Research Update: Caltrans Risk-Based Seismic Design (CT-RBSD) for Bridges

25th March 2025

Presented By –

Farzin Zareian

Banatao Auditorium, Berkeley, CA • March 25-26

2025 PEER Annual Meeting

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Acknowledgments

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

Sharon Yen, Mark Mahan, Tony Yoon, Amir Malek, Sam Ataya, Ashraf Ahmed, Toorak Zokaie, Christian Unanwa | Team

PEER

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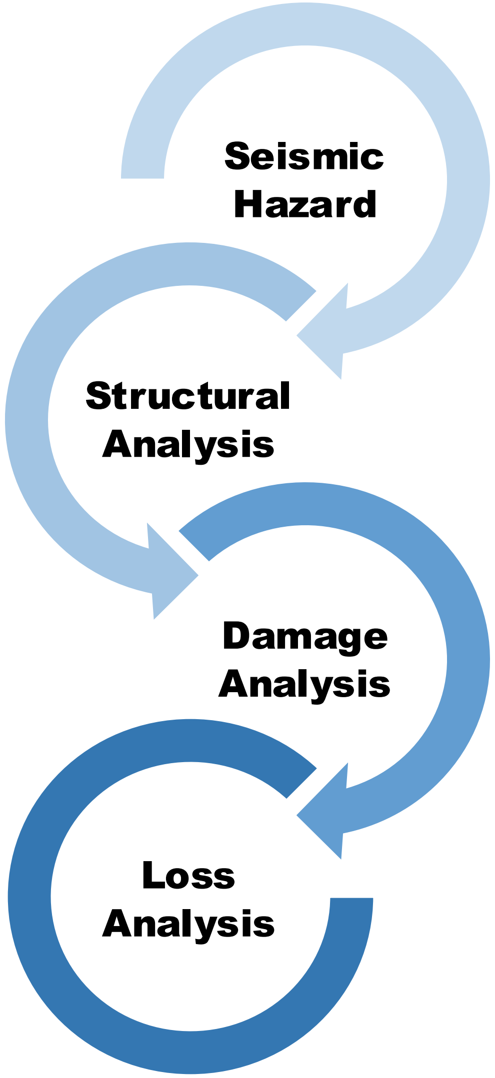
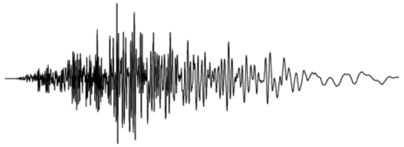
Chris Traina

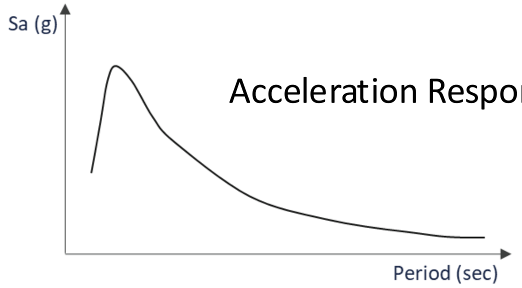
Saurabh Singhal
Graduate Student Investigator

Performance-Based Design

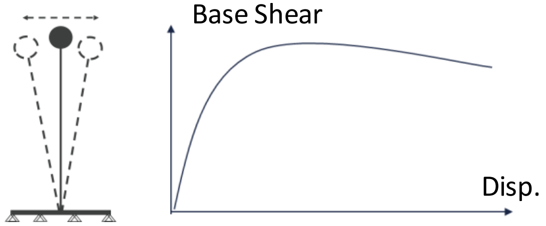


Ground motion time history

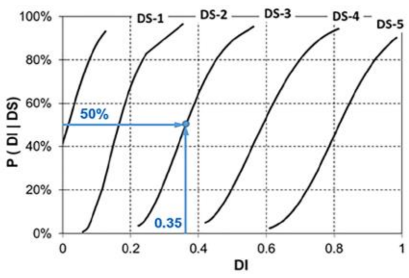




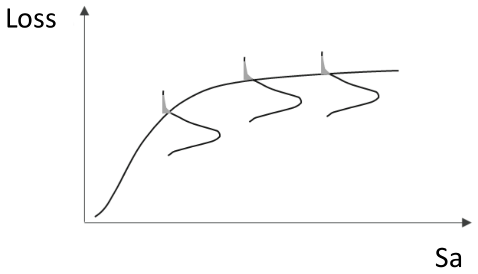
- Equivalent Static Analysis
- Elastic Dynamic Analysis
- Nonlinear Time History Analysis

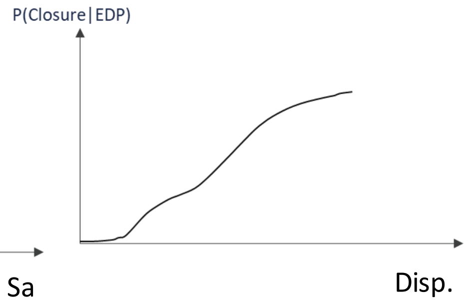


Probability of exceeding a damage state (e.g. collapse)

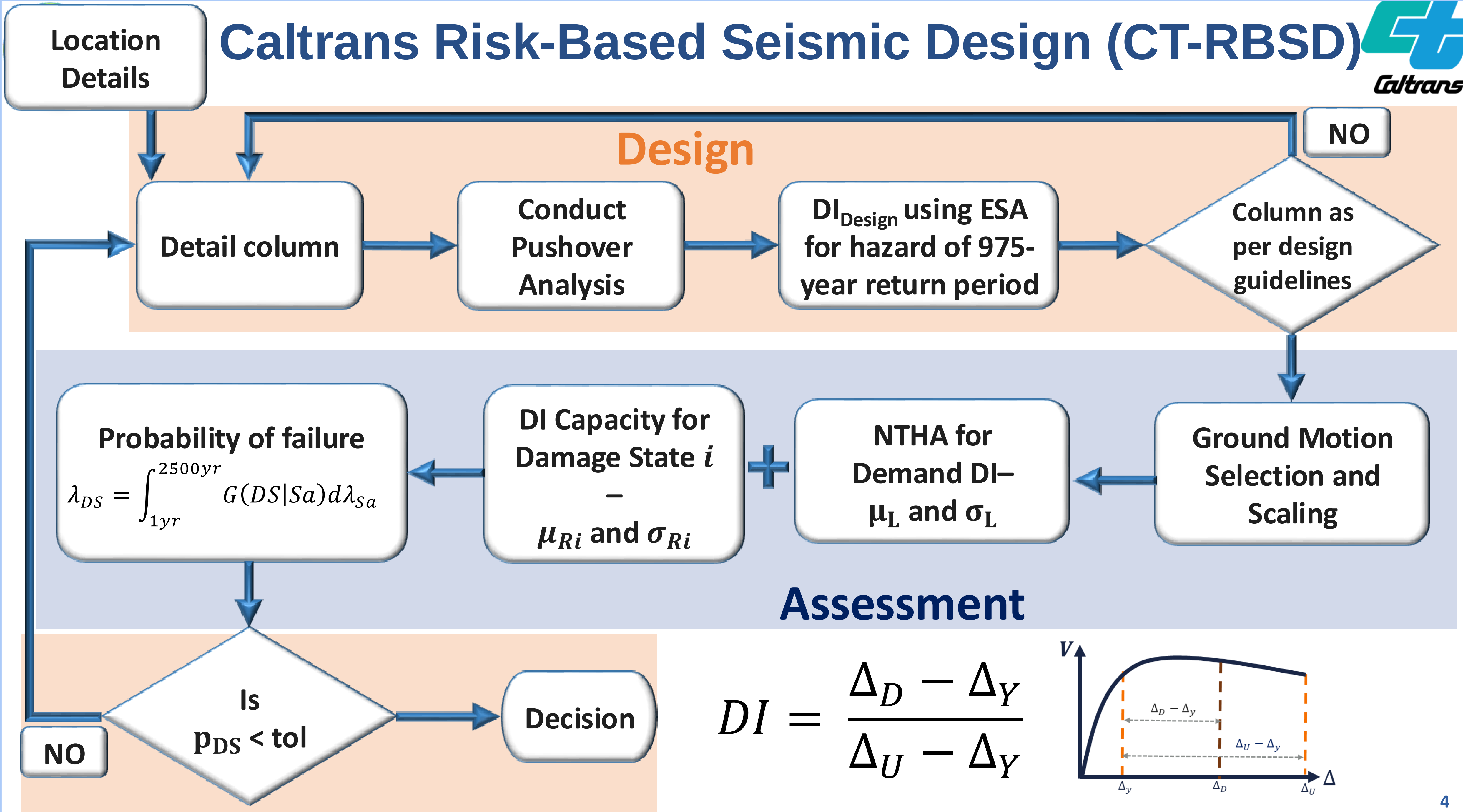


Expected losses such as repair cost and repair time





Caltrans Risk-Based Seismic Design (CT-RBSD)



$$DI = \frac{\Delta_D - \Delta_Y}{\Delta_U - \Delta_Y}$$

Caltrans Risk-Based Seismic Design (CT-RBSD)

Probability of failure

$$\lambda_{DS} = \int_{1yr}^{2500yr} G(DS|Sa)\, d\lambda_{Sa}$$

DI Capacity for Damage State i – μ_{Ri} and σ_{Ri}

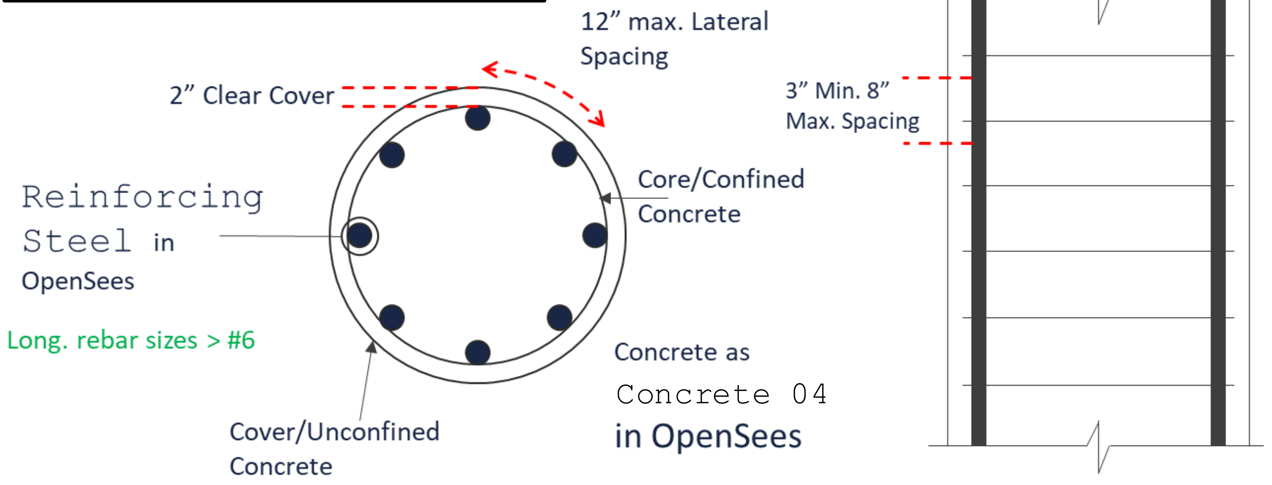
+

NTHA for Demand DI– μ_L and σ_L

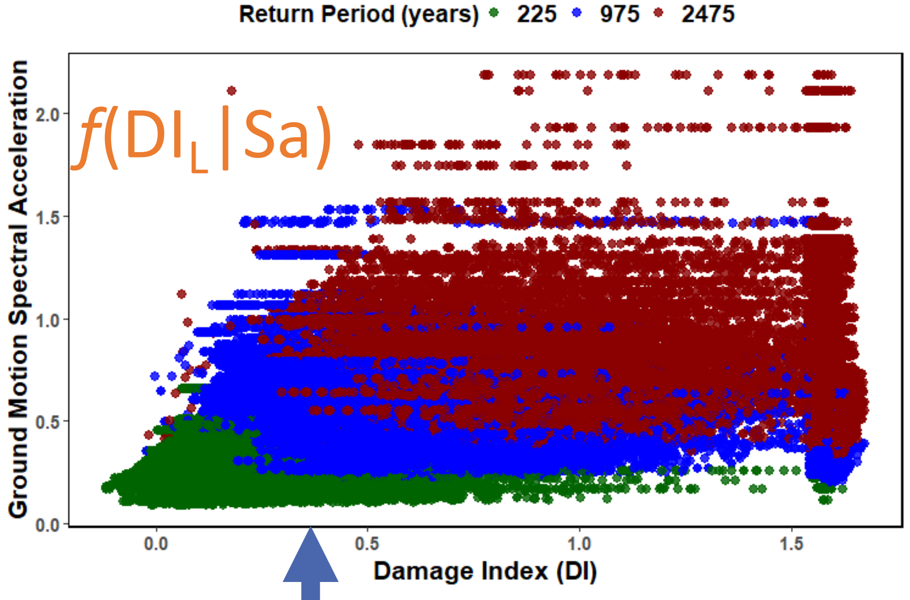
Ground Motion Selection and Scaling

Assessment

Bridge Column Model



Target Hazard (975 year)



Target DI (0.35)

Caltrans Risk-Based Seismic Design (CT-RBSD)

Probability of failure

$$\lambda_{DS} = \int_{1yr}^{2500yr} G(DS|Sa)\, d\lambda_{Sa}$$

←

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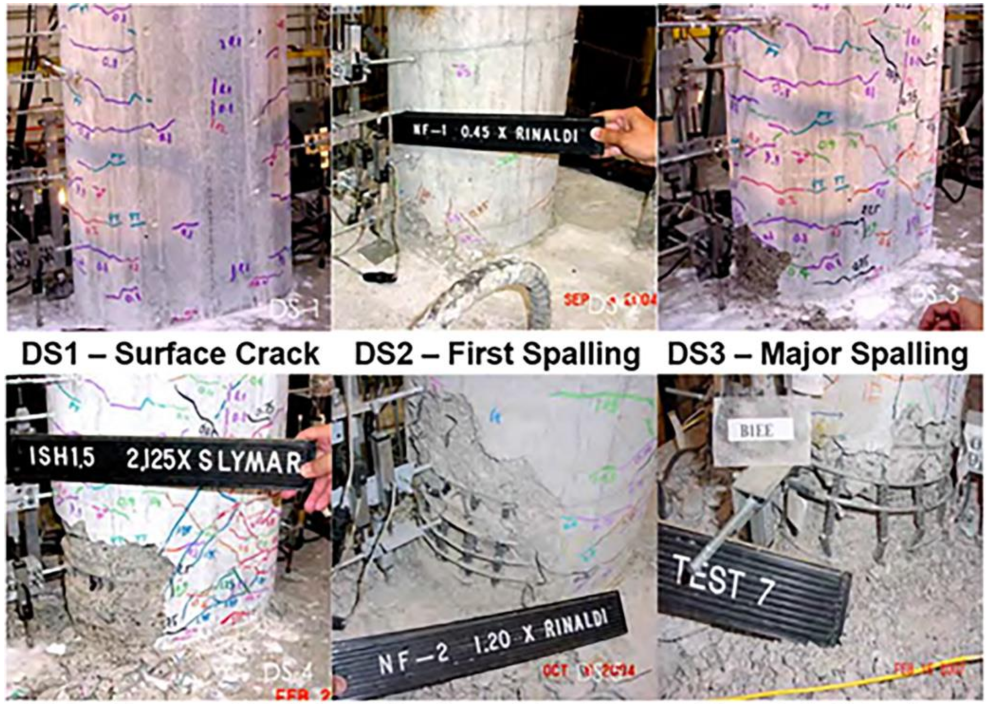
\+

NTHA for Demand DI– μ_L and σ_L

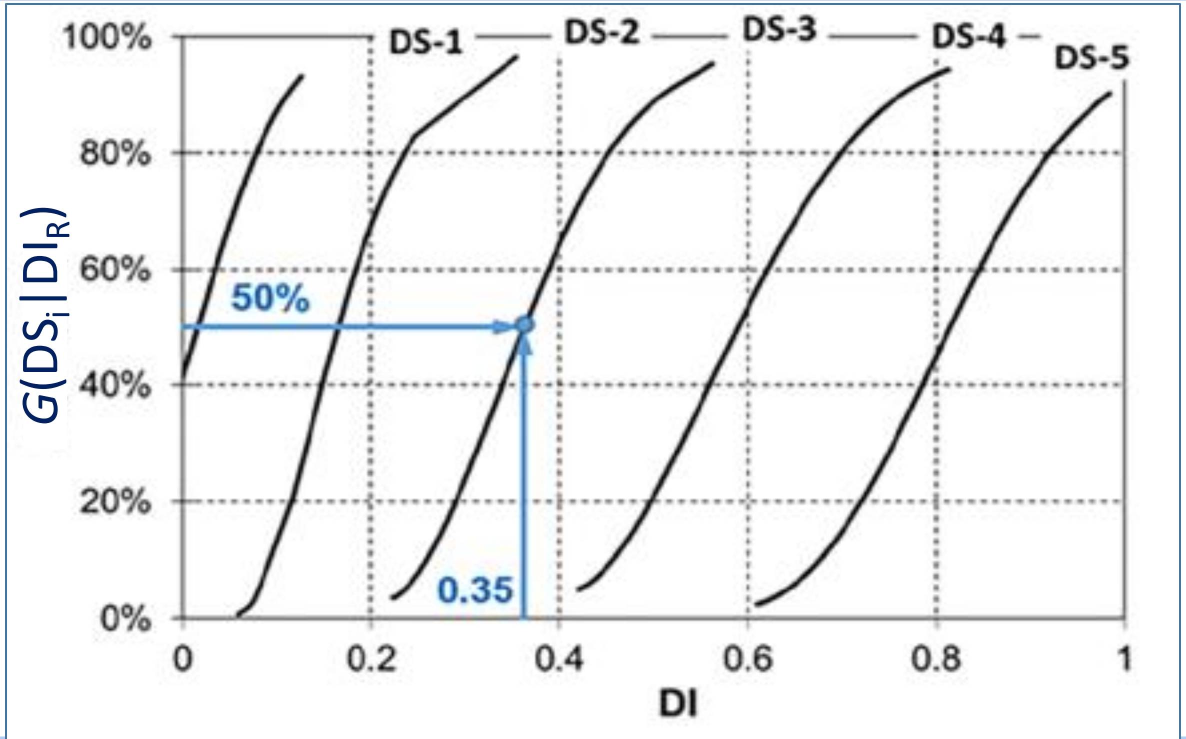
←

Ground Motion Selection and Scaling

Assessment



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



Caltrans Risk-Based Seismic Design (CT-RBSD)

Probability of failure

$$\lambda_{DS} = \int_{1yr}^{2500yr} G(DS|Sa)\, d\lambda_{Sa}$$

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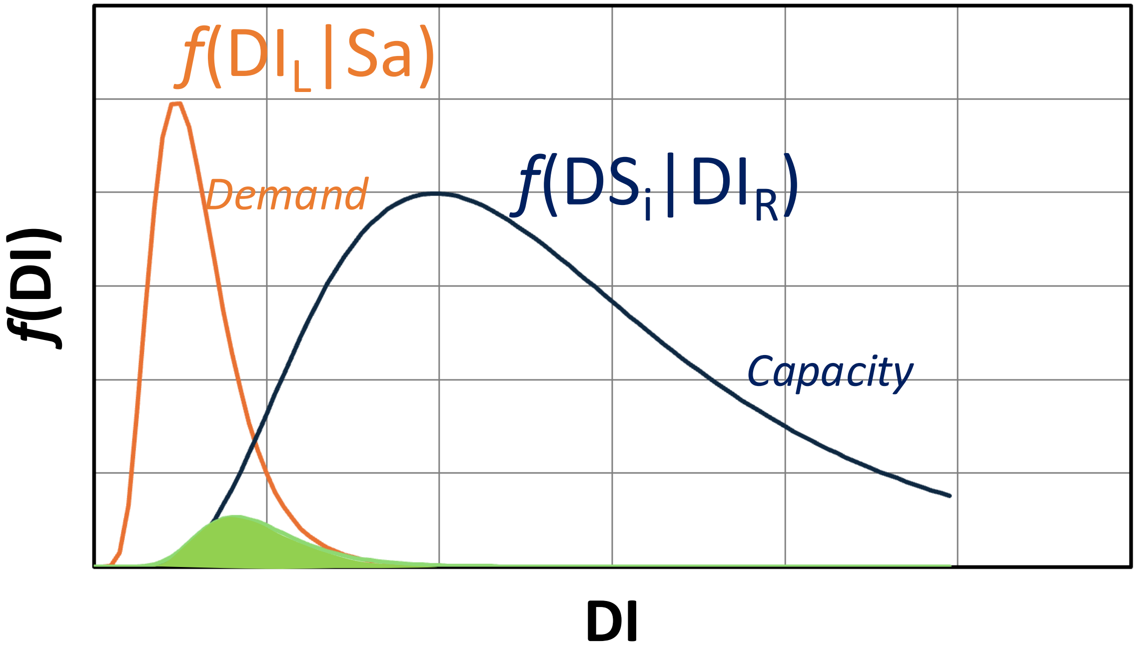
Ground Motion Selection and Scaling

Assessment



$$G(DS_i|Sa) = \int G(DS_i|DI_R) X f(DI_L|Sa)(dDI_L)$$

Caltrans Risk-Based Seismic Design (CT-RBSD)

Probability of failure

$$\lambda_{DS} = \int_{1yr}^{2500yr} G(DS|Sa)\, d\lambda_{Sa}$$

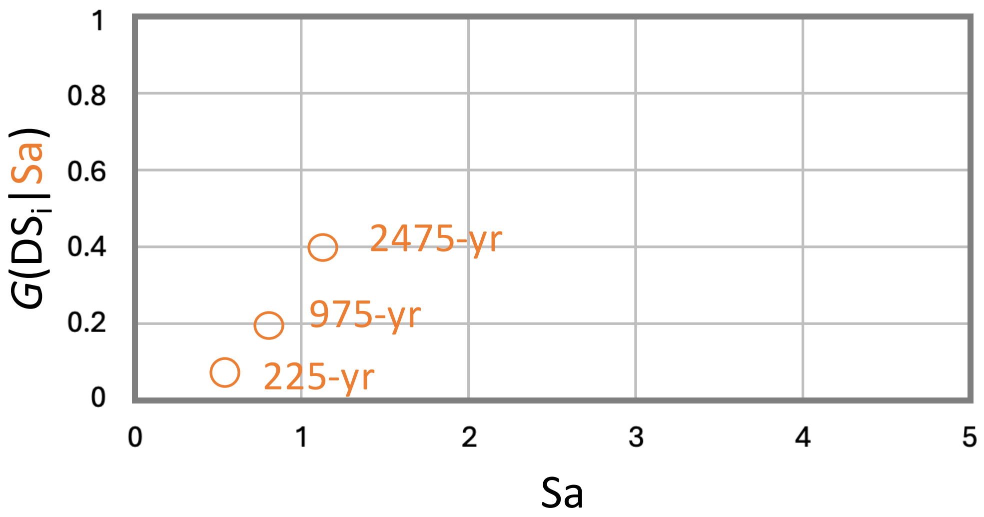
← **DI Capacity for Damage State i – μ_{Ri} and σ_{Ri}** + **NTHA for Demand DI– μ_L and σ_L** ← **Ground Motion Selection and Scaling**

Assessment

$G(\mathrm{DS_i}\,|\,\mathrm{Sa})$

$$\beta_{DS_i}|Sa = \frac{\ln\left(\frac{\mu_{R_i}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{R_i}^2+1}}\right)}{\sqrt{\ln[(\delta_L^2+1)(\delta_{R_i}^2+1)]}} \rightarrow G(\mathrm{DS_i}|\mathrm{Sa}) = 1-\Phi(\beta_{DS_i}|Sa) \rightarrow$$

Damage State Fragility Curve



Caltrans Risk-Based Seismic Design (CT-RBSD)

Probability of failure

$$\lambda_{DS} = \int_{1yr}^{2500yr} G(DS|Sa)\, d\lambda_{Sa}$$

←

DI Capacity for Damage State i – μ_{Ri} and σ_{Ri}

+

NTHA for Demand DI– μ_L and σ_L

←

Ground Motion Selection and Scaling

Assessment

$G(DS_i | Sa)$

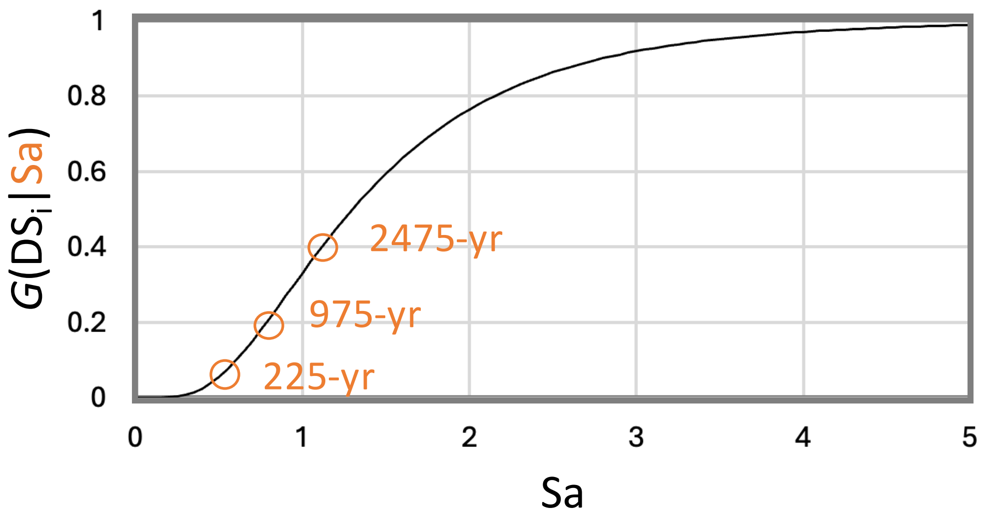
$$\beta_{DS_i}|Sa = \frac{\ln\left(\frac{\mu_{R_i}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{R_i}^2+1}}\right)}{\sqrt{\ln[(\delta_L^2+1)(\delta_{R_i}^2+1)]}}$$

→

$$G(DS_i|Sa) = 1 - \Phi(\beta_{DS_i}|Sa)$$

→

Damage State Fragility Curve



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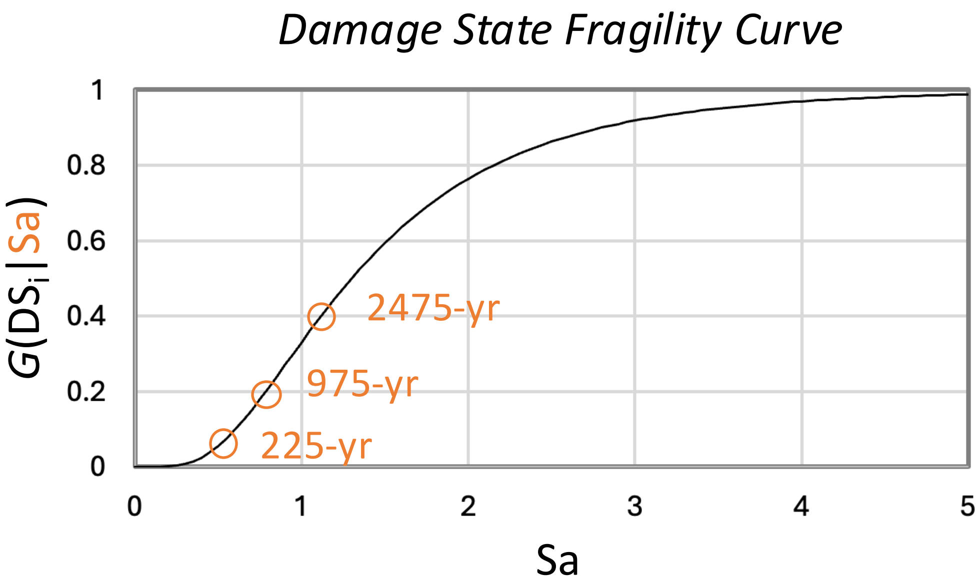
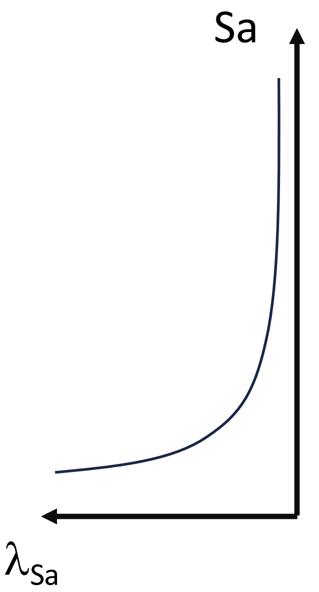
Ground Motion Selection and Scaling

Assessment

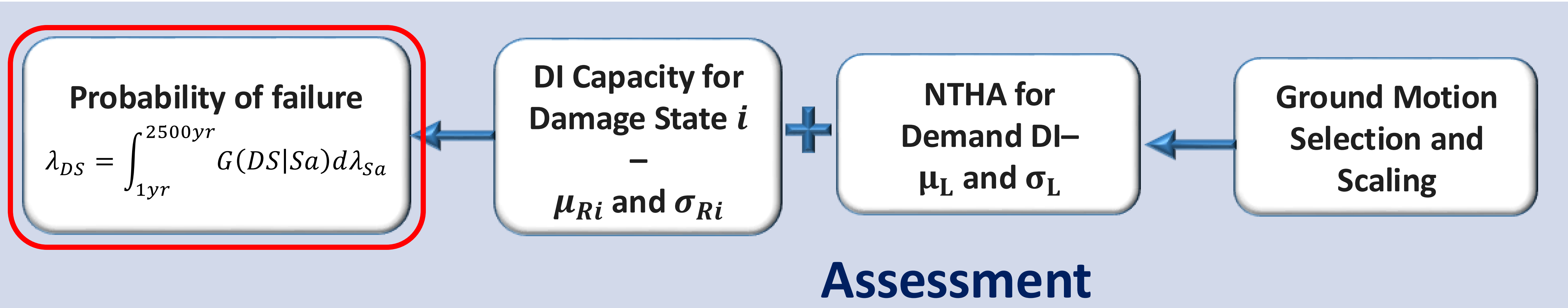




$$\lambda_{DS_i} = \int_{1yr}^{2500yr} G(DS_i|Sa)\,d\lambda_{Sa}$$

Integrate fragility over hazard

Caltrans Risk-Based Seismic Design (CT-RBSD)



$$\lambda_{DS_i} = \int_{1yr}^{2500yr} G(DS_i|Sa)\, d\lambda_{Sa}$$

$$P_{DS_i} in\ 75\ years = 1 - \exp(-\lambda_{DS_i} \times 75)$$

Caltrans Risk-Based Seismic Design (CT-RBSD)

Probability of failure

$$\lambda_{DS} = \int_{1yr}^{2500yr} G(DS|Sa)\,d\lambda_{Sa}$$

←

DI Capacity for Damage State i – μ_{Ri} and σ_{Ri}

+

NTHA for Demand DI– μ_L and σ_L

←

Ground Motion Selection and Scaling

?? **Assessment**

$$\beta_{DS_i}|Sa = \frac{\ln\left(\frac{\mu_{R_i}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{R_i}^2+1}}\right)}{\sqrt{\ln[(\delta_L^2+1)(\delta_{R_i}^2+1)]}}$$

Caltrans Risk-Based Seismic Design (CT-RBSD)

Probability of failure

$$\lambda_{DS} = \int_{1yr}^{2500yr} G(DS|Sa)\, d\lambda_{Sa}$$

DI Capacity for Damage State i – μ_{Ri} and σ_{Ri}

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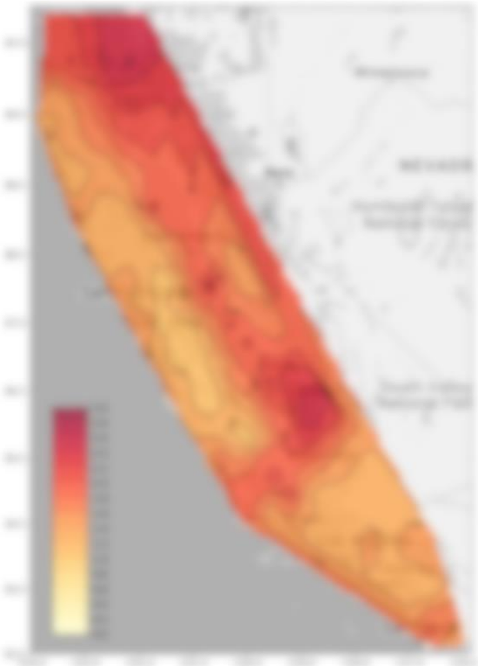
Ground Motion Selection and Scaling

Assessment

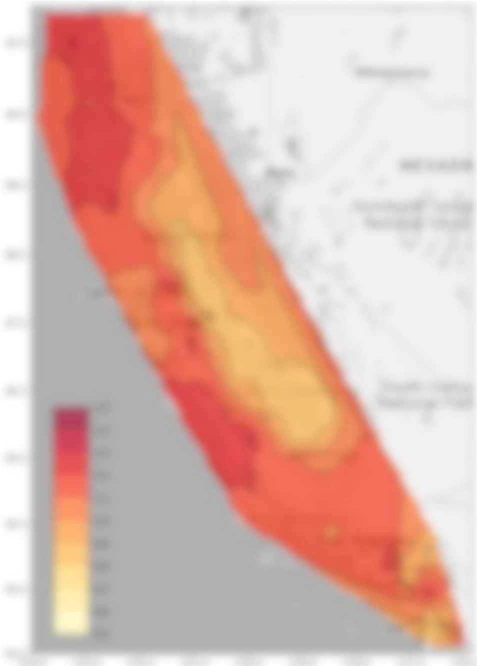
Coefficient of Variation, δ_L



$$\beta_{DS_i}|Sa = \frac{\ln\left(\frac{\mu_{R_i}}{\mu_L}\sqrt{\frac{\delta_L^2+1}{\delta_{R_i}^2+1}}\right)}{\sqrt{\ln[(\delta_L^2+1)(\delta_{R_i}^2+1)]}}$$

$$\mu_L = \frac{\varphi_L \times \Delta_{ESA} - \Delta_y}{\Delta_u - \Delta_y}$$

Displacement Adjustment Factor, φ_L

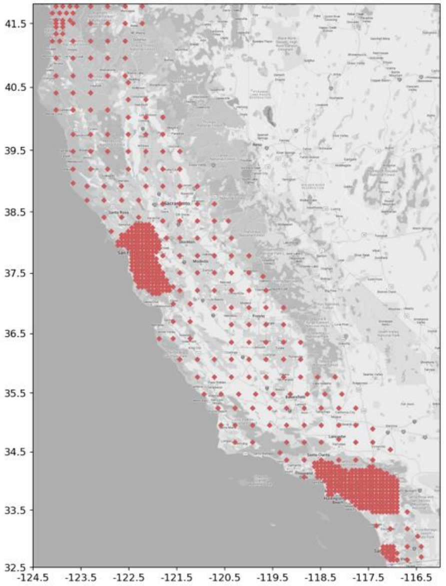


Data and Models

Site Class

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

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



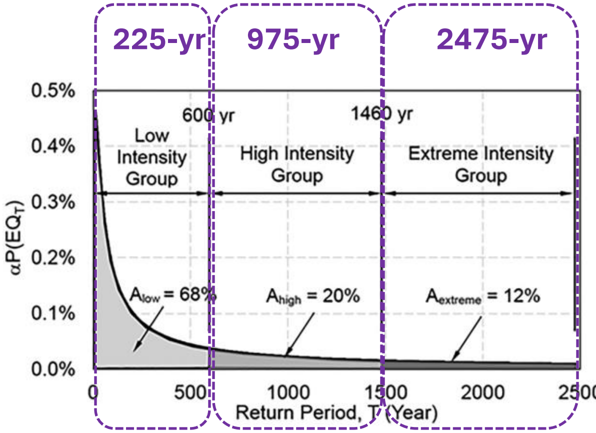
664 Locations

Bridge Column Geometric Parameters

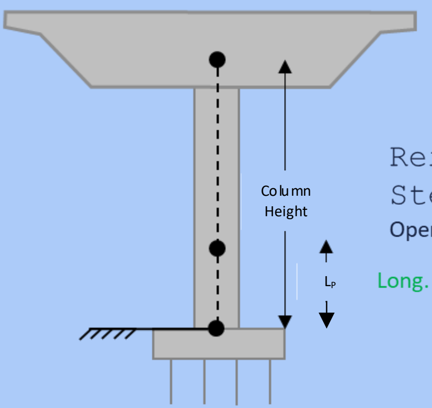
Parameter	Cases
Column Height (ft)	20, 30, 40, 50
Axial Force	$0.05f'_cA_g$, $0.10f'_cA_g$, $0.15f'_cA_g$
Long. Reinf. Ratio (%)	1.0, 1.75, 2.5
Diameter (ft)	5, 6, 7, 8
Hoop Rebar Sizes	#5, #6, #7, #8
Hoop Spacings (in)	3, 4, 5, 6, 7, 8

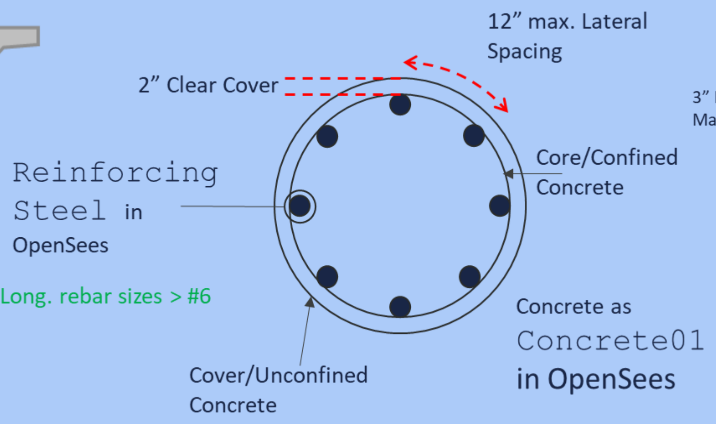
(Total Column Designs ~800,000)

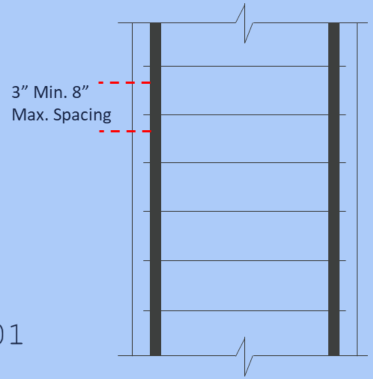
3 Representative Hazard Levels



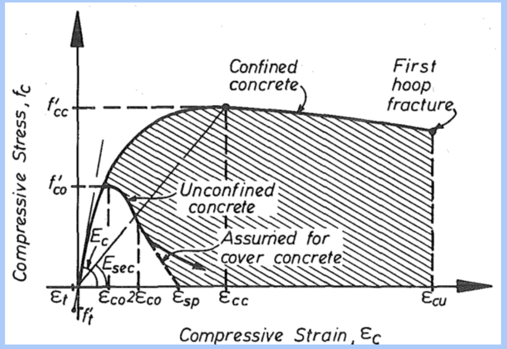
Bridge Column Model







Expected Unconfined Concrete Strength	5 ksi
Unconfined concrete compressive strain	0.002
Ultimate unconfined compressive strain	0.005
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

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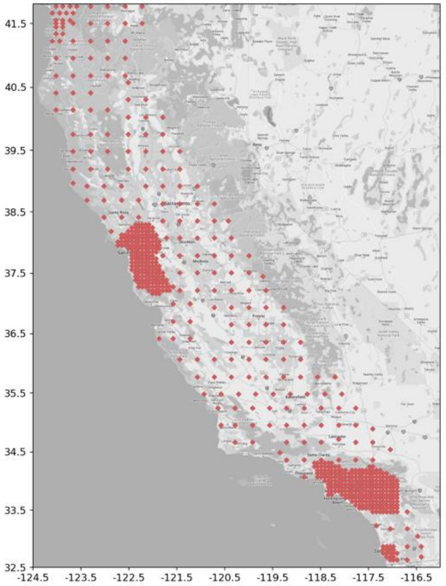
×



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×

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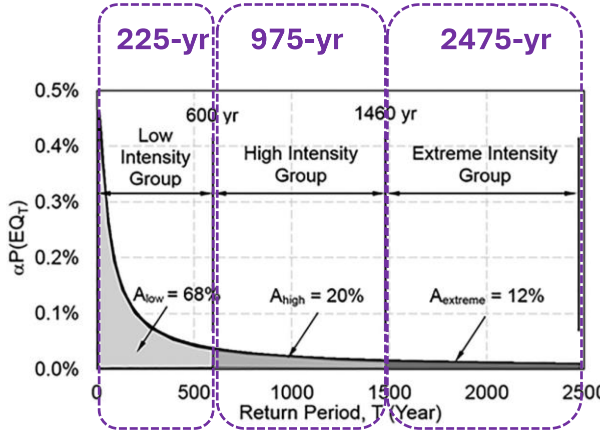


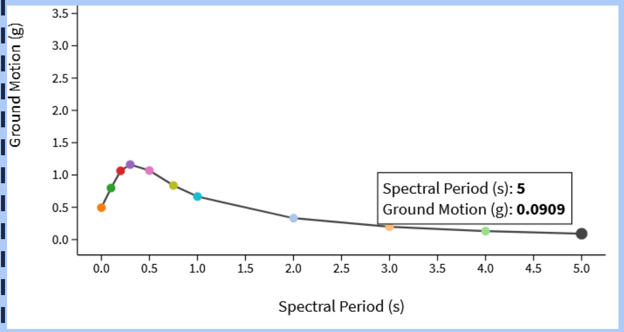
Ground Motion Model

Site Class

+

Hazard Level

→



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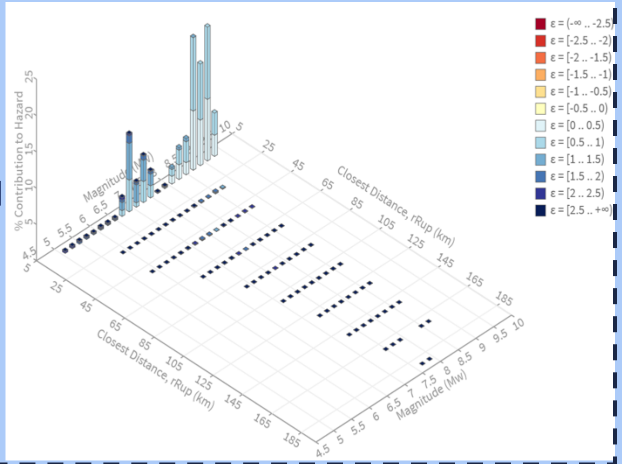


- ✓ *Uniform Hazard Curve and Hazard Deaggregation from USGS Unified Hazard Tool 2018*

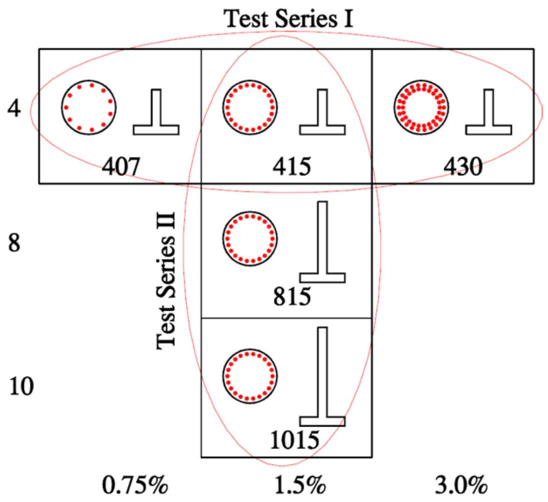
→

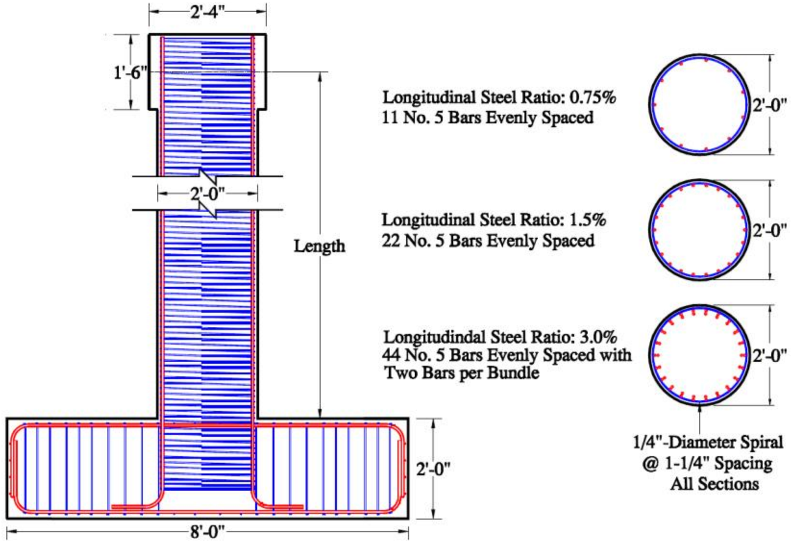
51 Ground Motions

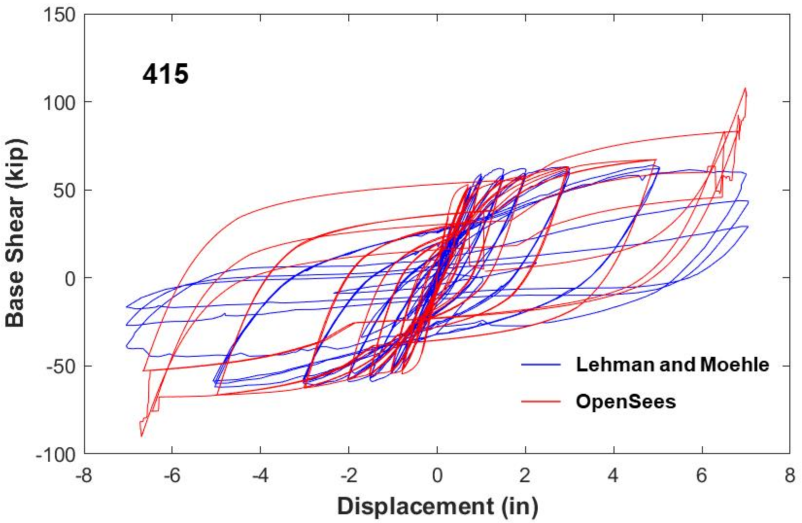
- ✓ *GM simulation algorithm by Razaeian et al. (2012) and Dabaghi et al. (2018)*

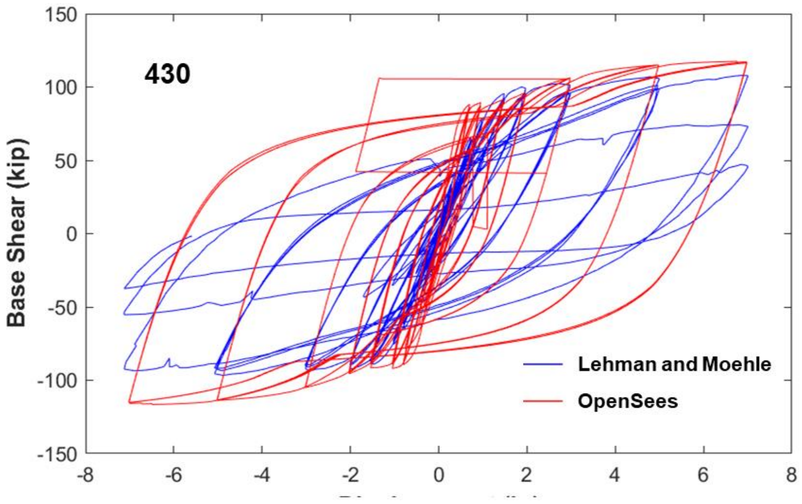
Structural Model Validation

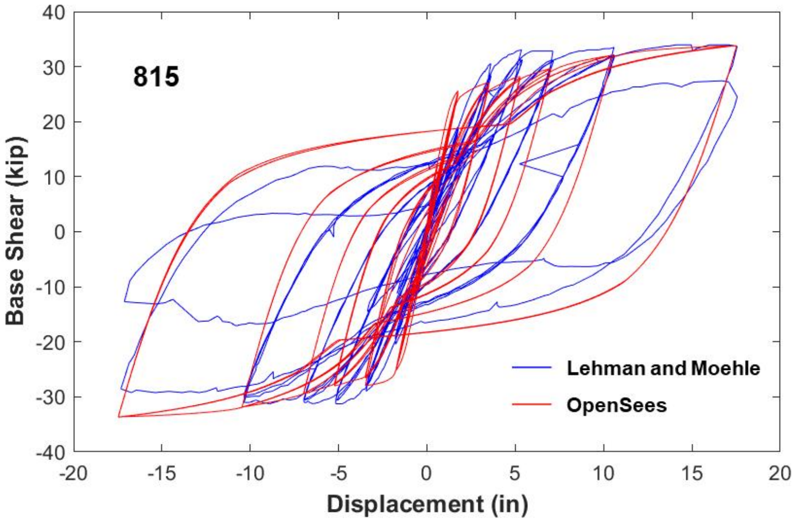
Lehman and Moehle (2000)

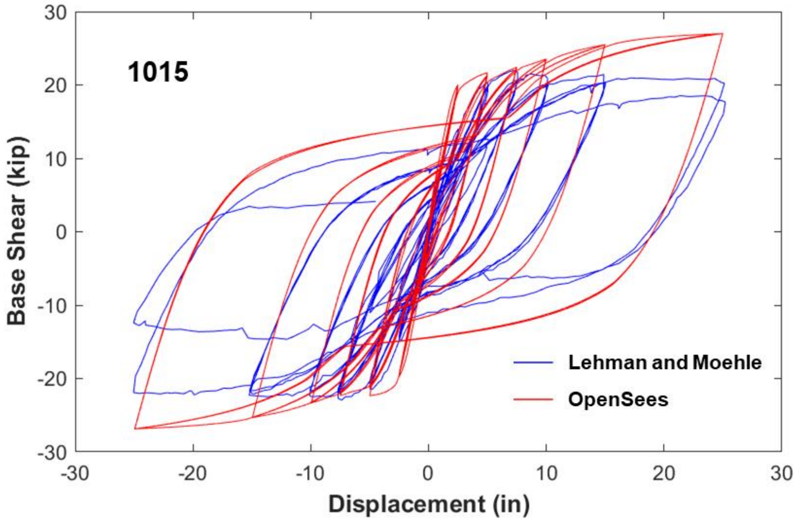












GMM Model Validation

Reference Models:

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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, Abrahamson, and Liu (2020). New Scenario-Based Cumulative Absolute Velocity Models for Shallow Crustal Tectonic Settings, BSSA (2021) 111 (1): 157–172

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	$Sa(T_{pgv})$	$Sa(T_1)$
$D_{5\text{-}75}$	PGA	$Sa(T_1)$
$D_{5\text{-}95}$	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

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

- **Four locations, with V_{S30} = 259 m/sec:**
  - **Eureka (Latitude = 40.790, Longitude = -124.179)**
  - **Oakland (Latitude = 37.800, Longitude = -122.280)**
  - **LA Downtown (Latitude = 34.050, Longitude = -118.259)**
  - **San Diego (Latitude = 32.724, Longitude = -117.158)**
- **Three hazard levels : 225-year, 975-year, and 2475-year return period with 51 ground motions each.**
- **Two sets of columns – with the natural period of 1 sec and 2 sec.**
- **Top three event scenarios (E1, E2, E3) obtained from hazard deaggregation by the USGS tool.**

GMM Model Validation

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

↓

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

↓

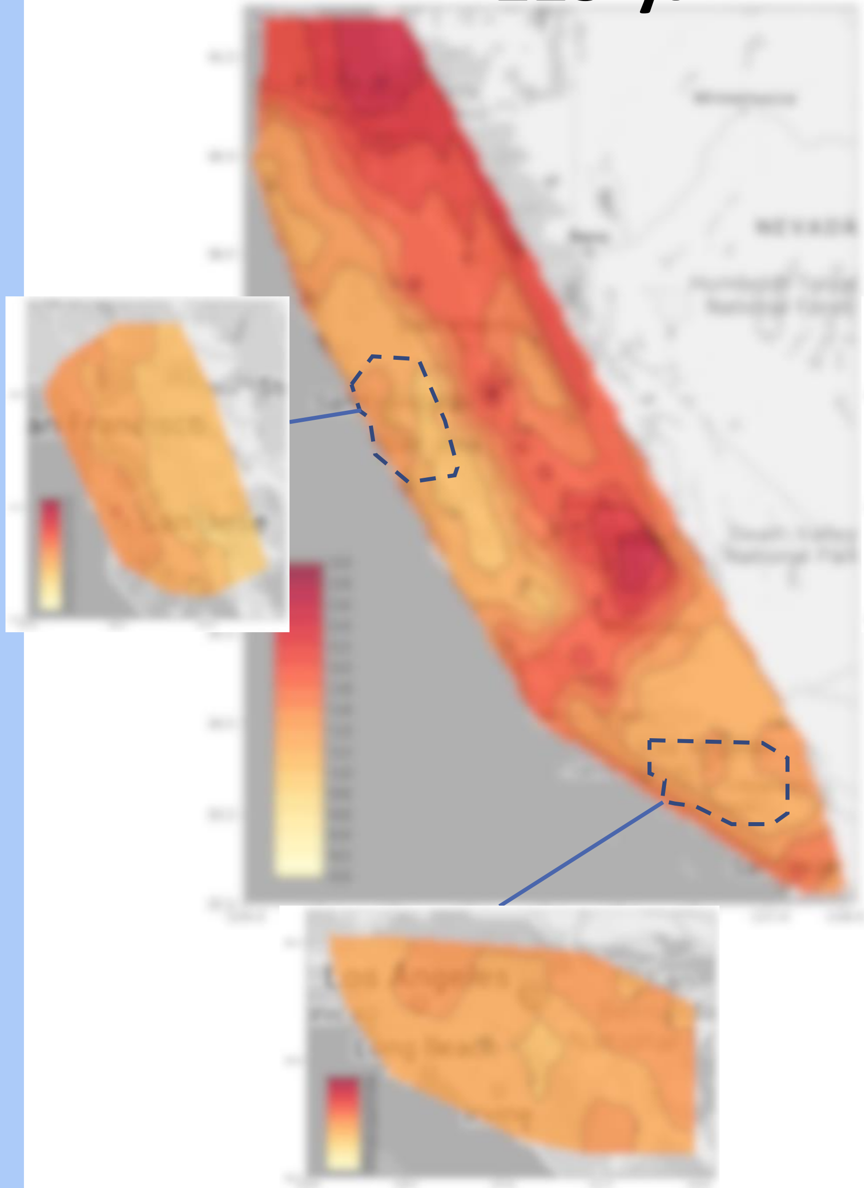
Distribution of the Secondary IM using models

1. ***Assessing the Significance of Secondary IMs in Column Response***
2. ***Comparing SecIM Distributions with Peer-Reviewed Models***
3. ***Validating Individual Ground Motion SecIMs Against Peer-Reviewed Distributions***

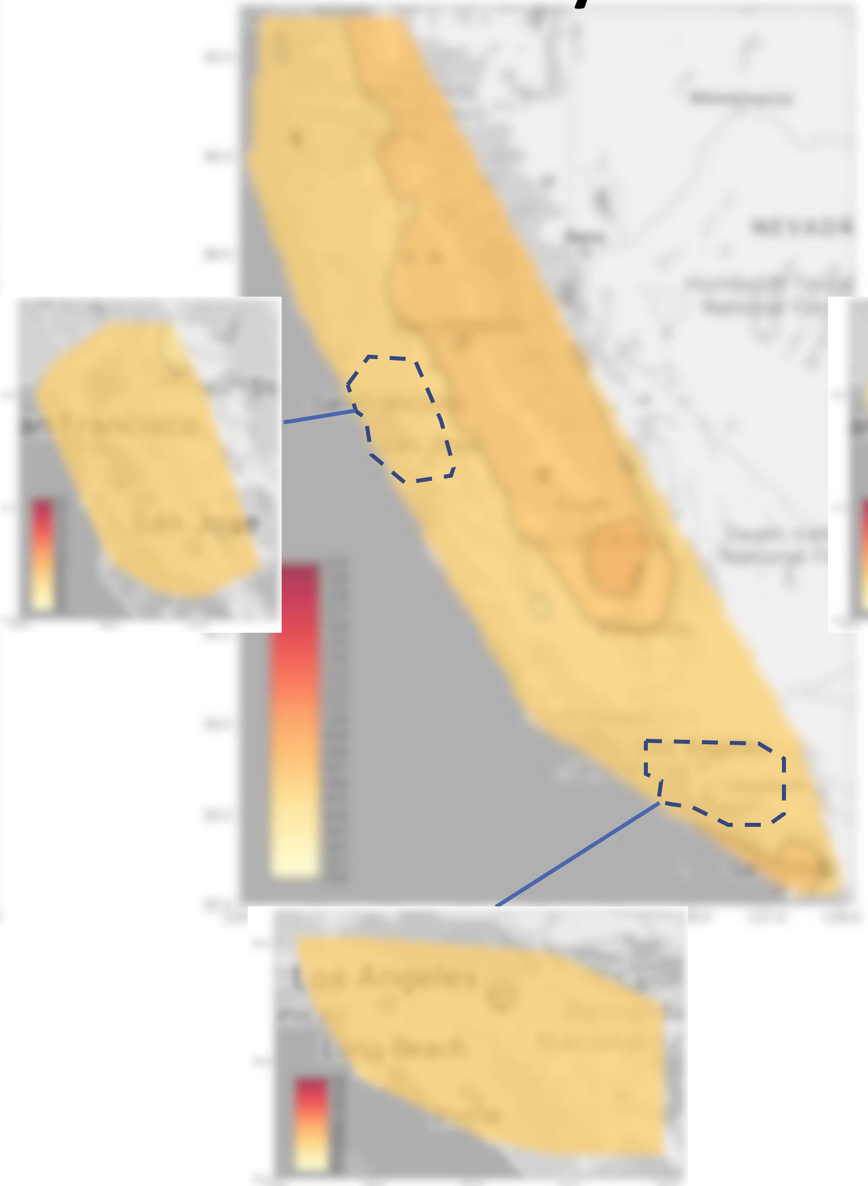
- Preliminary analysis suggested that PGV is the only significant Secondary IM
- Use GMs with –
  - Mean PGV within 25%-75% confidence interval of model mean PGV
  - All PGV values fall between 5%-95% confidence interval

COV_L Maps for Site Class D (V_{S30} = 259 m/s)

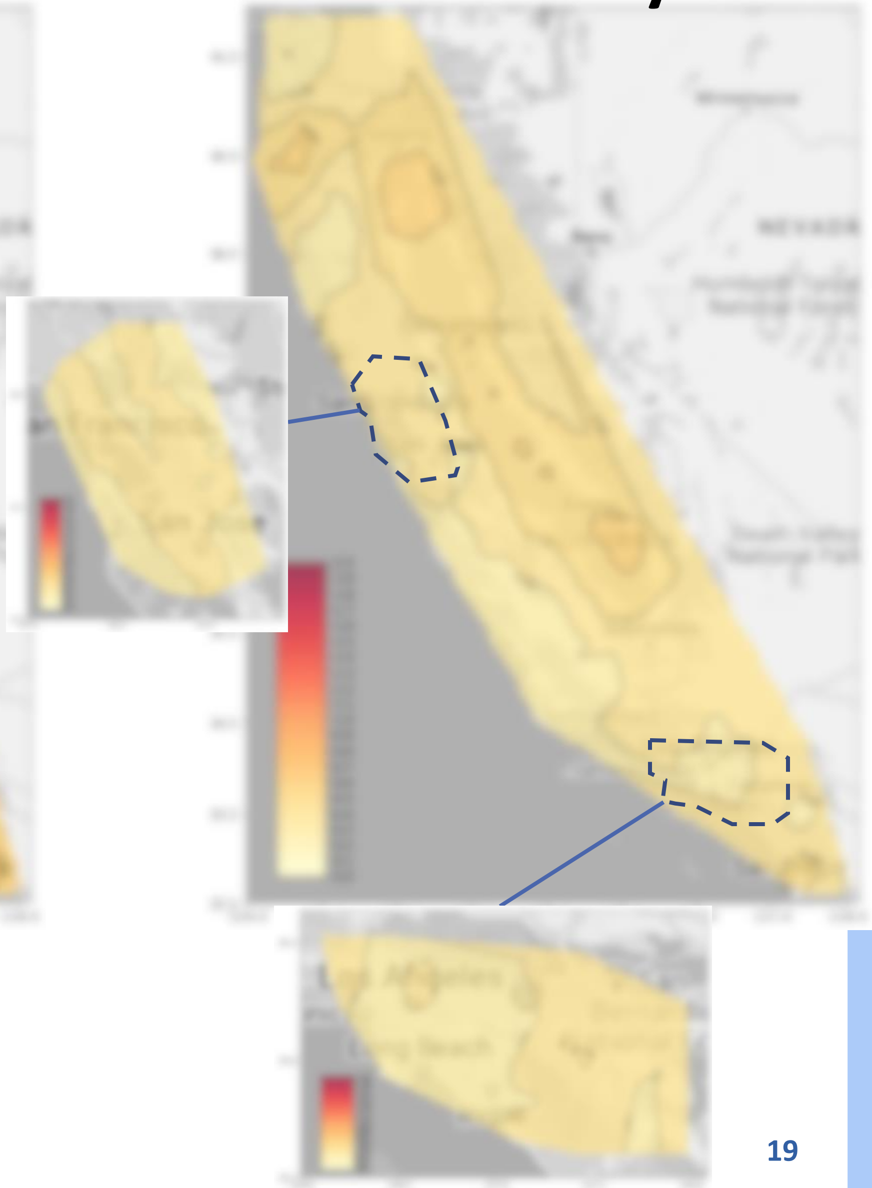
225-yr



975-yr

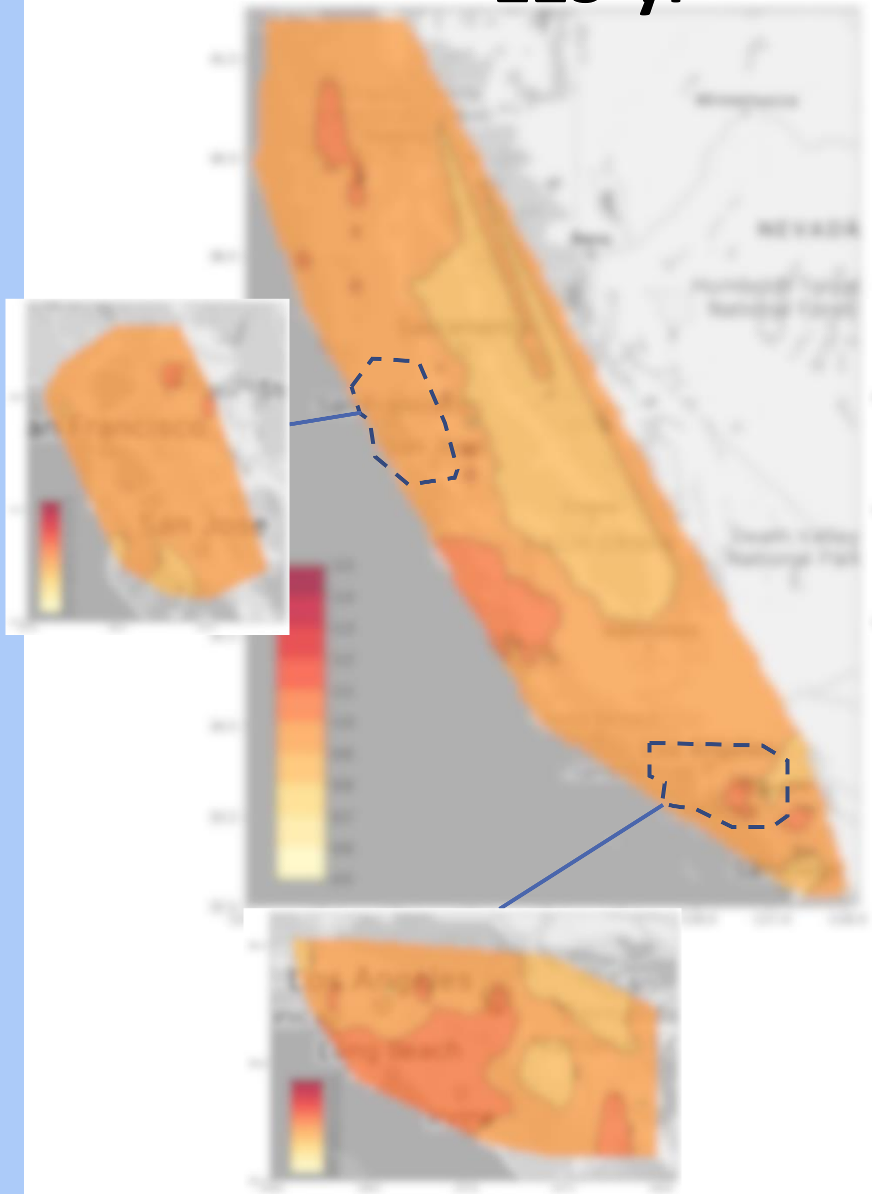


2475-yr

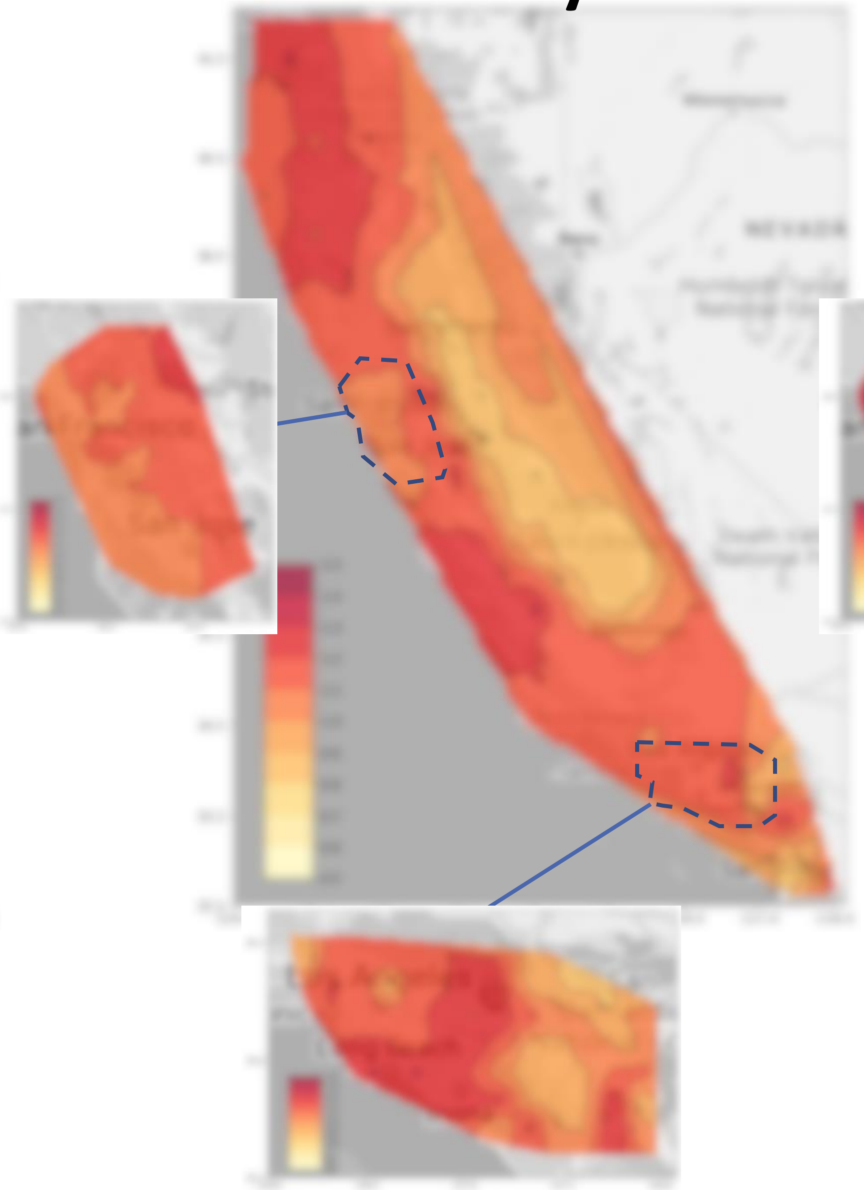


Displacement Adjustment Factor for Site Class D (V_{S30} = 259 m/s)

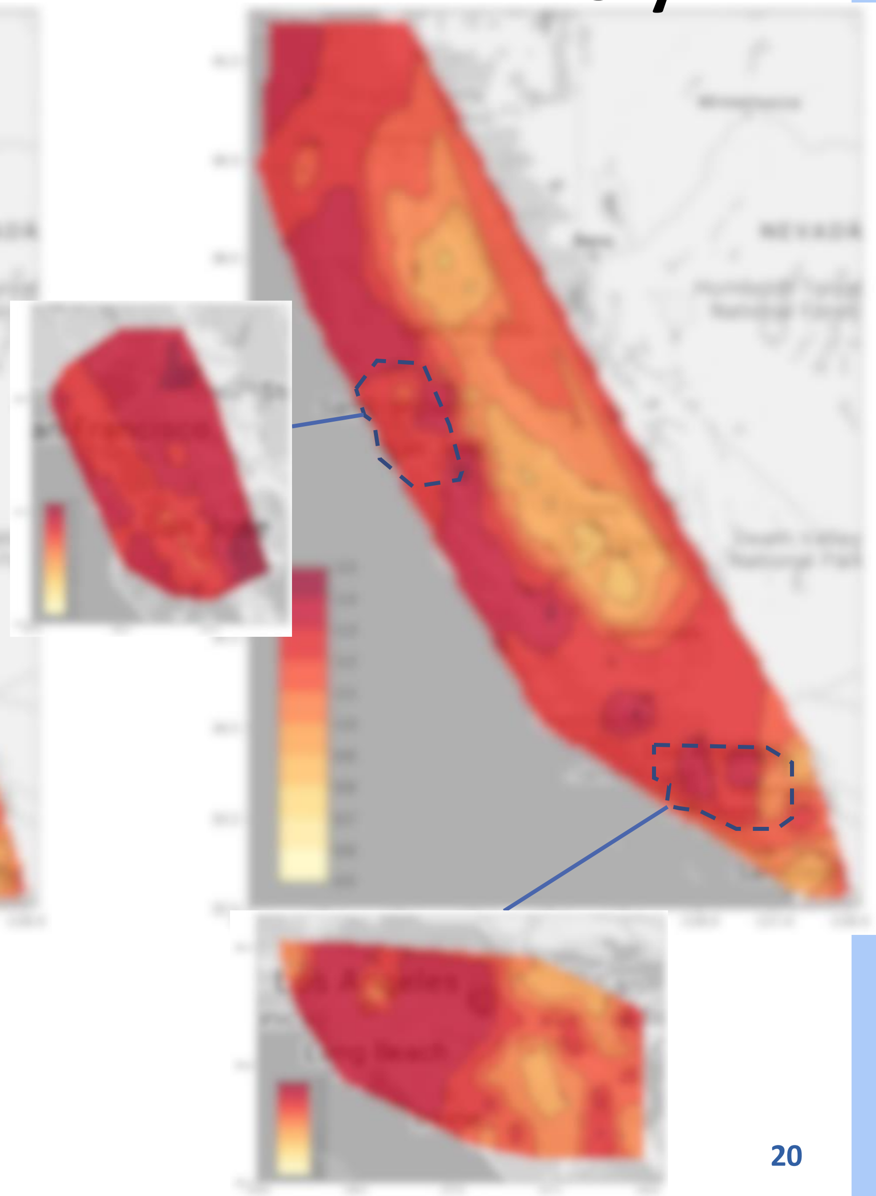
225-yr



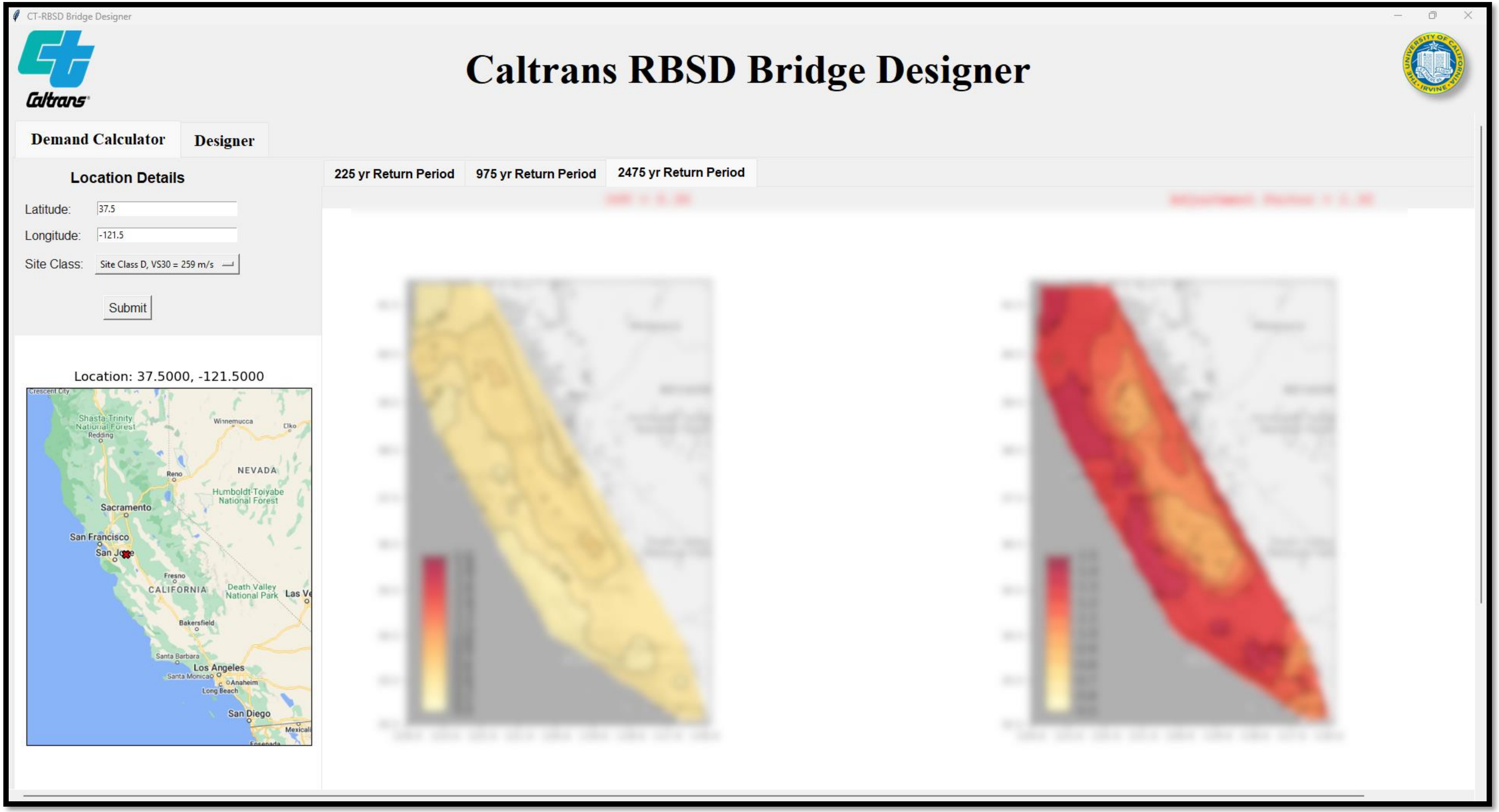
975-yr



2475-yr

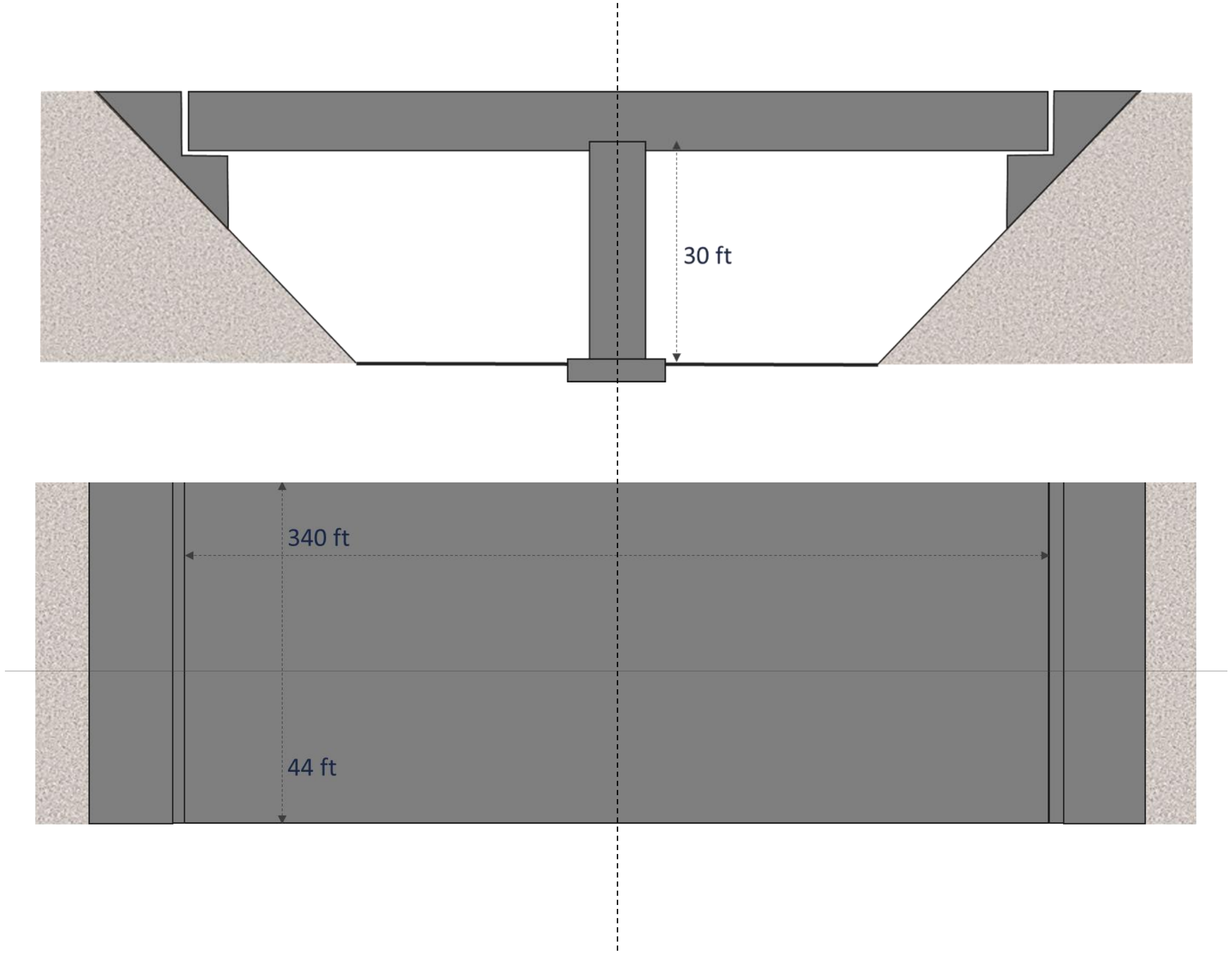


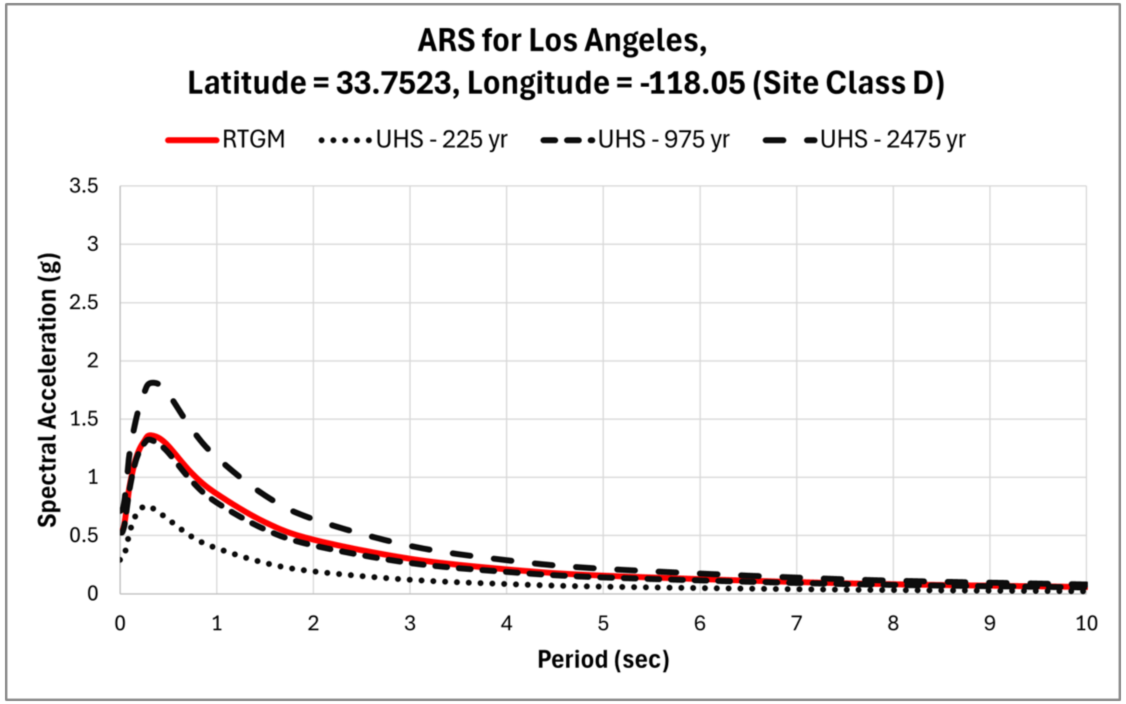
CT-RBSD Demand Tool



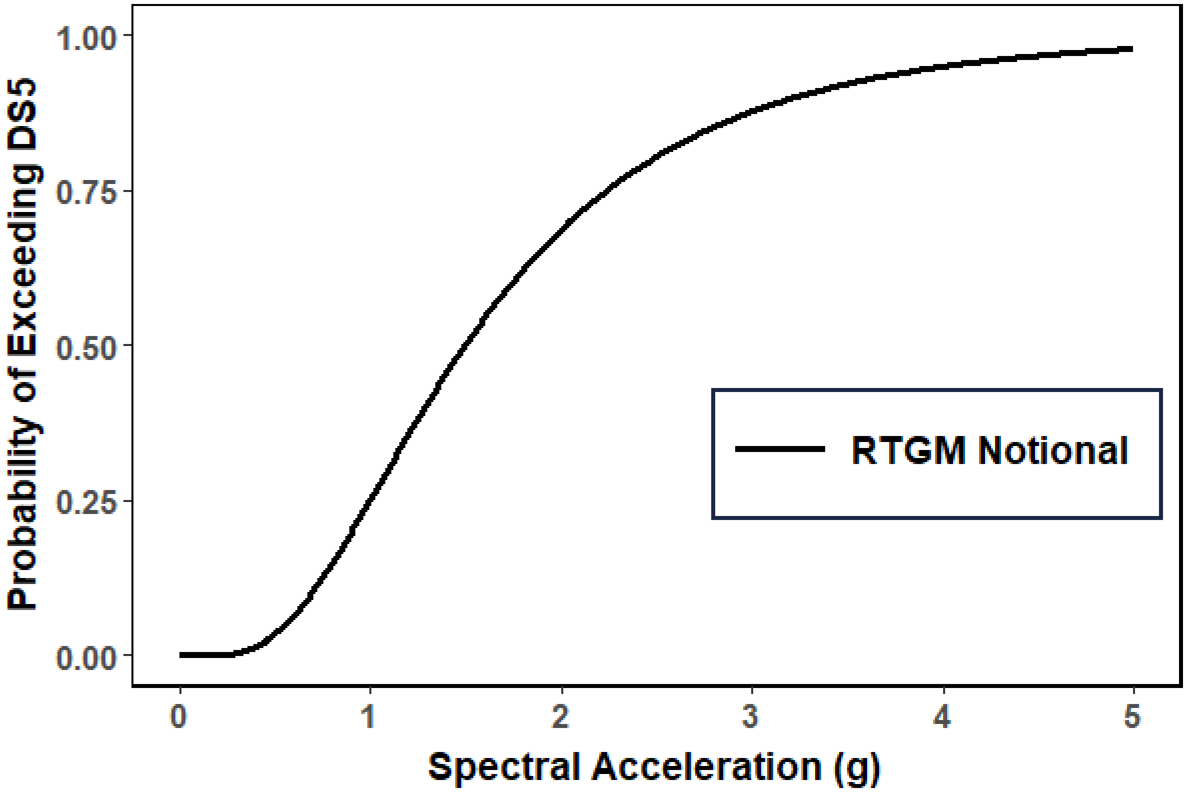
CT-RBSD Example

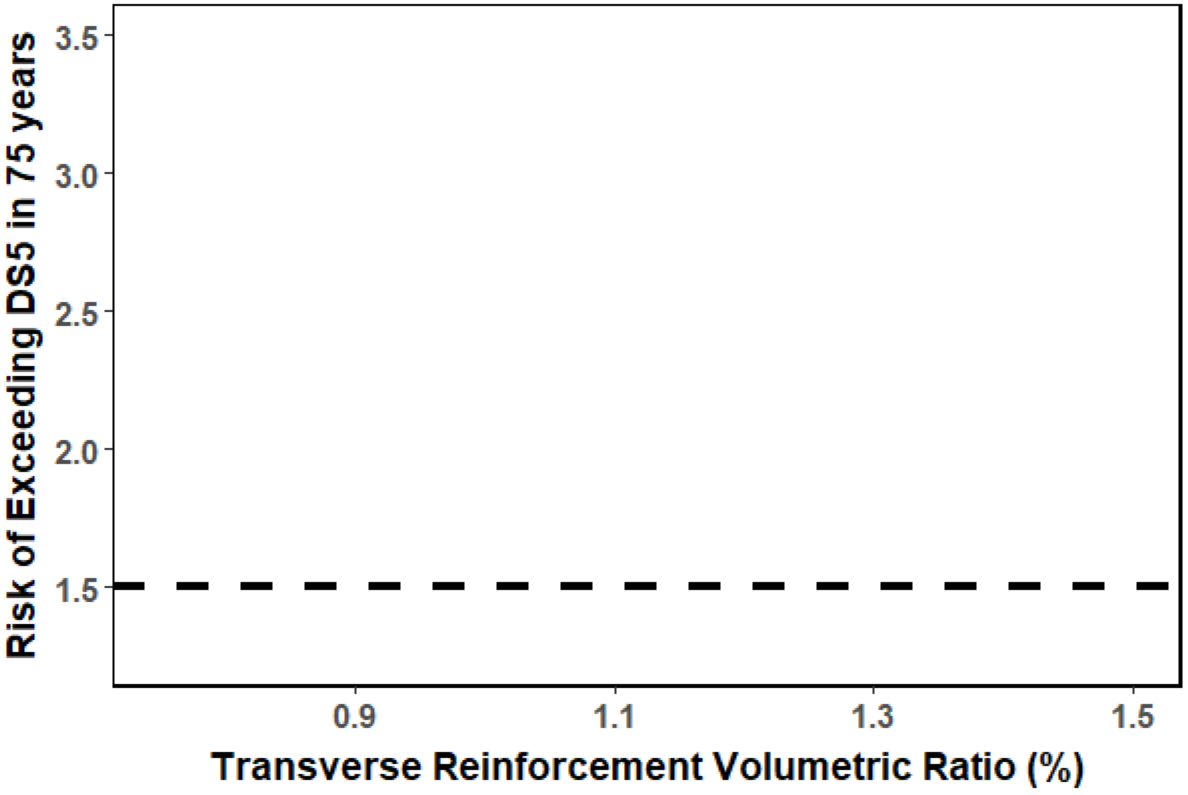
Case II – LA, Height = 30 ft, Diameter = 5 ft, Axial Load = 0.14 $f'_c A_g$, Long. Reinf. = 22 - #11,
Hoop = #8 @ 6”





CT-RBSD Example

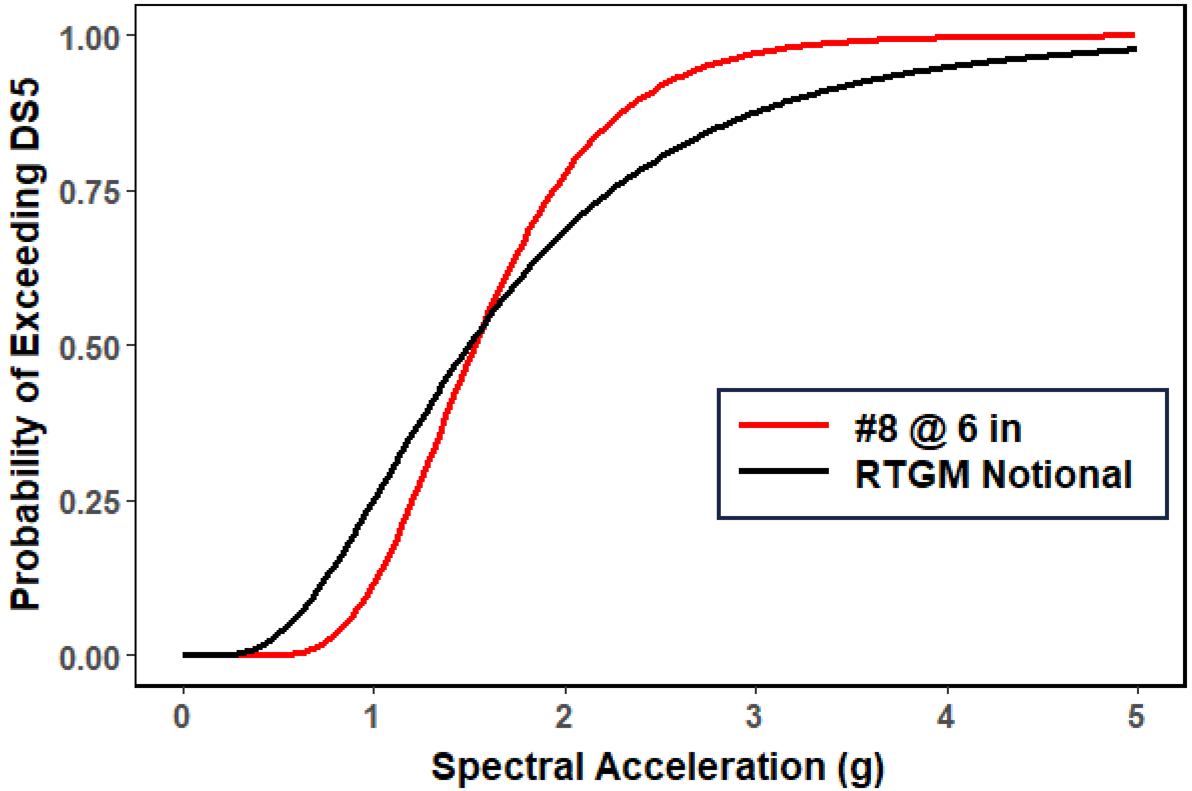


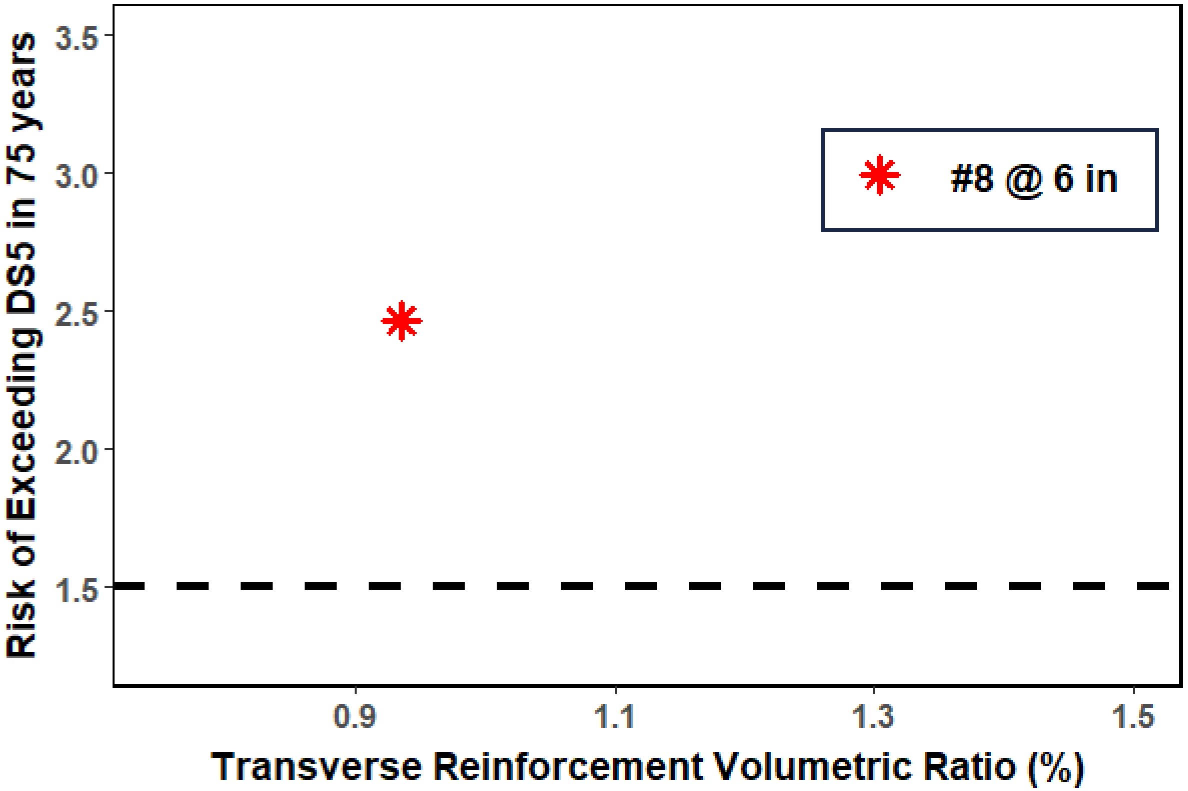


Case II – LA, Height = 30 ft, Diameter = 5 ft, Axial Load = 0.14 f'_cA_g, Long. Reinf. = 22 - #11,

Hoop = #8 @ 6”

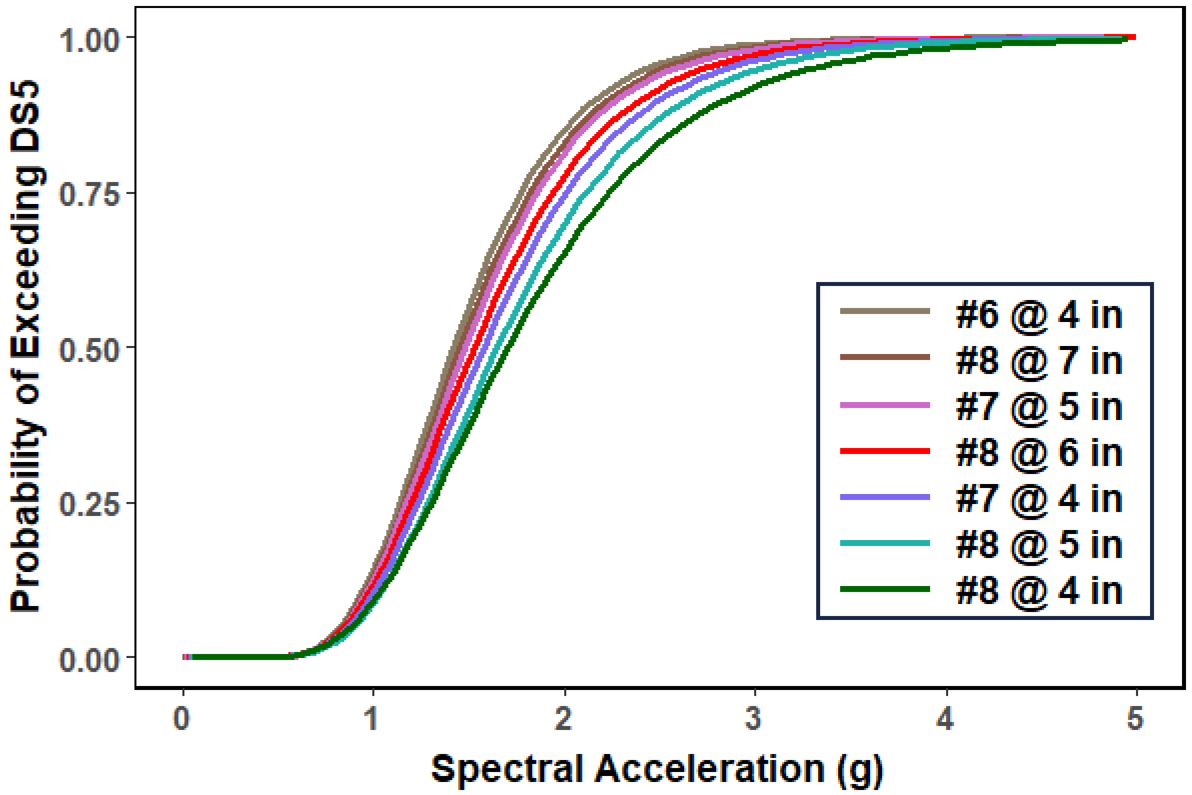
CT-RBSD Example

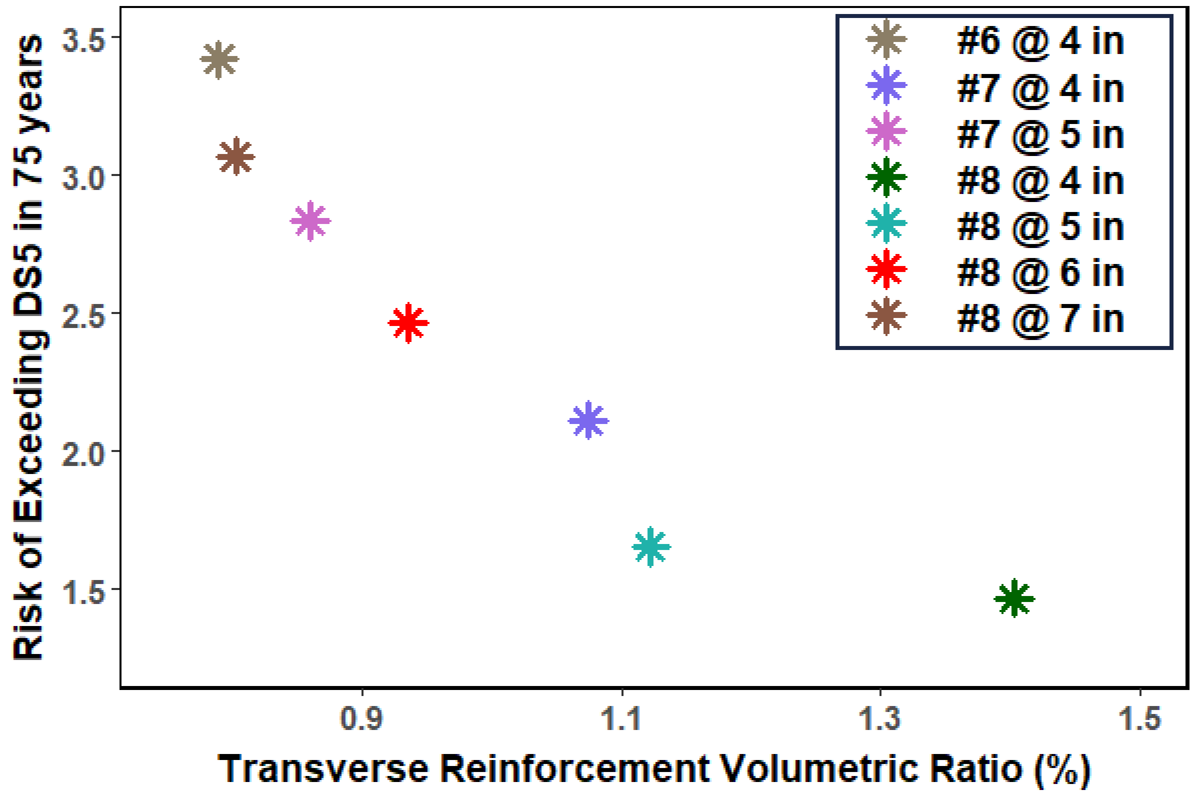




Case II – LA, Height = 30 ft, Diameter = 5 ft, Axial Load = 0.14 $f'_c A_g$, Long. Reinf. = 22 - #11,
Hoop = #8 @ 6”

CT-RBSD Example





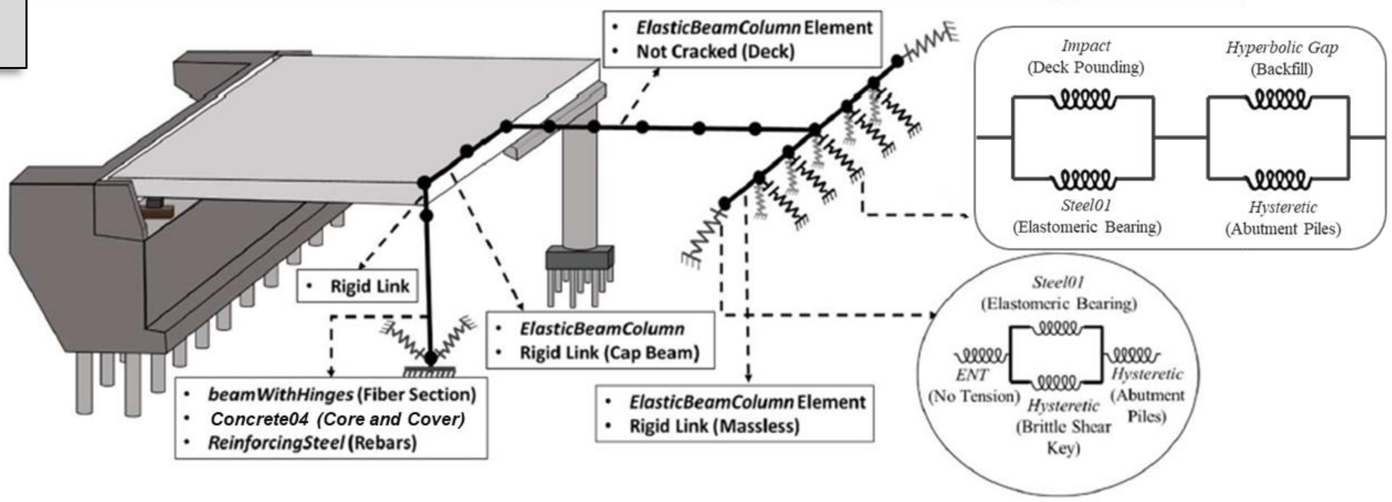
Case II – LA, Height = 30 ft, Diameter = 5 ft, Axial Load = 0.14 $f'_c A_g$, Long. Reinf. = 22 - #11

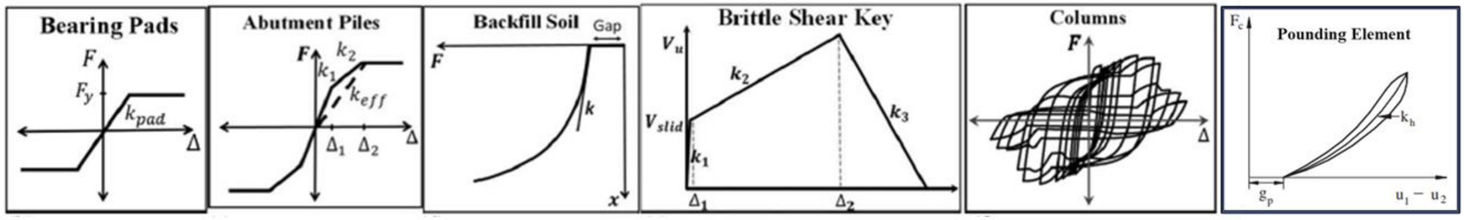
Further Understanding Caltrans Bridge's "Risk"

Model Description

Three different types of bridges:

- Two-Span Single-Column
- Two-Span Two-Column Bent
- Two-Span Three-Column Bent



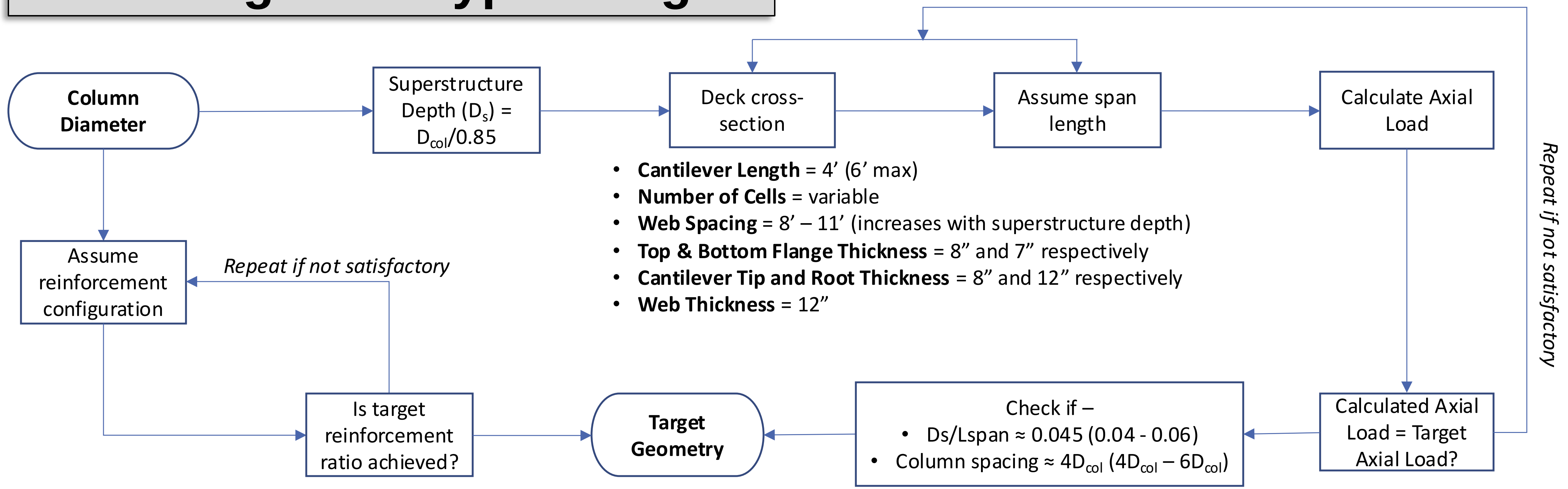


Further studies under CT-RBSD to compare Caltrans bridge behavior with the Single Column study

- **"Archetype" Bridge Study: Design bridges per Caltrans standard; investigate the demand maps and estimated risk**
- **"100 Real Bridge" Study: Develop model of 100 real bridges and assess risk**

Further Understanding Caltrans Bridge's "Risk"

Modelling Archetype Bridges



Estimate with tuning parameter as 'Axial Load' and 'Reinforcement Ratio'

The following references were used for assumptions required to estimate realistic bridge parameters:

- AASHTO LRFD Bridge Design Specifications 8th edition, 2017
- Caltrans Bridge Design Manual
- Caltrans Seismic Design Criteria v2.0, 2019
- *Refined Bridge Deck Design and Analysis (PEER Project, PEER-Bridge TO2)*

Summary

- CT-RBSD highlights:
    - Streamlined by auxiliary tools (maps).
    - Capable of computing the risk of all damage states.
    - Capable of designing for any risk value as desired by the stakeholders.
- Bridge columns designed using RTGM-ARS + SDC 2.0 arrive at a risk of **~**1% - **~**3.5% for incipient collapse (DS5) in 75 years.
- Future studies will help determine the threshold risk for future design codes.
    - Archetype Bridge Study.
    - The "100 Real Bridge" Study

Thank You