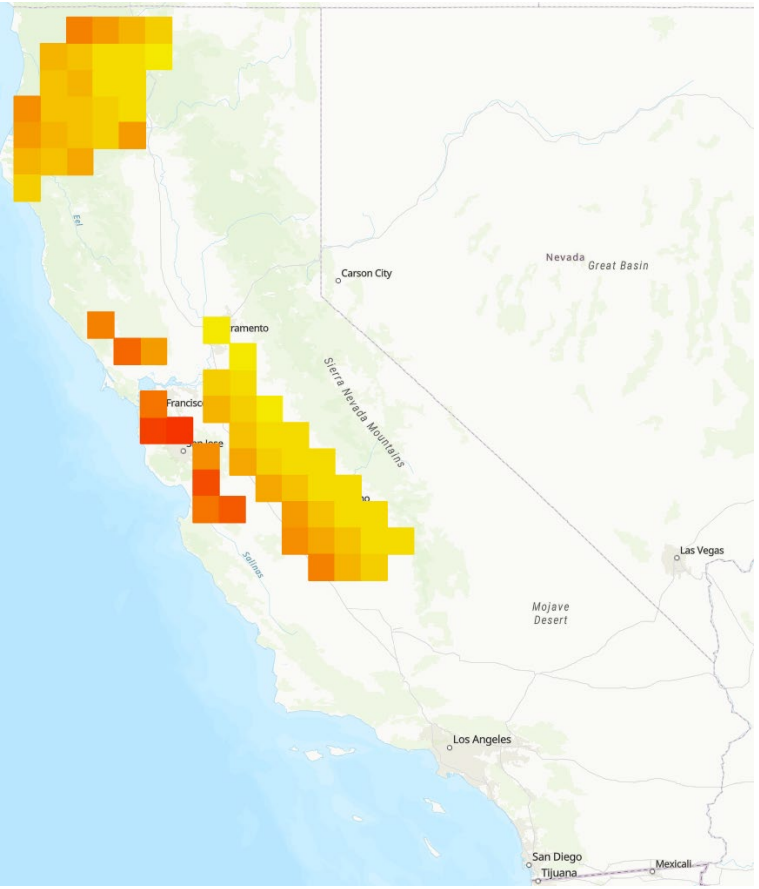


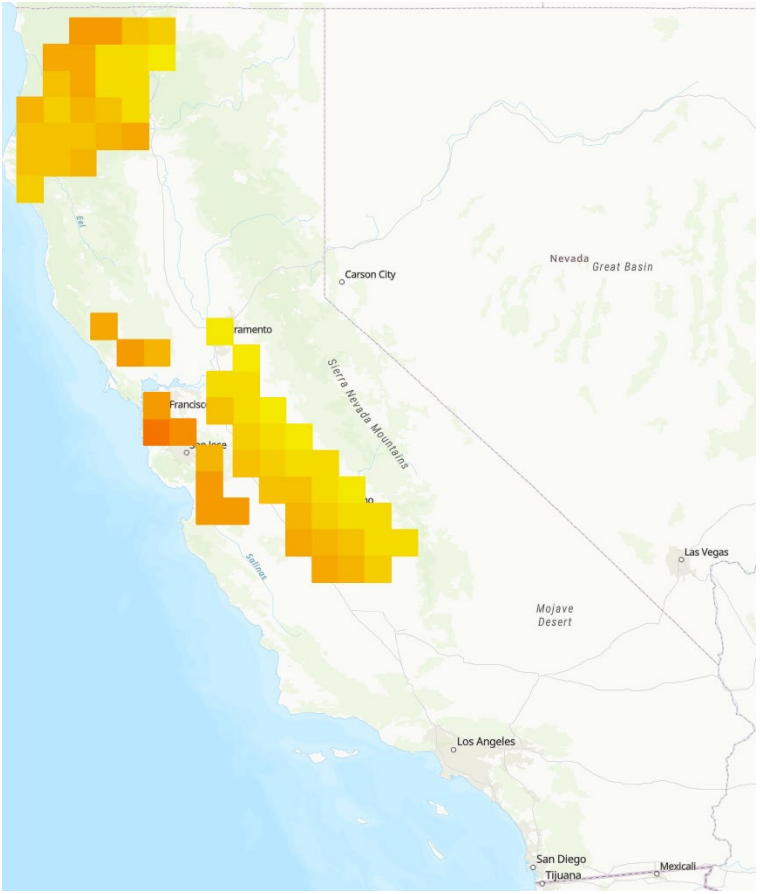
Return Period: 975 years

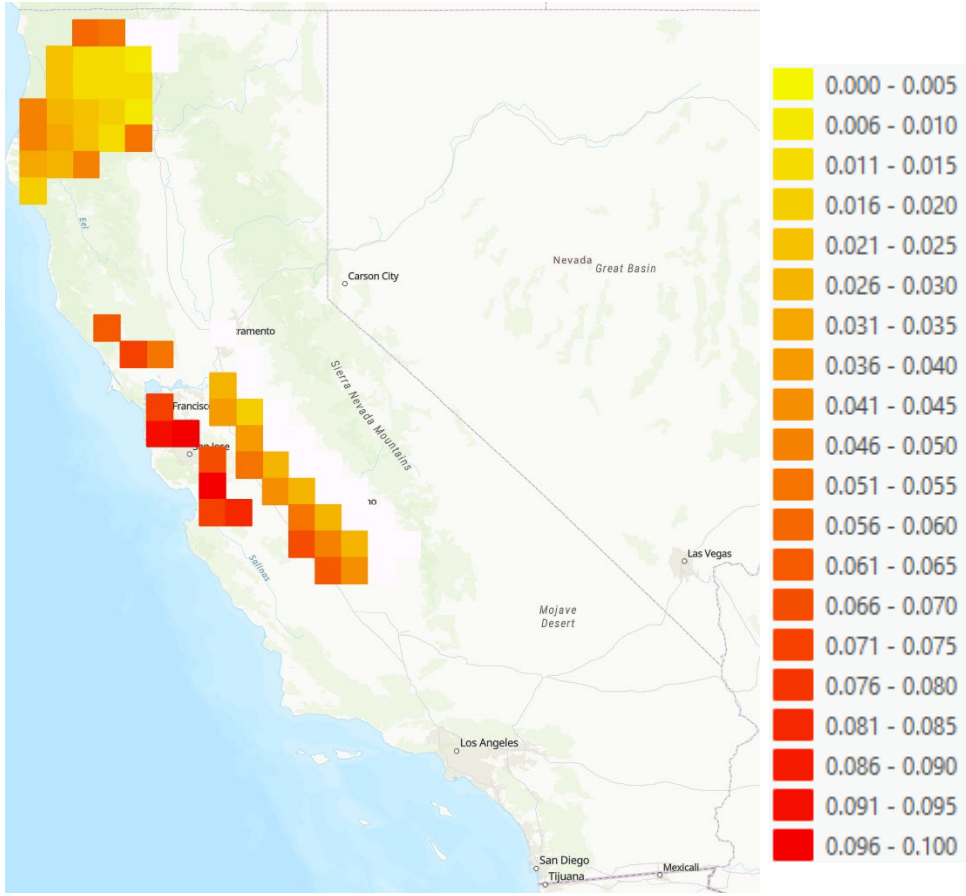


Return Period: 2475 years

Probability of Exceedance in 75 years for Damage State 3







PC24

PDCA Group with DI Design between 0.2 and 0.4

PC23

PDCA Group with DI Design between 0.2 and 0.3 or Recovery Bridges

PC34

PDCA Group with DI Design between 0.3 and 0.4 or Ordinary Bridges

Future Scope

- Complete contour maps of δ_L across California with respect to
  - The three hazard levels – 225, 975 and 2475 yrs return period
  - The two V_{S30} – 259 m/s and 537 m/s
- Refinement of grids for areas with large variations between adjacent locations
- Incorporation of bridge designs in place of column designs
- Example applications for bridge designers

Thank You, Discussion

Revision of Concepts

$$DI = \{di_1, di_2, di_3, \ldots\ldots, di_n\}$$

No Clubbing / Half Clubbing / Clubbing Methods

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

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

Numerical Integration Method

Tri-Part Probability of Failure Estimation

Part I : For values less than 0

$$Pf_1 = \frac{Number\ of\ values\ in\ DI\ less\ than\ 0}{n}$$

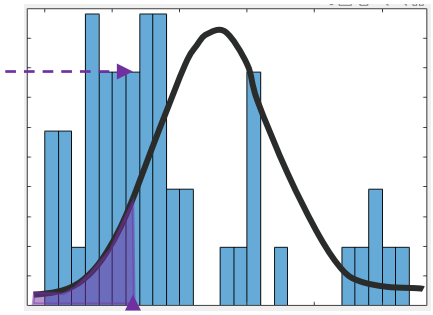
Part III : For values more than 1

$$Pf_3 = \frac{Number\ of\ values\ in\ DI\ more\ than\ 1}{n}$$

Total Probability

$$\boldsymbol{Pf = Pf_1 * 0 + (1 - Pf_1 - Pf_3) * I + Pf_3 * 1}$$

Part II : For values between 0 and 1



$$I = \sum_{DI} \underbrace{F_R(di)}_{\text{Capacity (Saiidi et al.)}} * \underbrace{fL(di)}_{\text{Demand (Histogram)}}$$

Probability Estimation for a Damage State

The individual hazard probabilities calculated using any of the four methods were integrated over the hazard curve for a Probability of Exceedance of Damage State i in a life span of 75 years for the respective bridge

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

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

$P(GM_{high}) = P(GM > GM_{600yr}) - P(GM > GM_{1725yr})$

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