TexNet CISR

Seismic Hazard and Risk Assessment for Induced Seismicity

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Civil, Architectural and Environmental Engineering

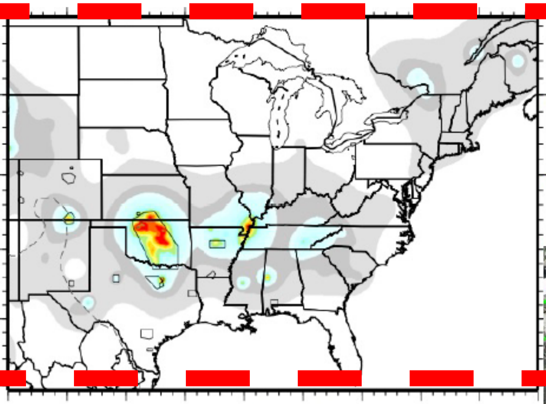
Bureau of Economic Geology

Seismic Risk Assessment

Risk = Hazard

Measure of ground shaking and its probability

Rathje, Grigoratos, Cox, Li, Yust, Savvaidis



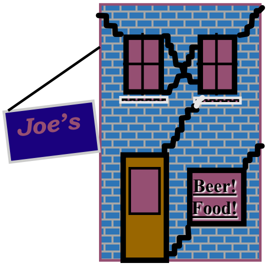
x Exposure

Characterization of built environment and inhabitants

Clayton, Khosravikia, Rathje, Grigoratos

x Vulnerability

Susceptibility of the exposure to damage/undesirable consequences

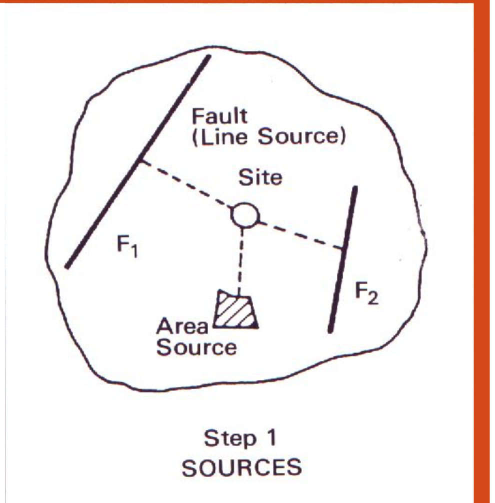


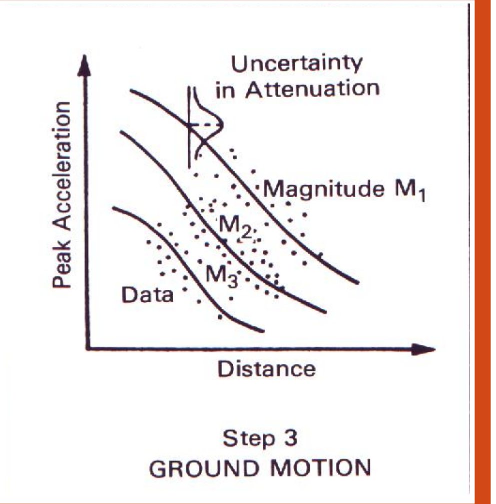
x Consequences

$$, number of people adversely affected

Seismic Hazard Assessment

Risk = Hazard x Exposure x Fragility x Consequences





(Reiter, 1990)

Seismic Source Characterization

Requires:

- Rate of earthquakes
- Magnitude (M) distribution
- Locations

For tectonic EQs:

- Stationary
- Use historical EQ catalog

For induced EQs:

- Time-dependent
- Relate seismicity to oil/gas operations (e.g., injection)

Ground Motion Characterization

Requires:

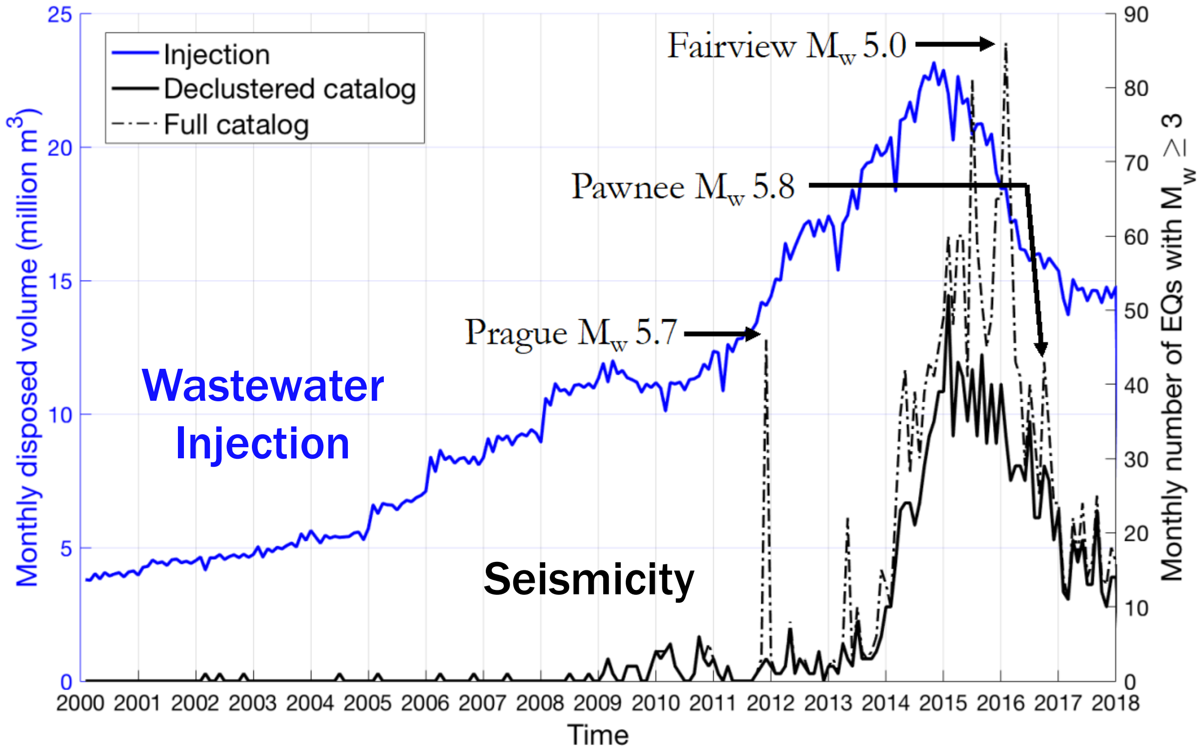
- Ground shaking as a function of M, distance (R), and soil/rock conditions (Vs30)
- Variability

For induced EQs:

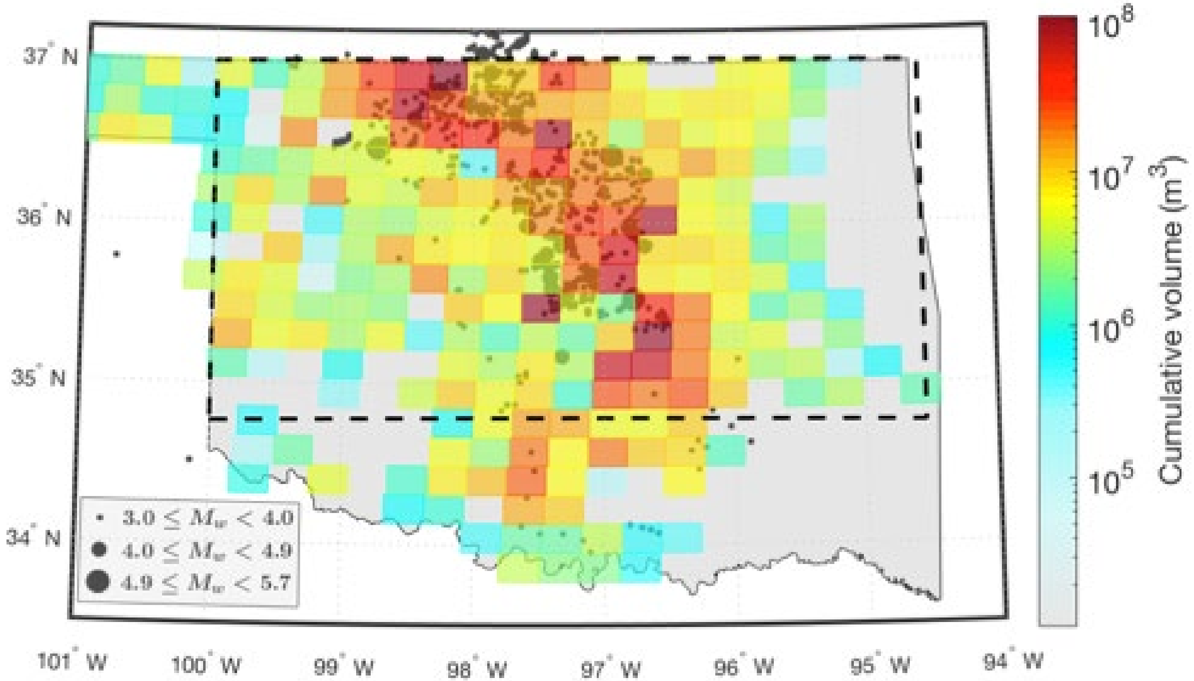
Use recordings from events in geologically similar regions

Temporal and Spatial Variations in Seismicity: Oklahoma

Temporal

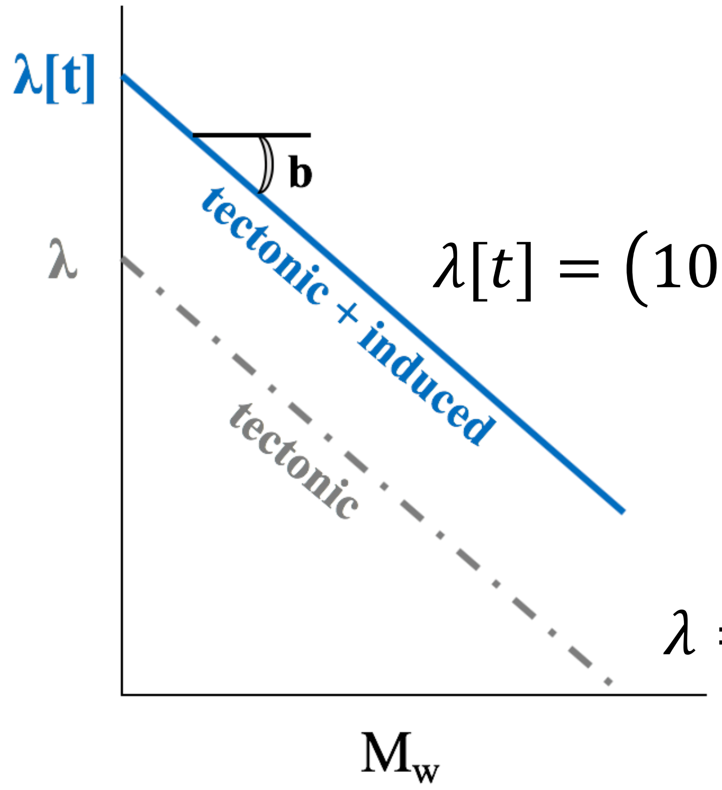


Spatial



Time-Dependent Gutenberg-Richter Relationship

Semi-empirical model with parameters derived from seismicity and injection data



monthly lagged distributed injection rate

Seismogenic Index

$$\lambda[t] = \left(10^{a_{tec}} + v_{lag}[\mathrm{t}] \cdot 10^{\Sigma}\right) \cdot 10^{-b \cdot m}$$

with $t_{lag}[\mathrm{t}] = \dfrac{\theta}{v[t]}$ ← monthly distributed injection rate

$$\lambda = 10^{a_{tec} - b \cdot m}$$

Free parameters:

$\boldsymbol{\theta}$ and Σ from monthly injection and seismicity data

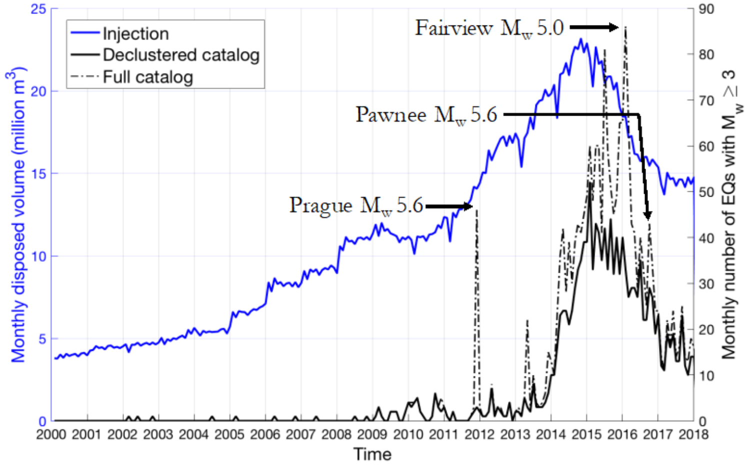
a_{tec} and **b** from background seismicity (<2009)

Spatial and temporal resolution:

Monthly injection/seismicity for 5-km x 5-km blocks

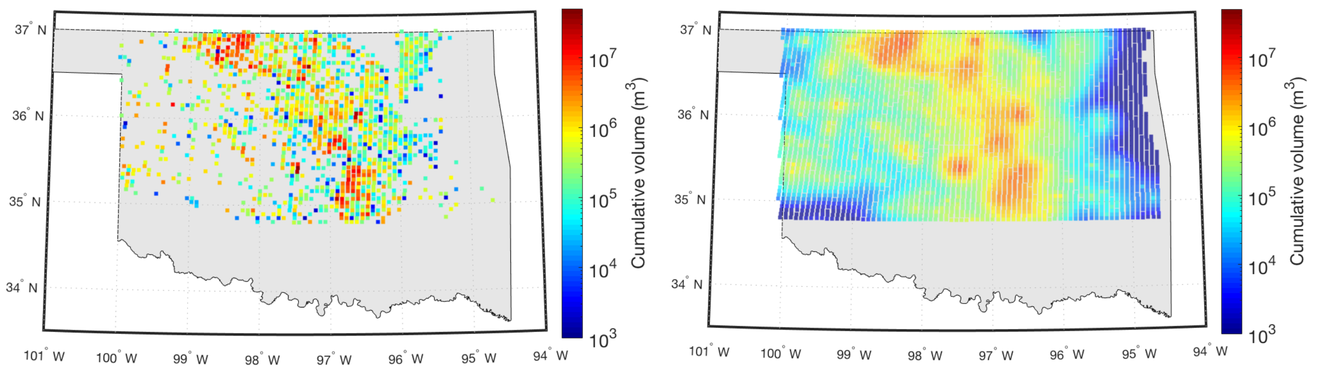
Application to Oklahoma

Monthly EQs and injection volumes 2000-2018

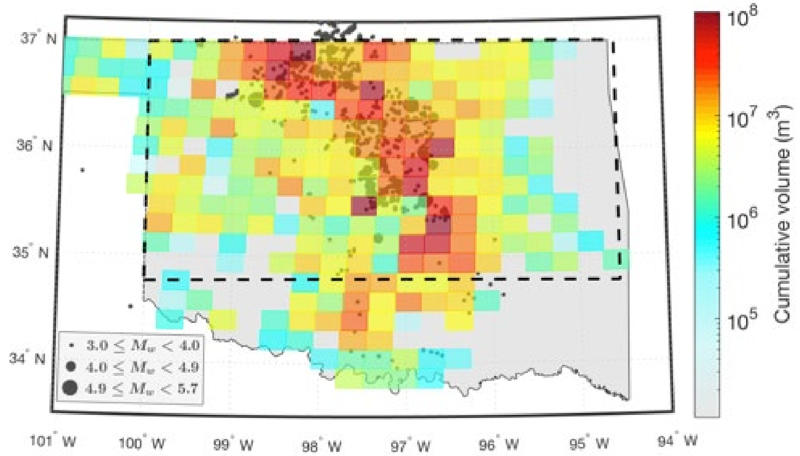


Gridded and Spatially Distributed Injection Volumes

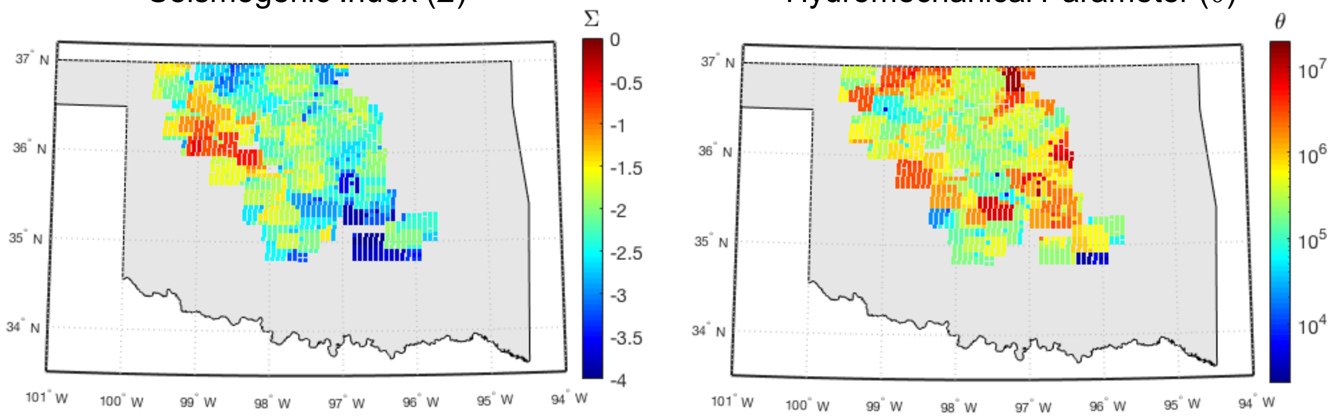
Cumulative 2006-2018



Cumulative injection volume (m³) 2006-2018



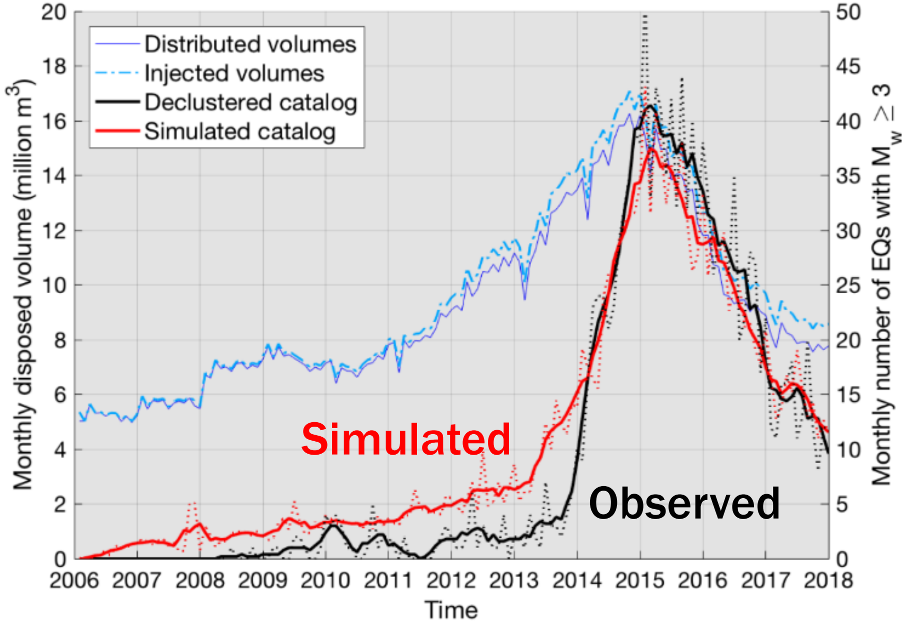
Spatially Varying Model Parameters



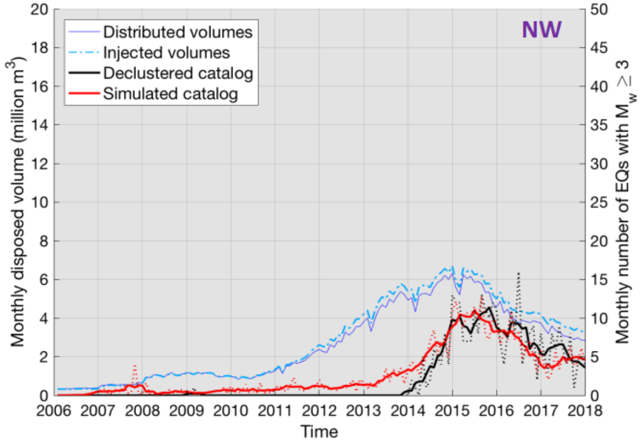
Simulated seismicity rates

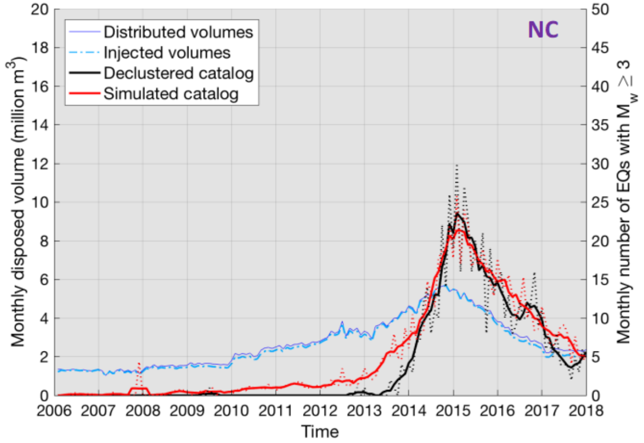
Calibration: Jan 2006 – Dec 2017

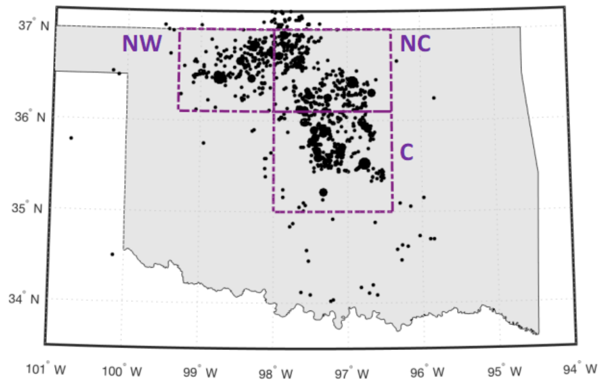
Full Study Area

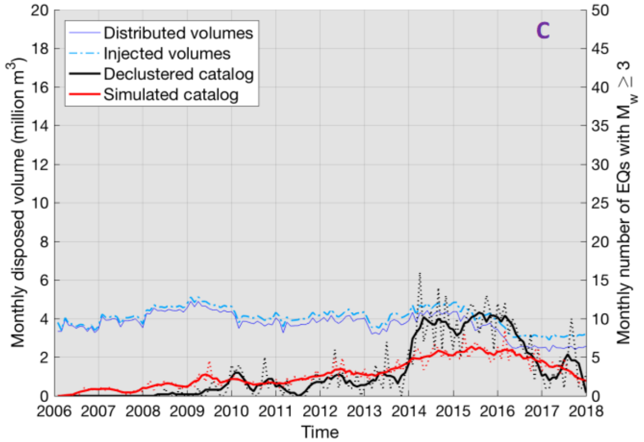


Sub-Regions









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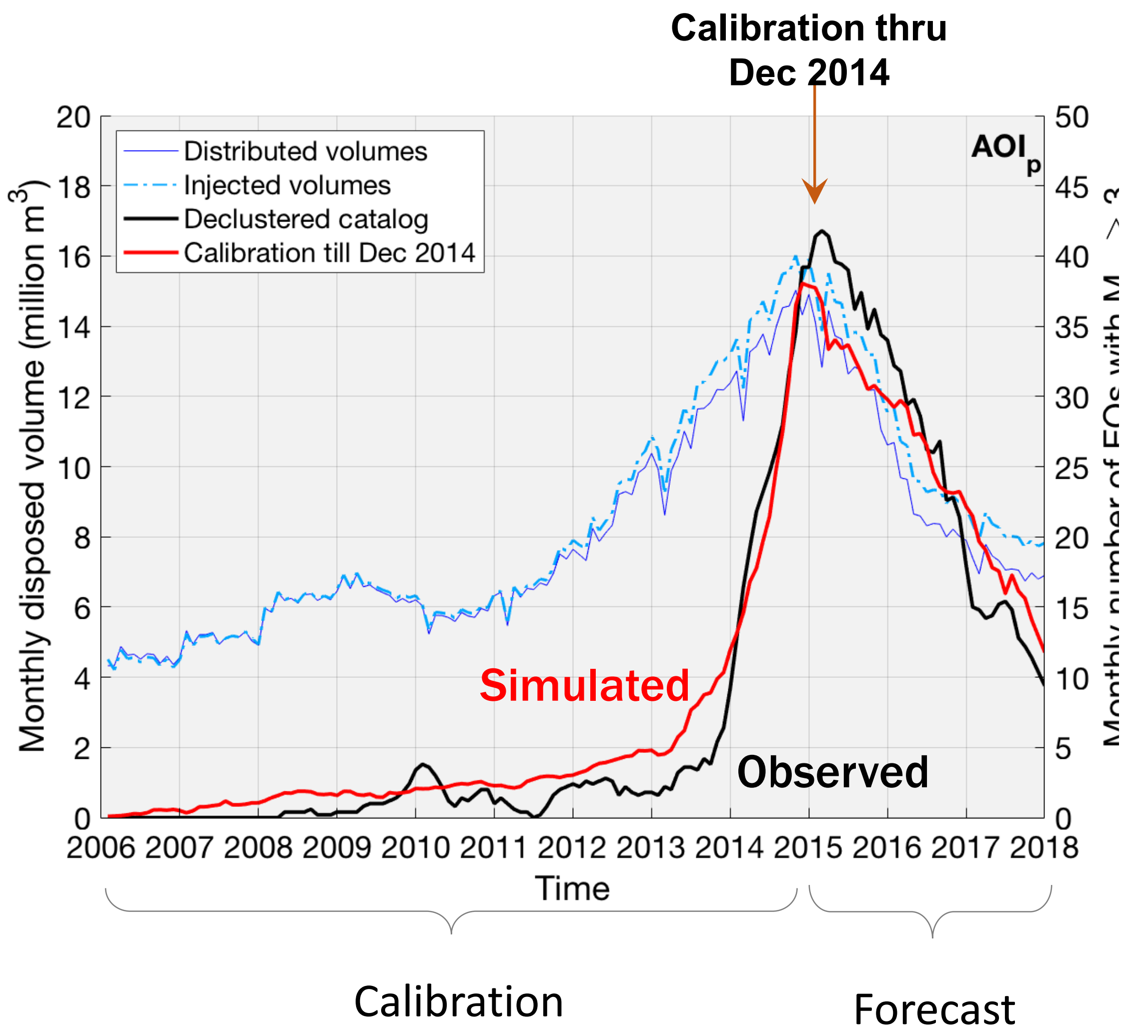
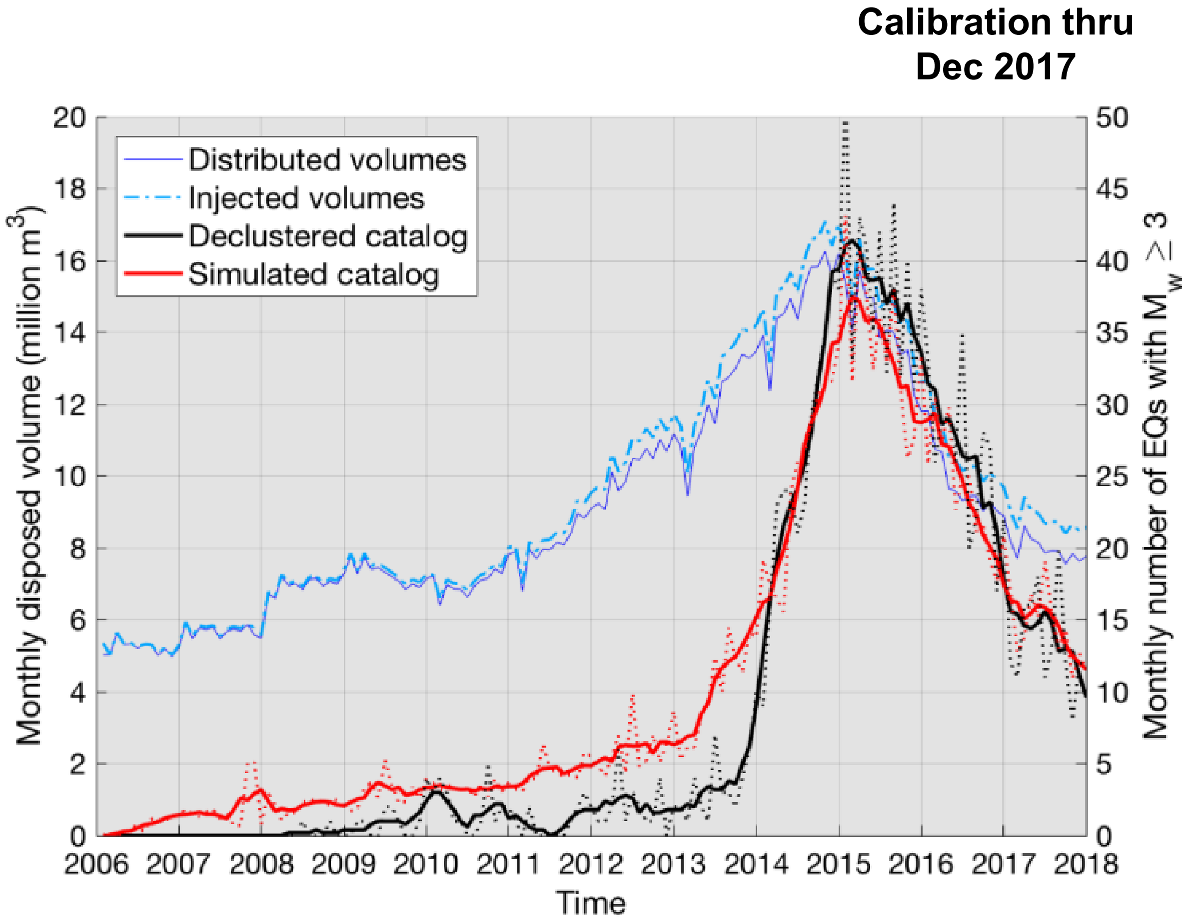
Hindcasting: calibrate parameters through Dec 2014

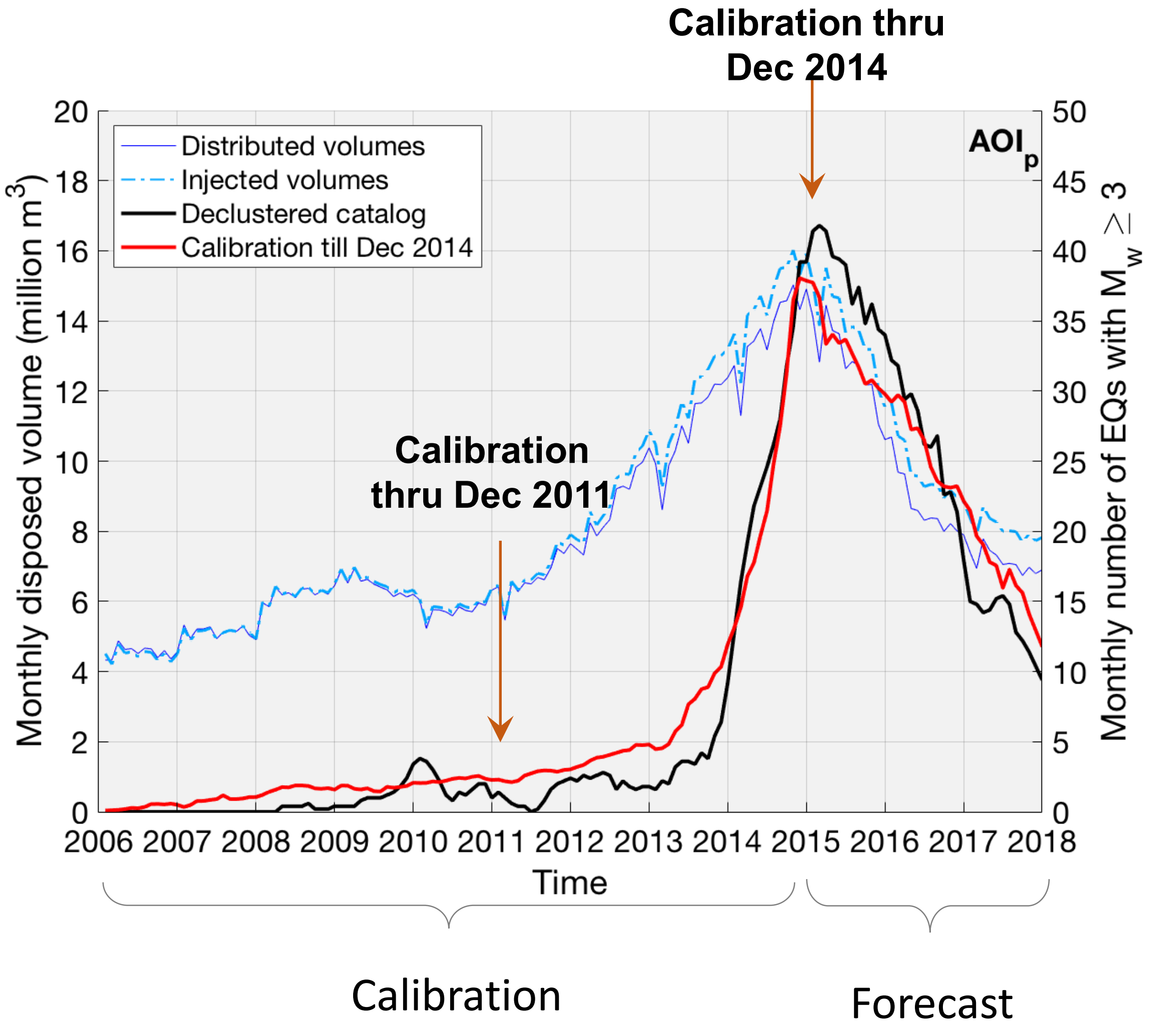
Model performance when we calibrate parameters thru Dec 2014 and then forecast the EQs, given the injection rates

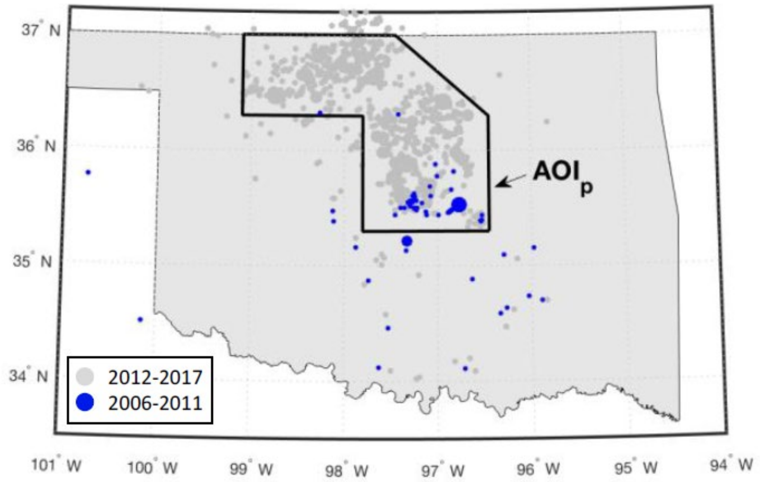




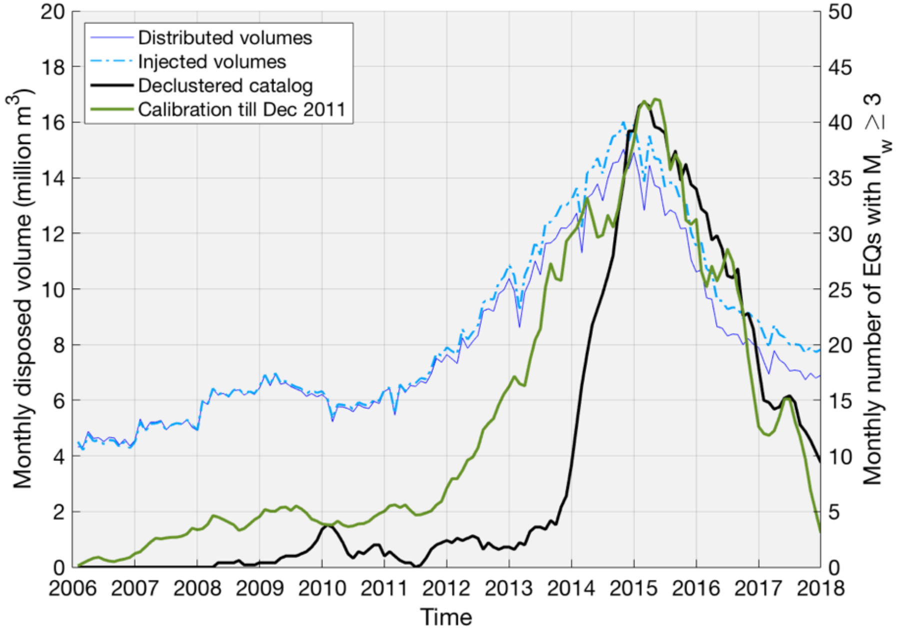
Hindcasting: calibrate parameters through **Dec 2011**

Model performance when we calibrate parameters thru Dec 2011 and then forecast the EQs, given the injection rates





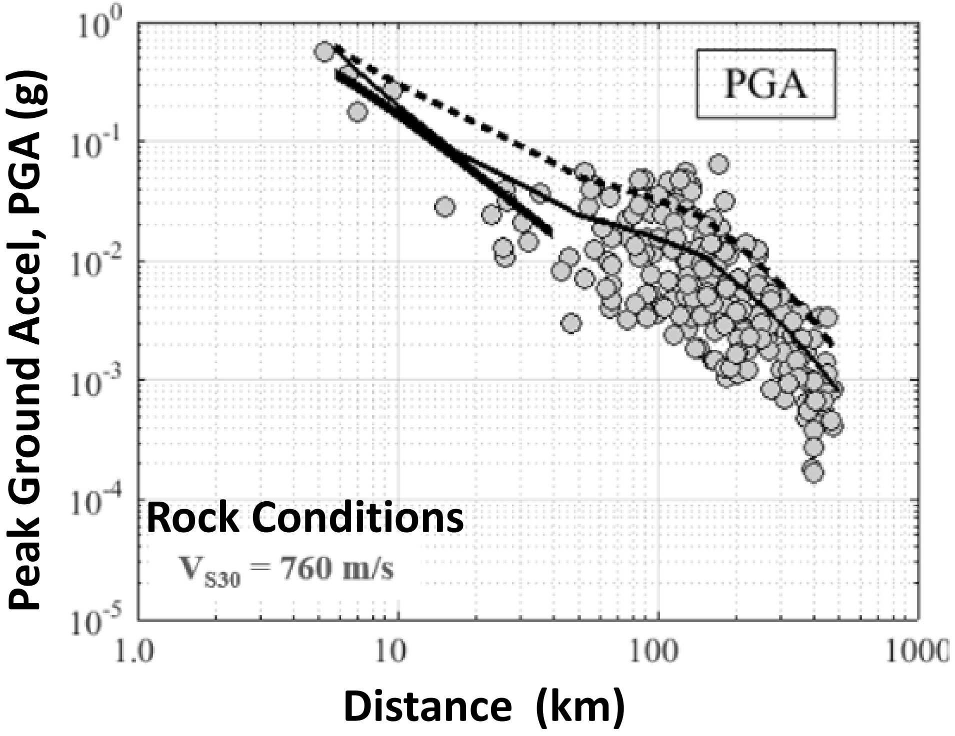
We need to spatially extrapolate Σ and θ



Ground Motion Characterization

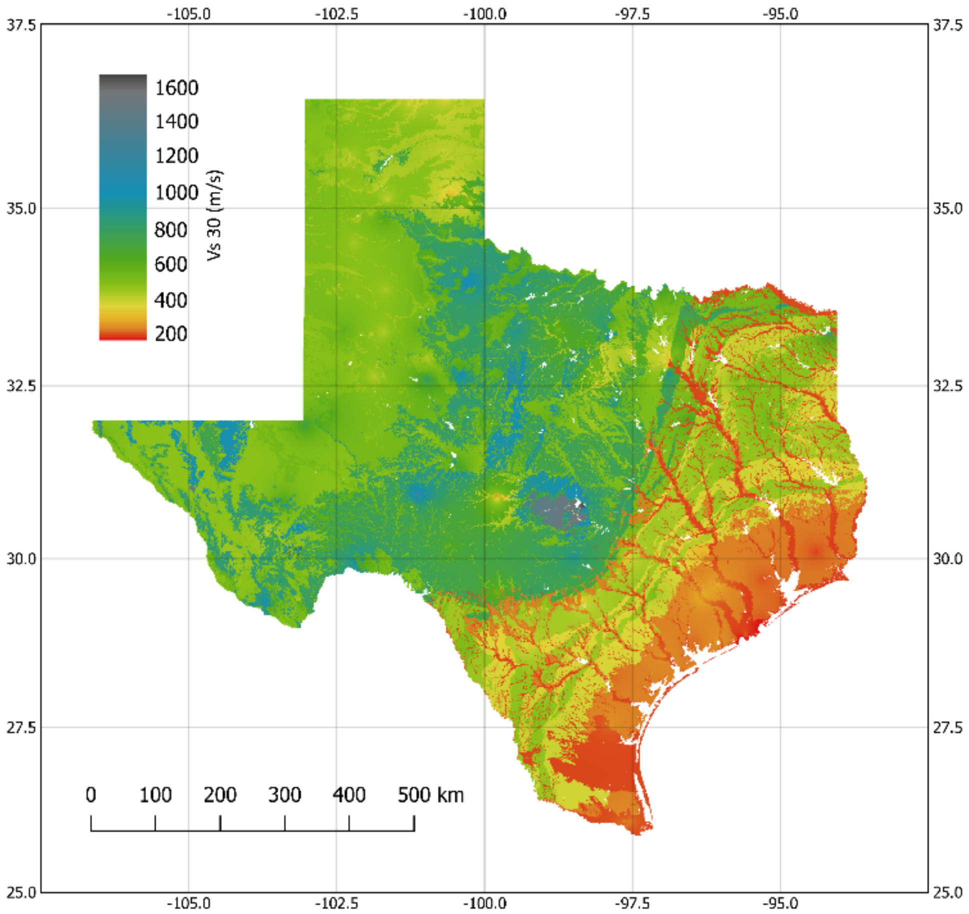
Empirical Ground Motion Model (GMM)

Using data from Texas, Oklahoma, and Kansas



Zalachoris and Rathje (2019) *EQ Spectra*

Characterization of Shear Wave Velocity (Vs30)



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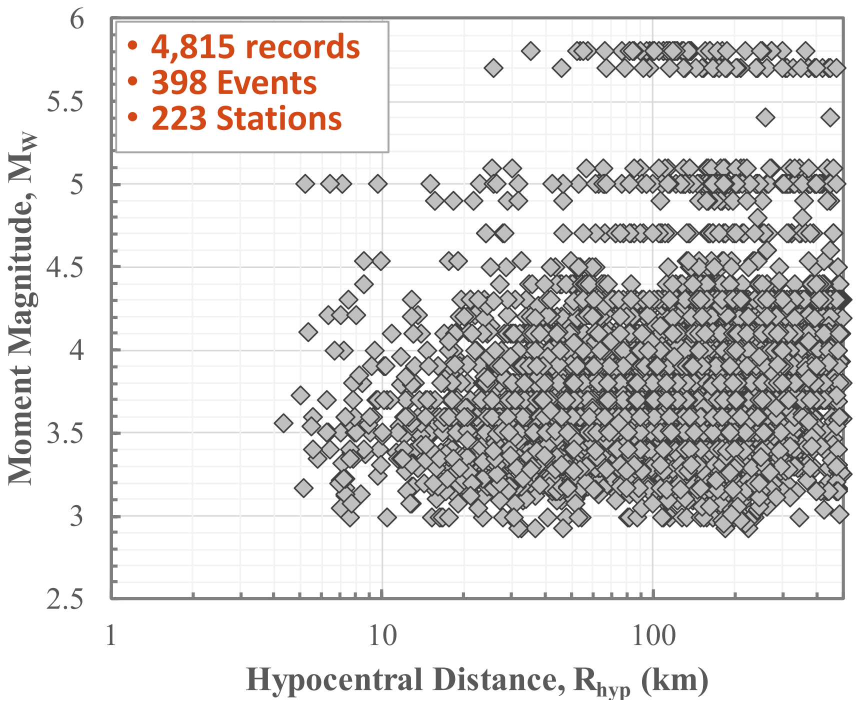
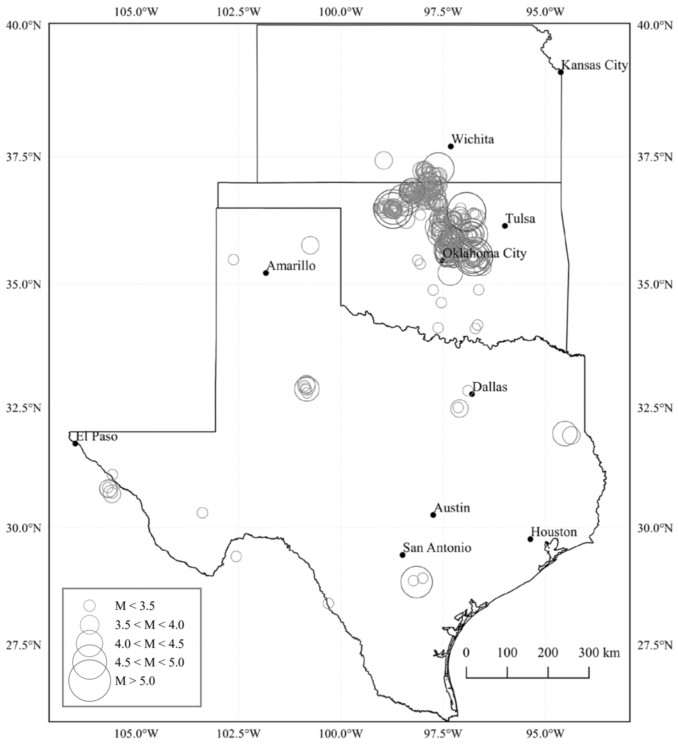
Ground Motion Model (GMM) Development

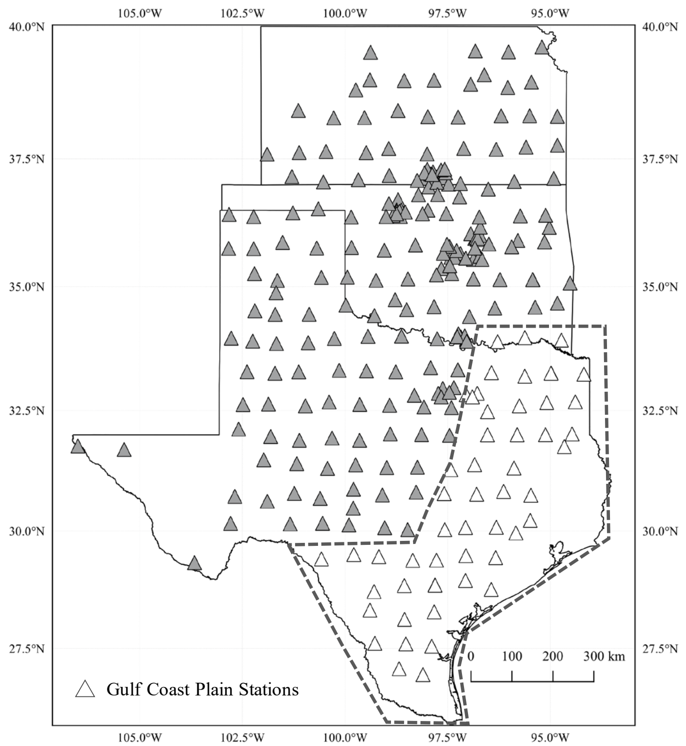
- Events in TX, OK and KS with M > 3.0 between 2005-2017
- Recordings from TX, OK and KS seismic stations (past and existing)



Events



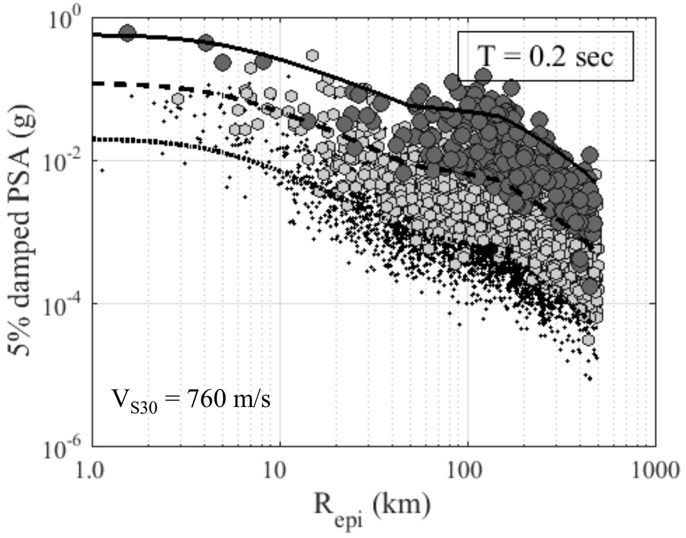
Stations

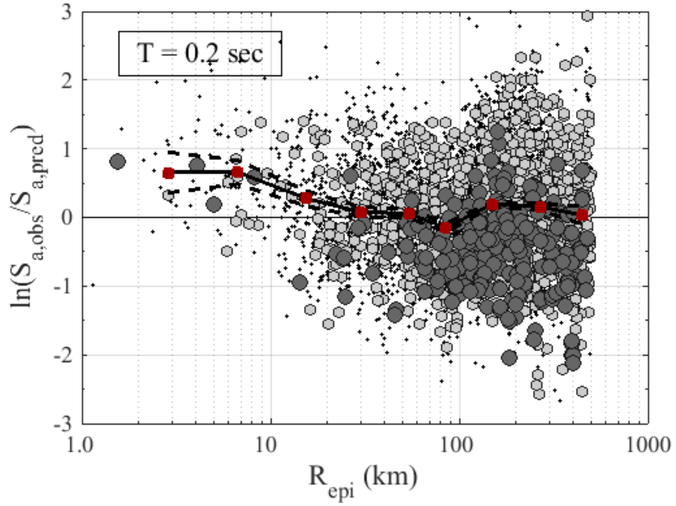


Zalachoris and Rathje (2019) *EQ Spectra*

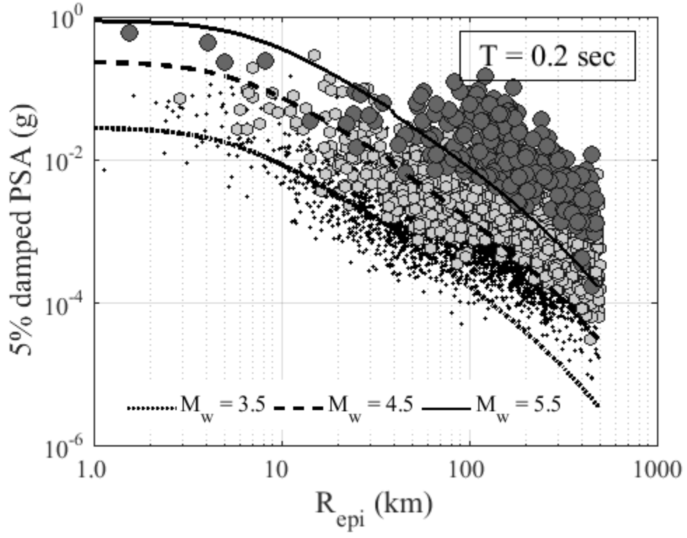
Assessment of Existing GMMs

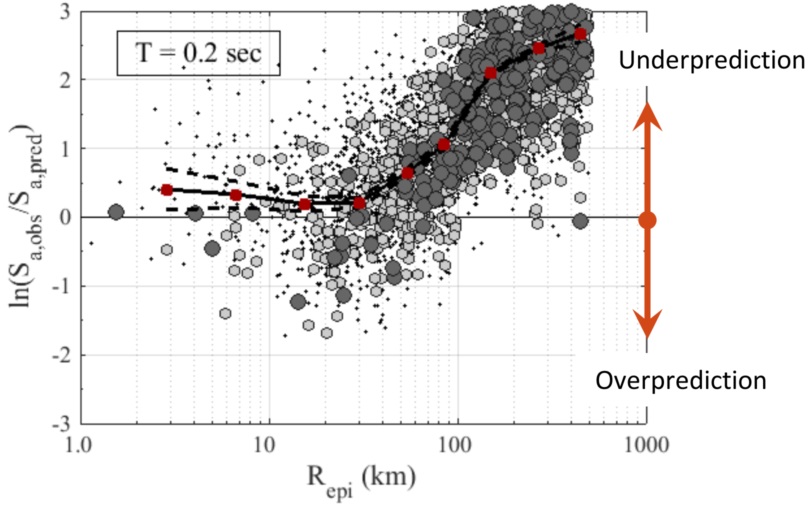
Hassani & Atkinson: NGA-East (2015)





Atkinson (2015): Potentially Induced EQs (PIEs)





Reference Empirical Approach

- Develop empirical adjustment for Hassani and Atkinson (2015) GMM using TX-OK-KS ground motion data

Adjustment Factors

At each frequency, *f*:

Overall Adjustment: $C = const.$

Distance Scaling: $F_R = \begin{cases} 0 & R \geq R_b \\ a \cdot \ln\left(\frac{R}{R_b}\right) & R < R_b \end{cases}$

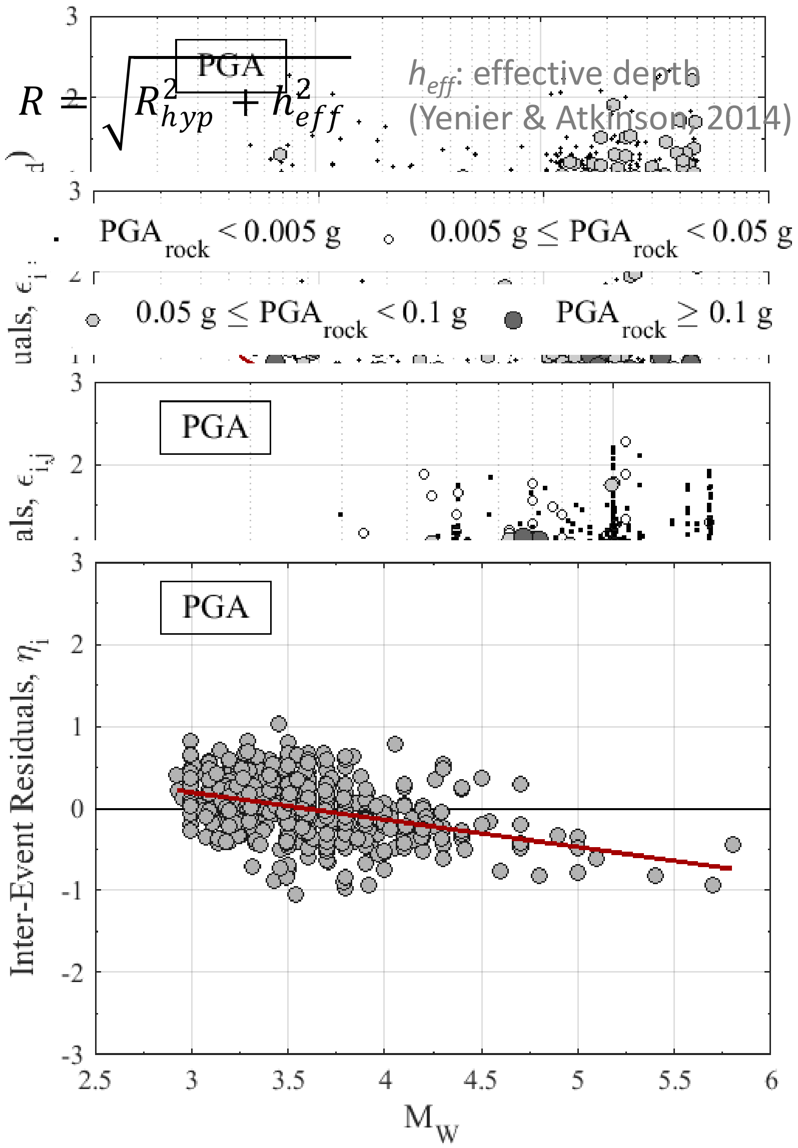
V_{S30} Scaling: $F_S = \begin{cases} 0 & V_{S30} > V_C^* \\ c^* \cdot \ln\left(\frac{V_{S30}}{V_C^*}\right) & V_{S30} \leq V_C^* \end{cases}$

Magnitude Scaling: $F_M = b_0 + b_1 \cdot M$

Final Model for Adjustment Factors:

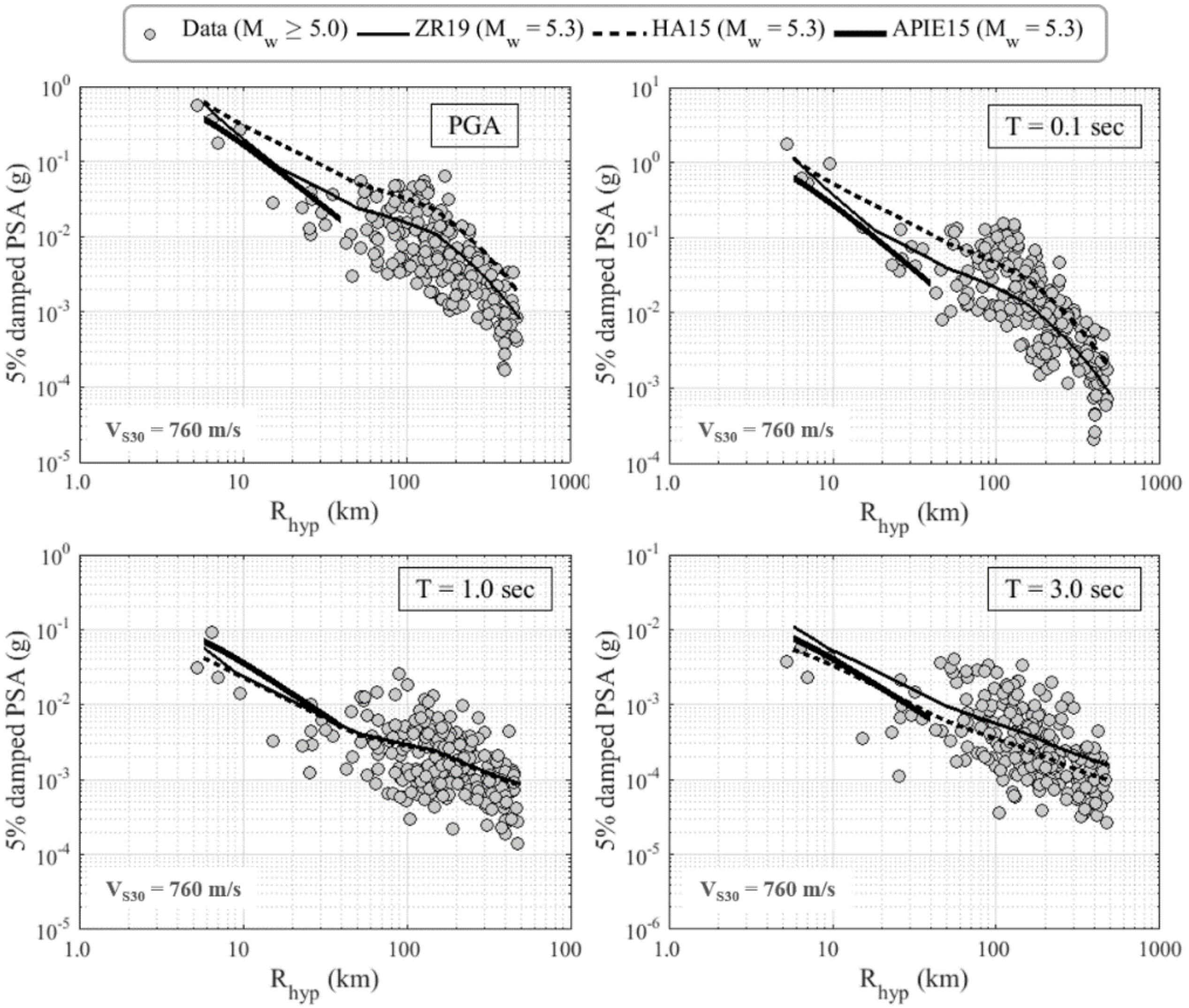
$$\ln F = C + F_R + F_S + F_M \implies$$

$$\implies PSA_{Tx-Ok-Ks} = F \cdot PSA_{HA15}$$

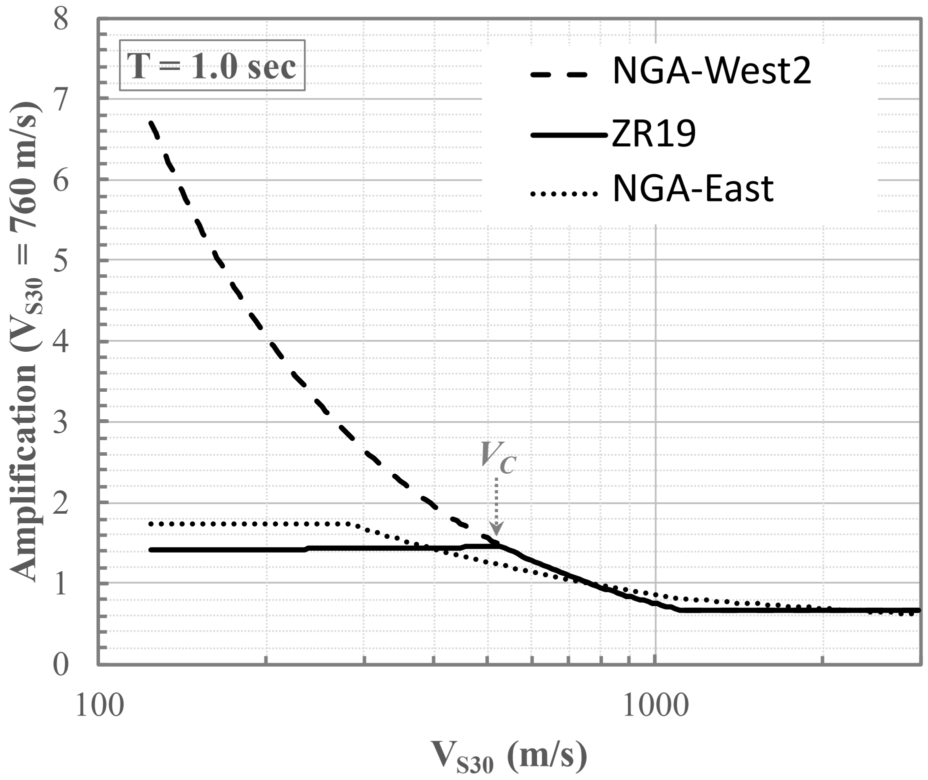


Zalachoris and Rathje (2019) Ground Motion Model

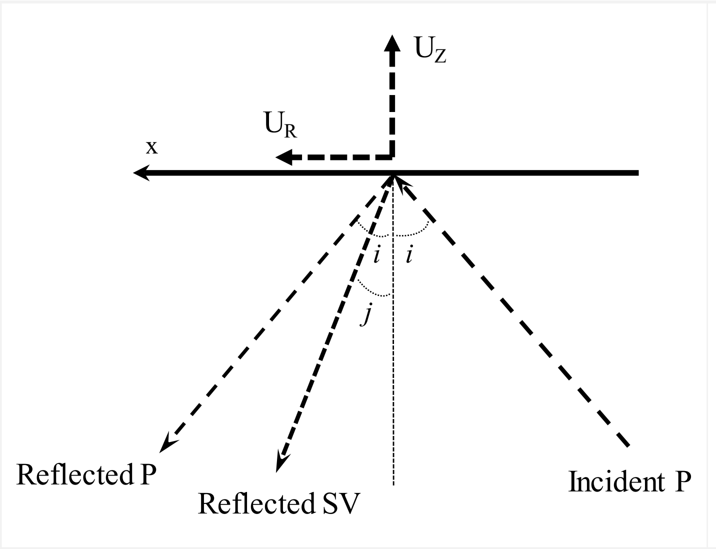
M ≥ 5.0, Vs30 = 760 m/s



Adjusted Vs30 Scaling



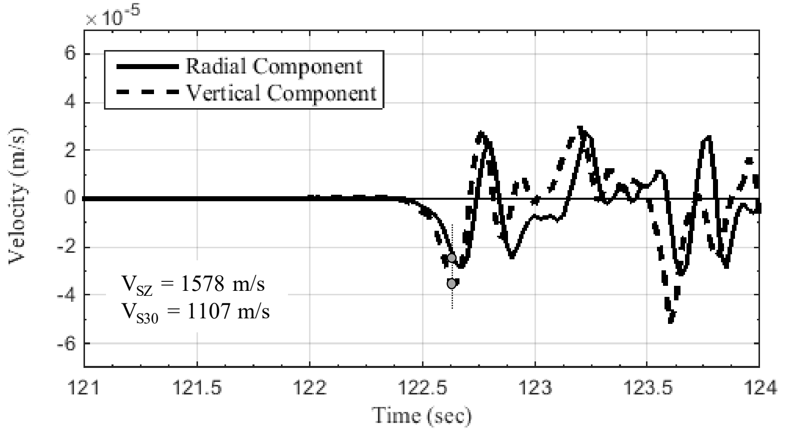
P-wave Seismogram Method



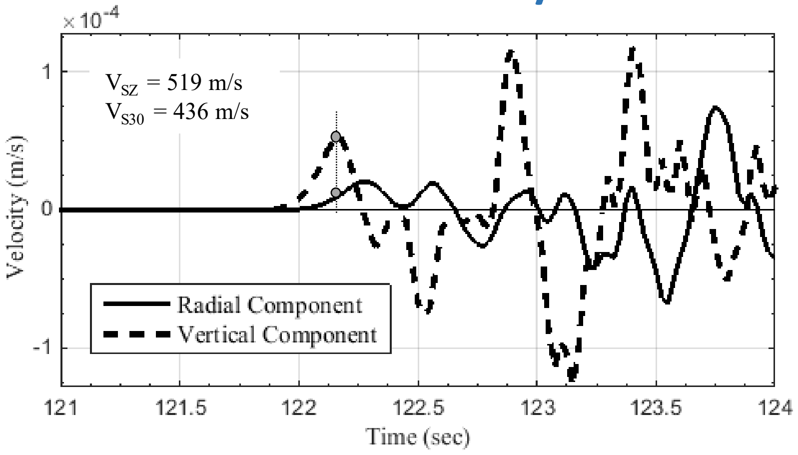
$$V_S = \frac{\cos j \pm \sqrt{\cos^2 j + 2\left(\frac{\dot{U}_R}{\dot{U}_Z}\right)^2}}{2p\left(\frac{\dot{U}_R}{\dot{U}_Z}\right)}$$

Ni et al. (2014), Kim et al. (2016)

Vs30 = 1107 m/s

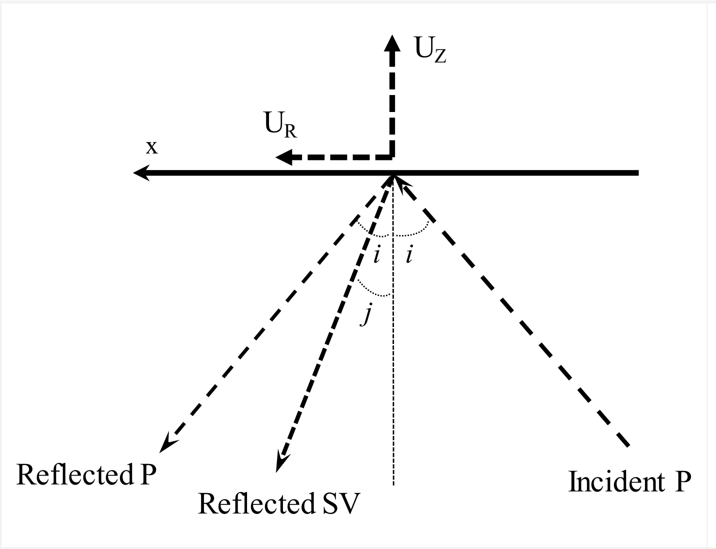


Vs30 = 436 m/s



Shear Wave Velocity Characterization

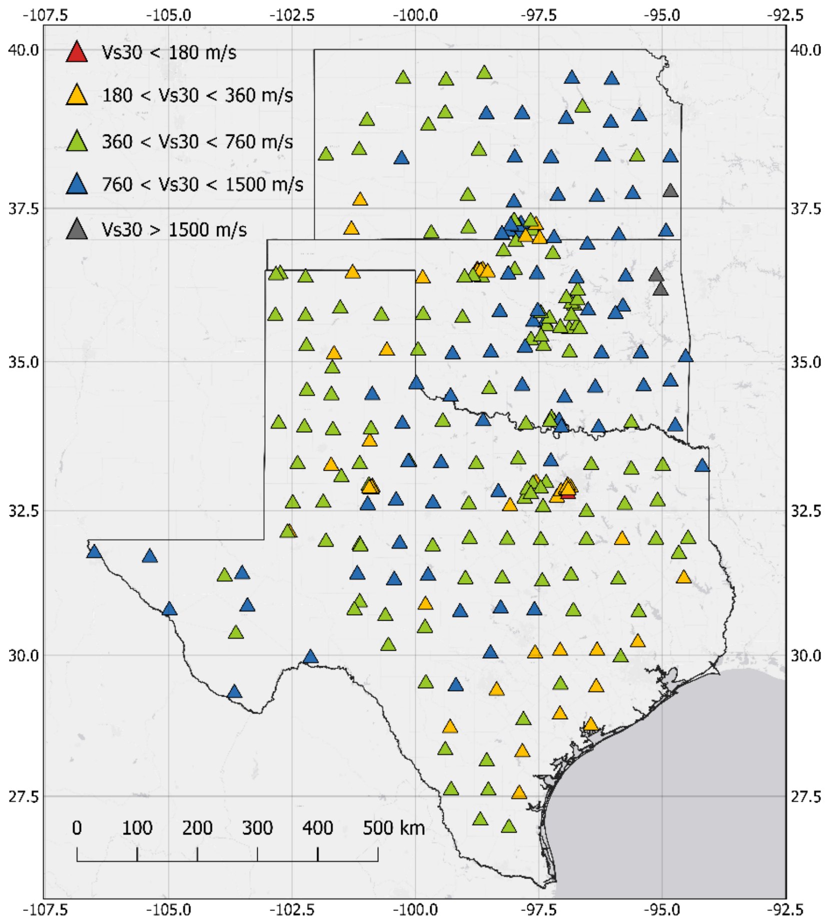
P-wave Seismogram Method



$$V_S = \frac{\cos j \pm \sqrt{\cos^2 j + 2\left(\frac{\dot{U}_R}{\dot{U}_Z}\right)^2}}{2p\left(\frac{\dot{U}_R}{\dot{U}_Z}\right)}$$

Ni et al. (2014), Kim et al. (2016)

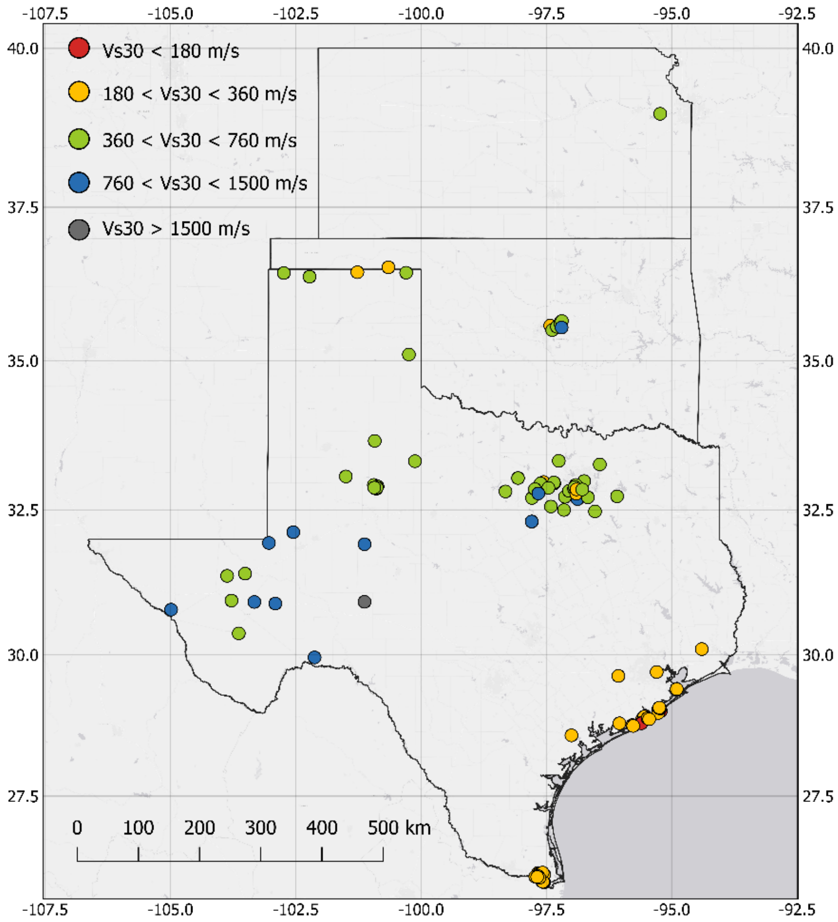
Vs30 at Recording Stations



Zalachoris et al. (2017) *EQ Spectra*

Field Measurements

In Situ Vs30 Measurements



Performed by Cox and Yust

Development of Comprehensive Vs30 Map

Geologic Proxy for Vs30:

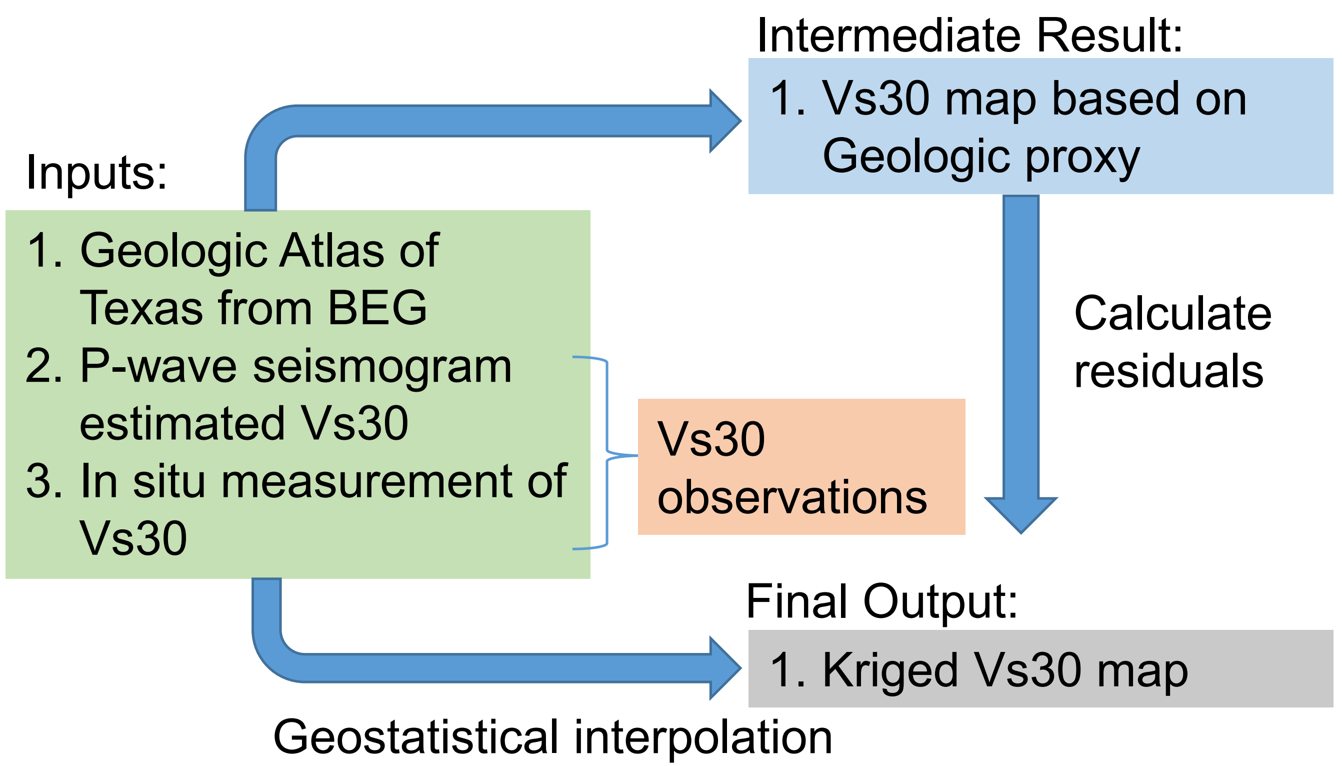
Age and Rock Type

Geologic Age	Rock Type	# pts	V_s (m/s)
Quaternary-Holocene (Outside of Gulf Coast)	A/C	11	484
Quaternary-Pleistocene (Outside of Gulf Coast)	A/B/C/D	30	526
Quaternary-Undivided (Outside of Gulf Coast)	A/B/C	18	588
Quaternary-Holocene (In Gulf Coast)	A/C	62	211
Quaternary-Pleistocene (In Gulf Coast)	B/C	7	242
Quaternary-Undivided (In Gulf Coast)	A/B	4	213
Tertiary	B	11	386
	C/D	30	466
	E	1	696
	F	2	838
Mesozoic	B/C/D	42	517
	E	37	765
Paleozoic	D	80	747
	E	12	971
	F	3	1638
Precambrian	F	2	1434

Rock Type Groups

Group A: Alluvial and terrace deposits
Group B: Clay, silt, and loess; not alluvium
Group C: Sand and gravel; not alluvium.
Group D: Mud/clay/silt/sand stone, conglomerate, marl, and shale
Group E: Limestone and chalk
Group F: Chert, basalt, granite, and rhyolite

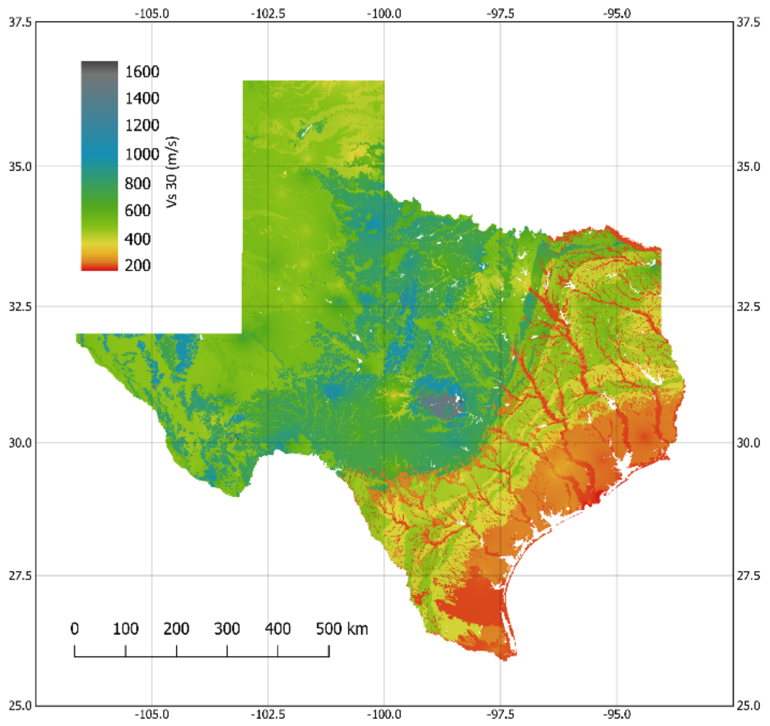
Mapping Approach



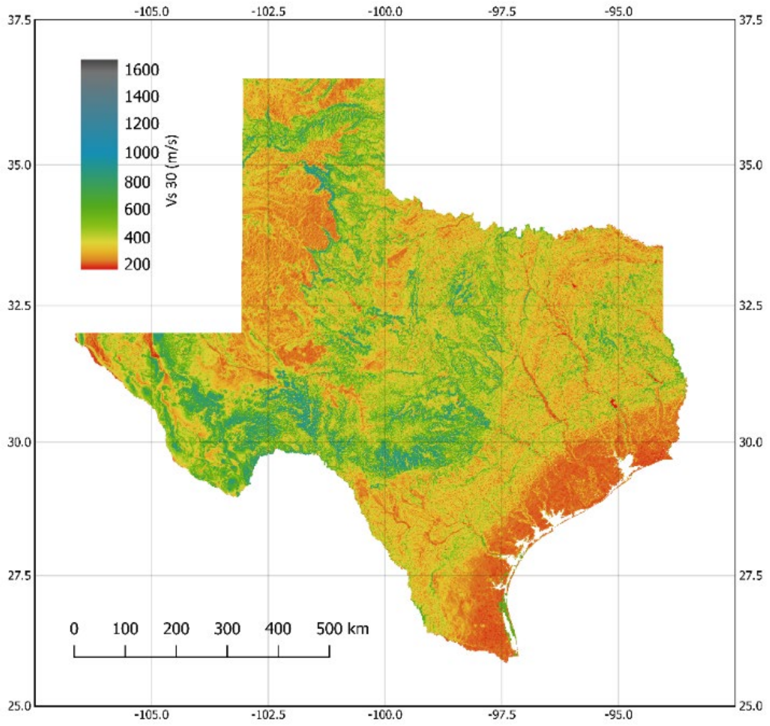
Zalachoris et al. (2017) *EQ Spectra*
Li et al. (in prep) *EQ Spectra*

Comparison of Vs30 Maps

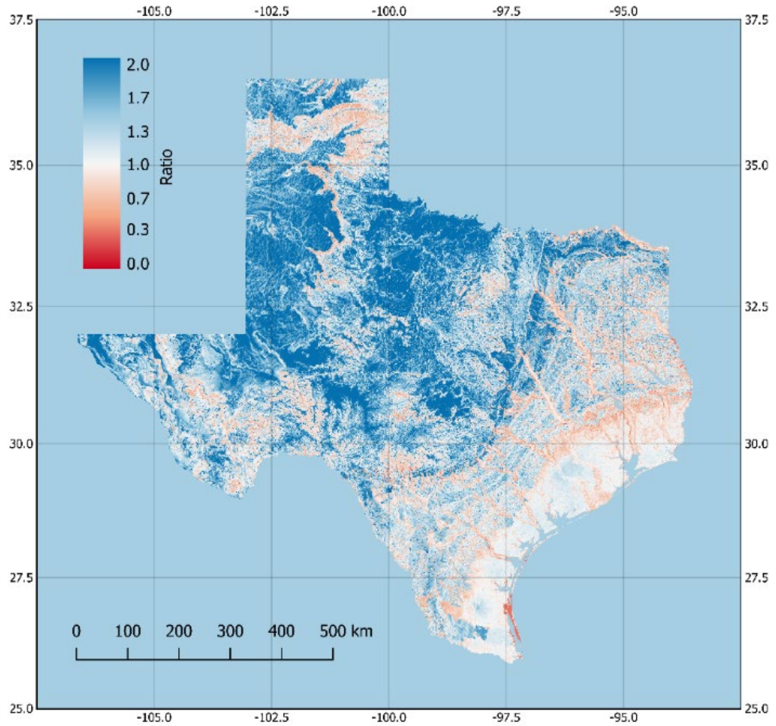
Texas-specific Vs30 Map (This study)



USGS Global Vs30 from Topographic Proxy



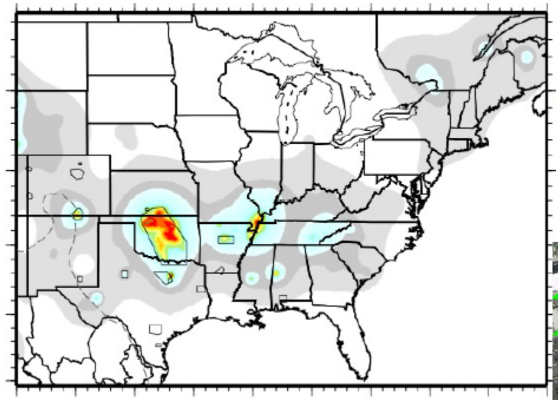
Ratio = Texas/USGS



Seismic Risk Assessment

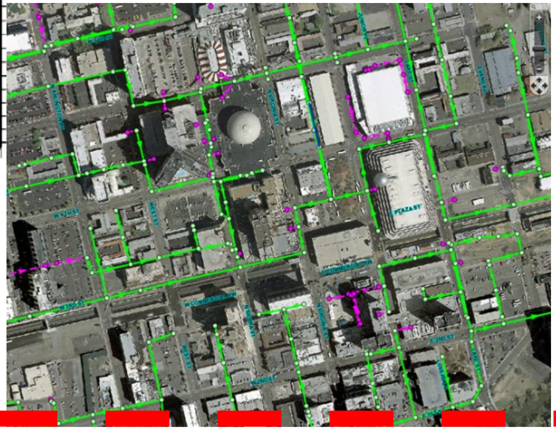
Risk = Hazard

Measure of ground shaking and its probability



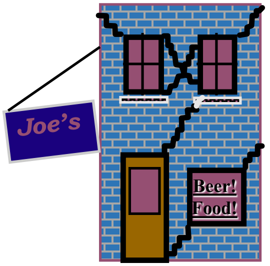
x Exposure

Characterization of built environment and inhabitants



x Fragility

Susceptibility of the exposure to damage/undesirable consequences

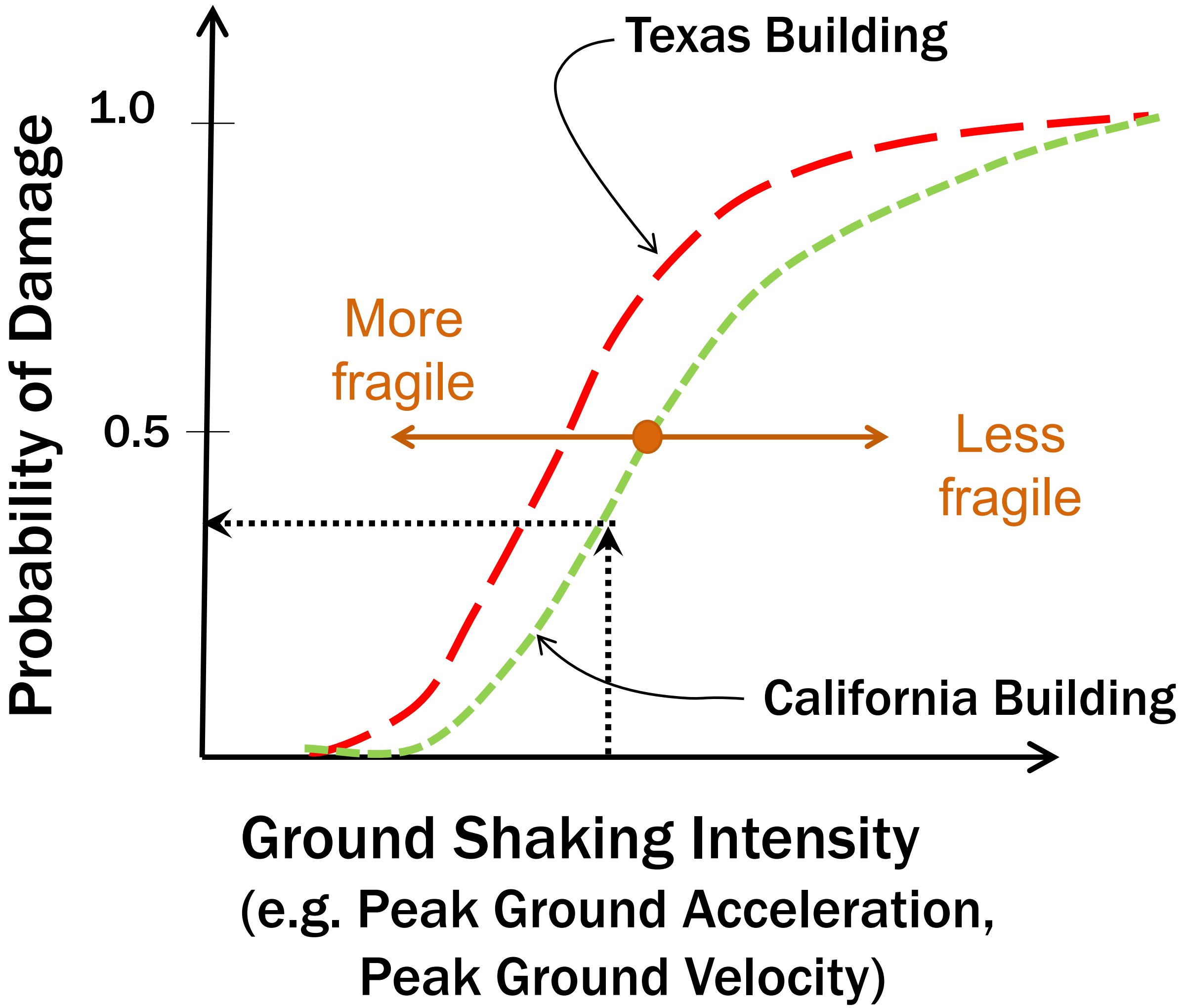


x Consequences

$$, number of people adversely affected

Fragility Curves

Used to predict the likelihood of damage for a given ground shaking intensity



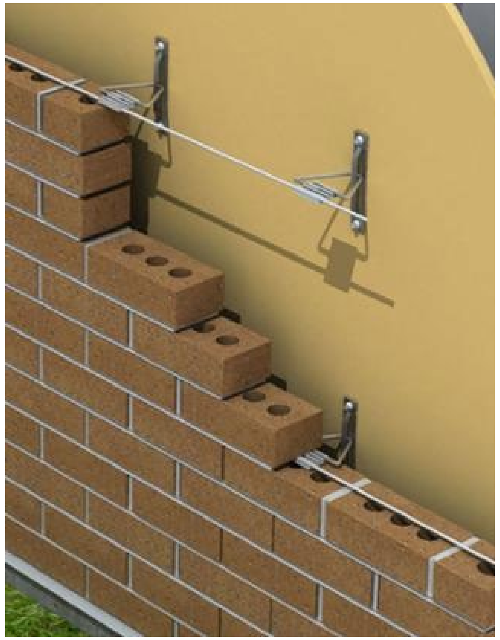
Clayton and Khosravikia

Masonry Facades: Effect of Construction Practices

Unreinforced brick:
- Commonly used in Texas
- Known to be vulnerable in earthquakes

M5.7 Prague, OK
(Nov. 2011)

In seismically-active areas:
- Brick facades and chimneys are avoided
- When used, more bracing is used to prevent collapse



Fragility curves must reflect local construction practices

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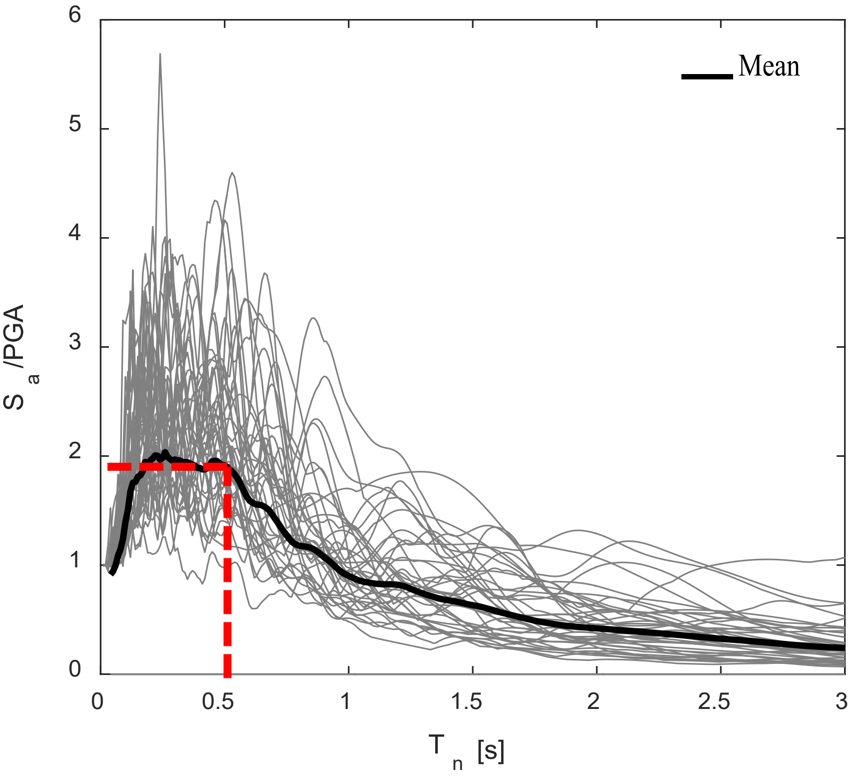
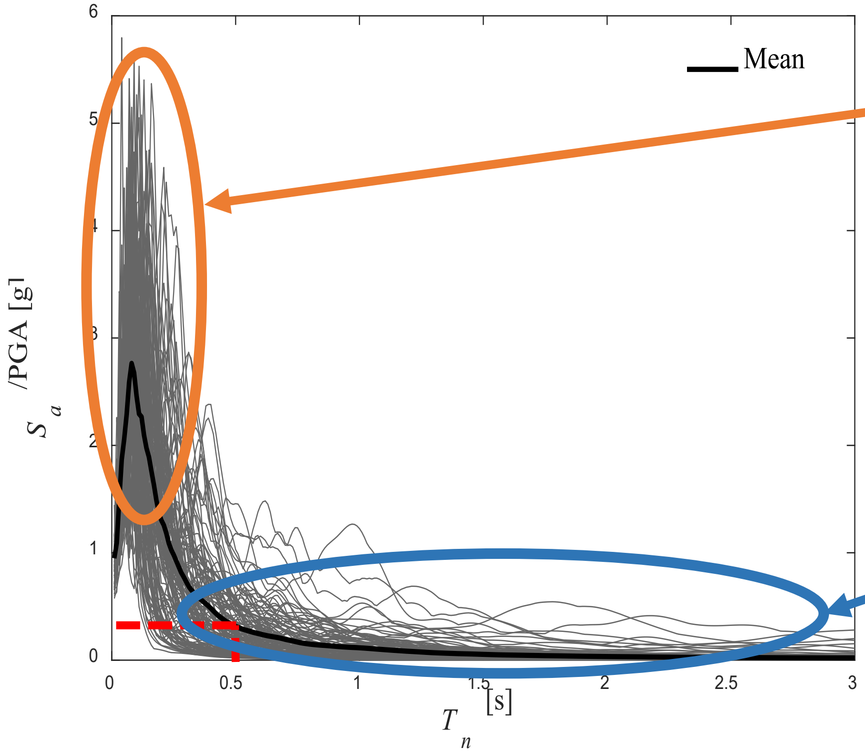
Effect of Ground Motions

Earthquake Frequency Content

"West coast" design motions



Texas/Oklahoma motions

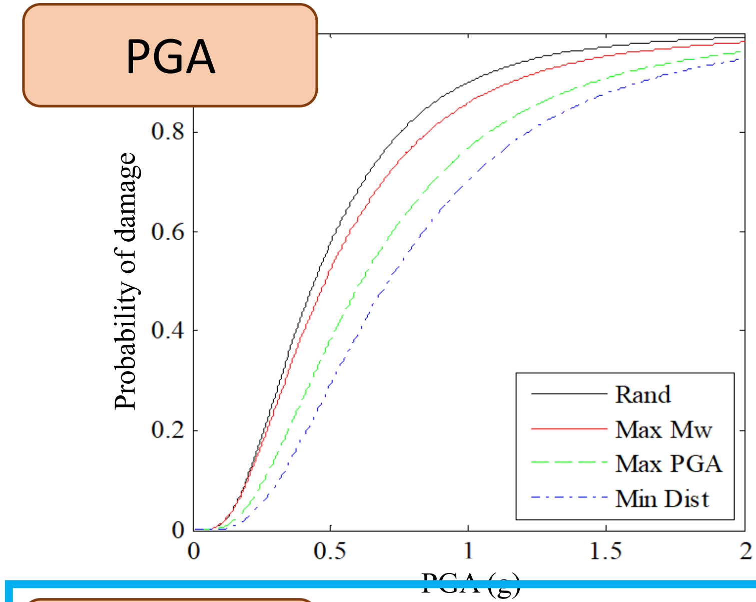


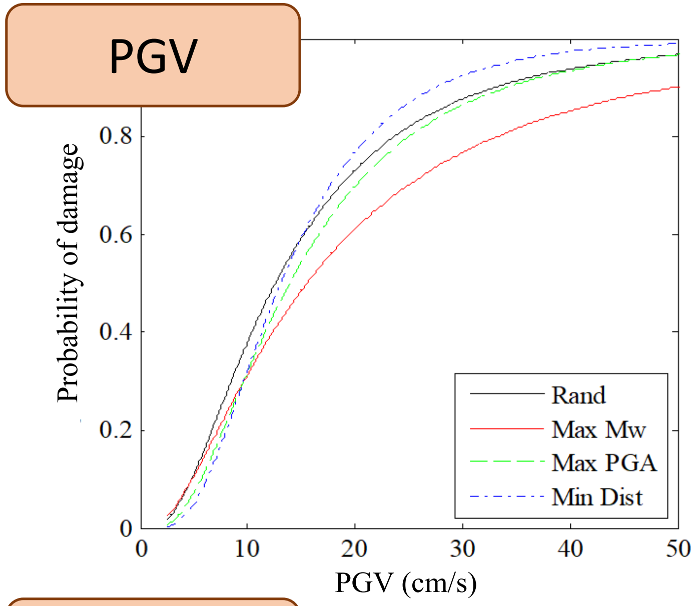
High frequency content = More damage to buildings with low natural period

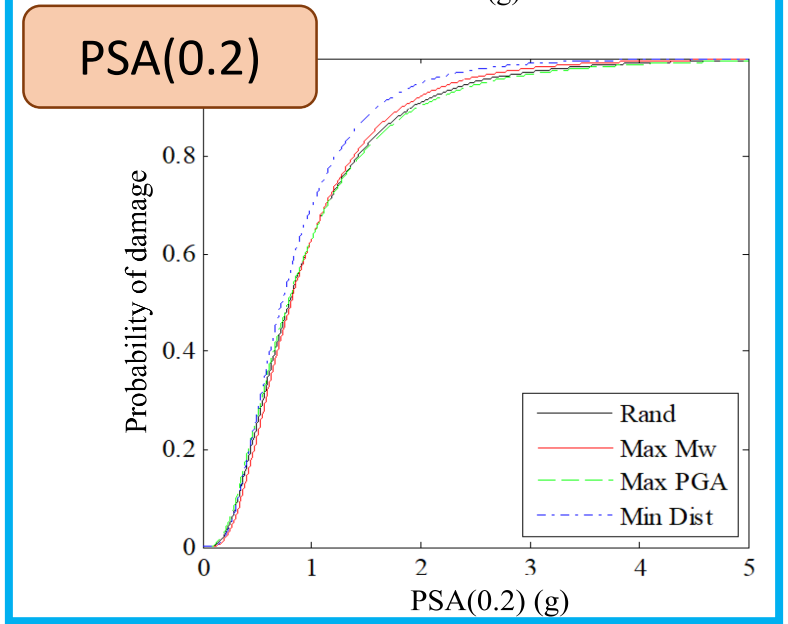
Low energy for long period waves = Less damage to buildings with higher natural period

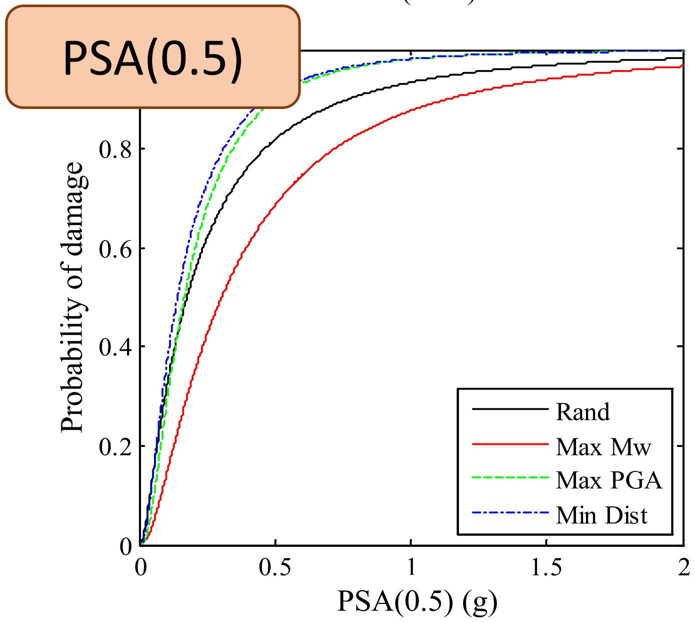
Fragility curves must reflect ground motion characteristics

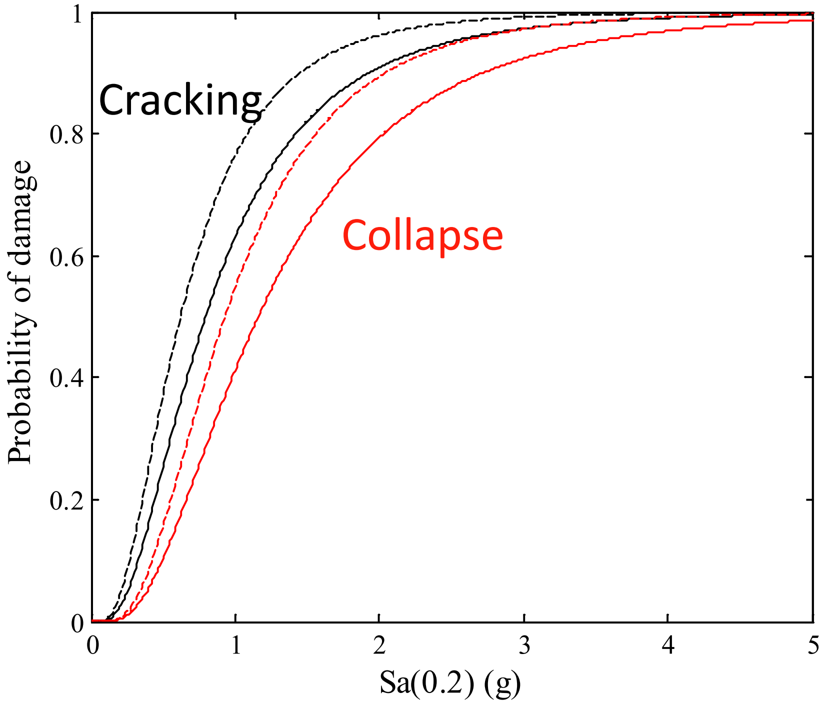
Masonry Façade Fragility: Comparison of intensity measures











	Brick Tie Type	Damage State
(solid black line)	Code compliant brick ties	Cracking
(solid red line)	Code compliant brick ties	Collapse
(dashed black line)	Thinner ties (more common)	Cracking
(dashed red line)	Thinner ties (more common)	Collapse

Bureau of Economic Geology TexNet CISR

Fragility of Different Types of Infrastructure

Residential Masonry Facades (TexNet - CISR)

(Clayton, Kurkowski, Khosravikia)

2016 M5.8 Pawnee, OK
(source: P. Clayton)

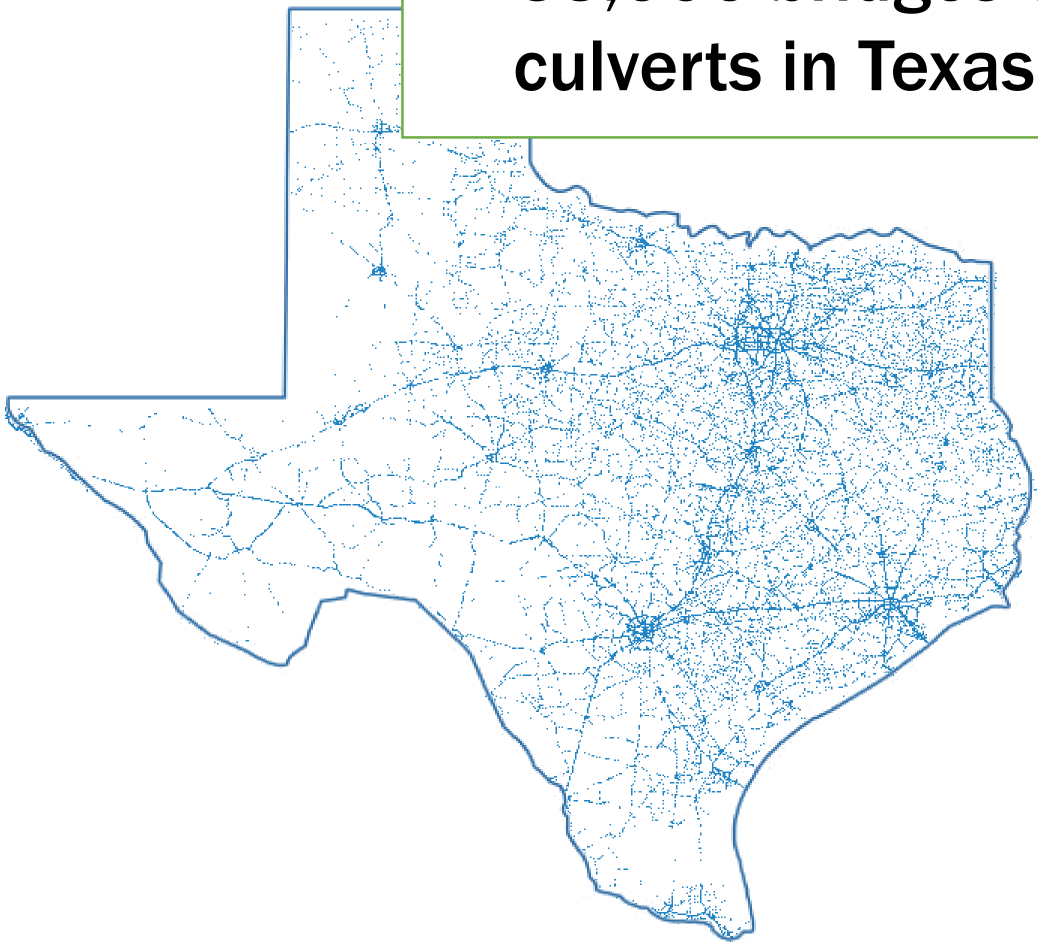
Bridges (TxDOT)

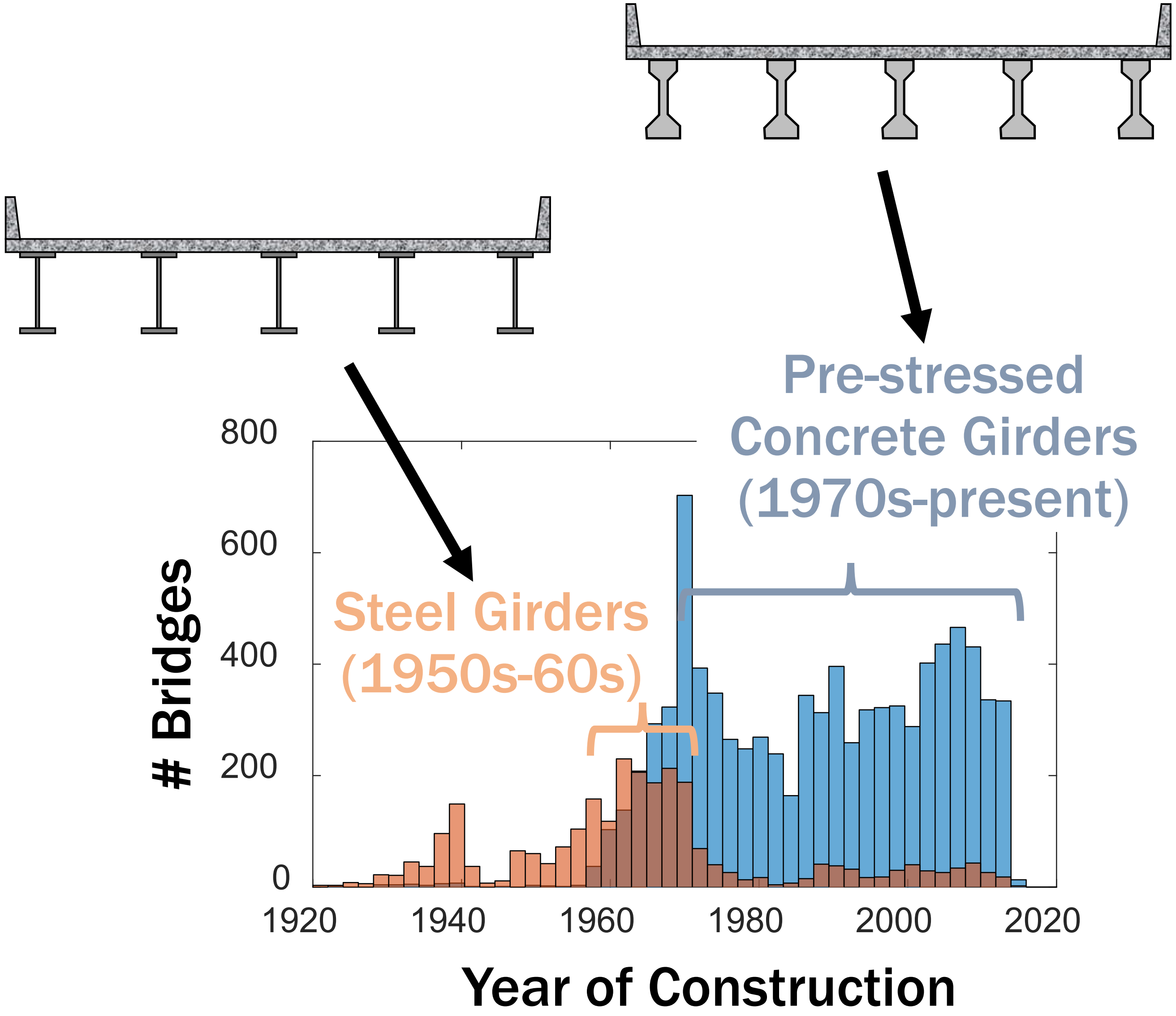
(Clayton, Cox, Rathje, Williamson, Khosravikia, Potter, Prakhov, Zalachoris)

2016 M5.8 Pawnee, OK
(source: P. Clayton)

Characterize Bridge Inventory

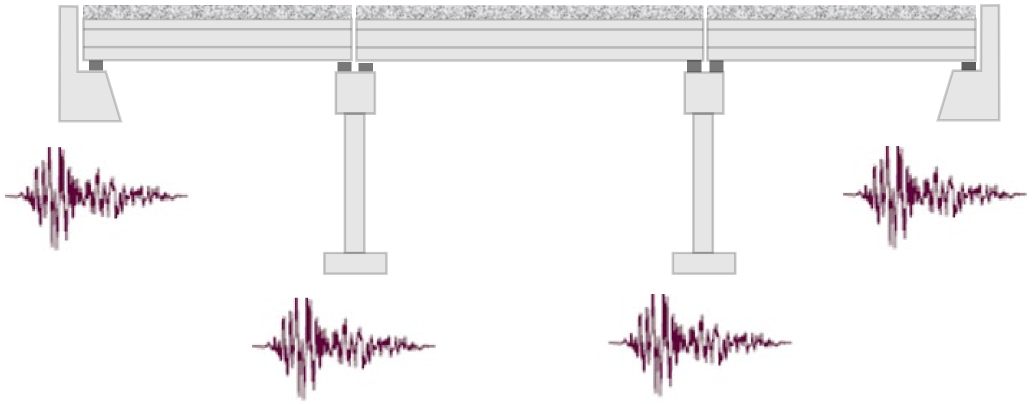
~53,000 bridges & culverts in Texas

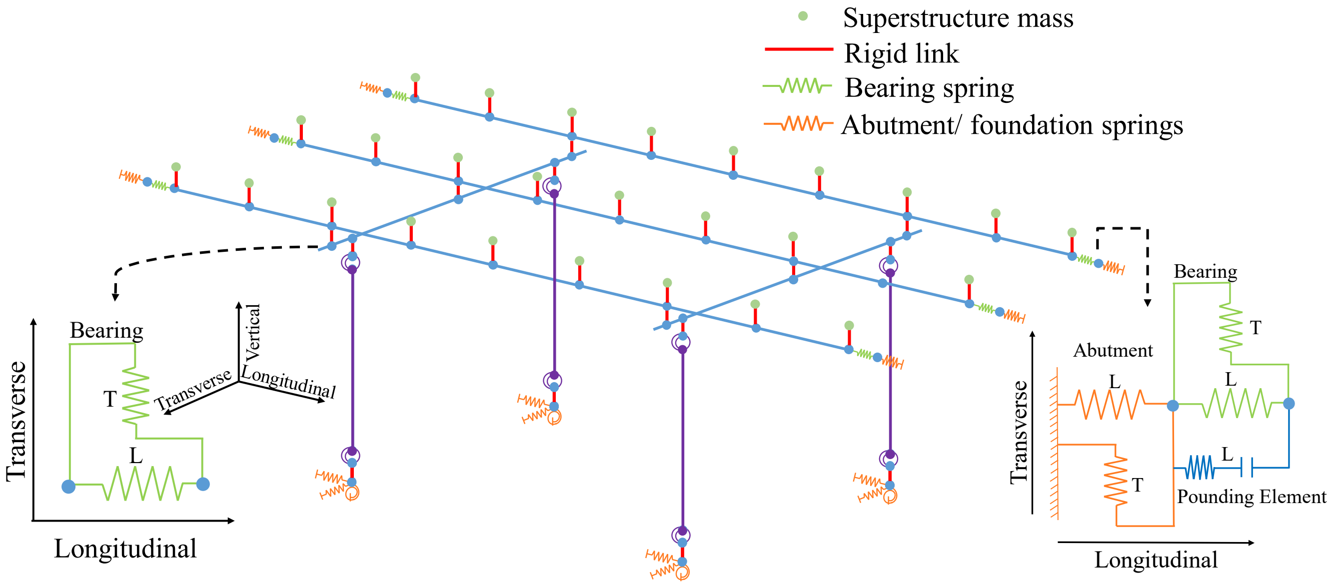




Characterize Bridge Vulnerability

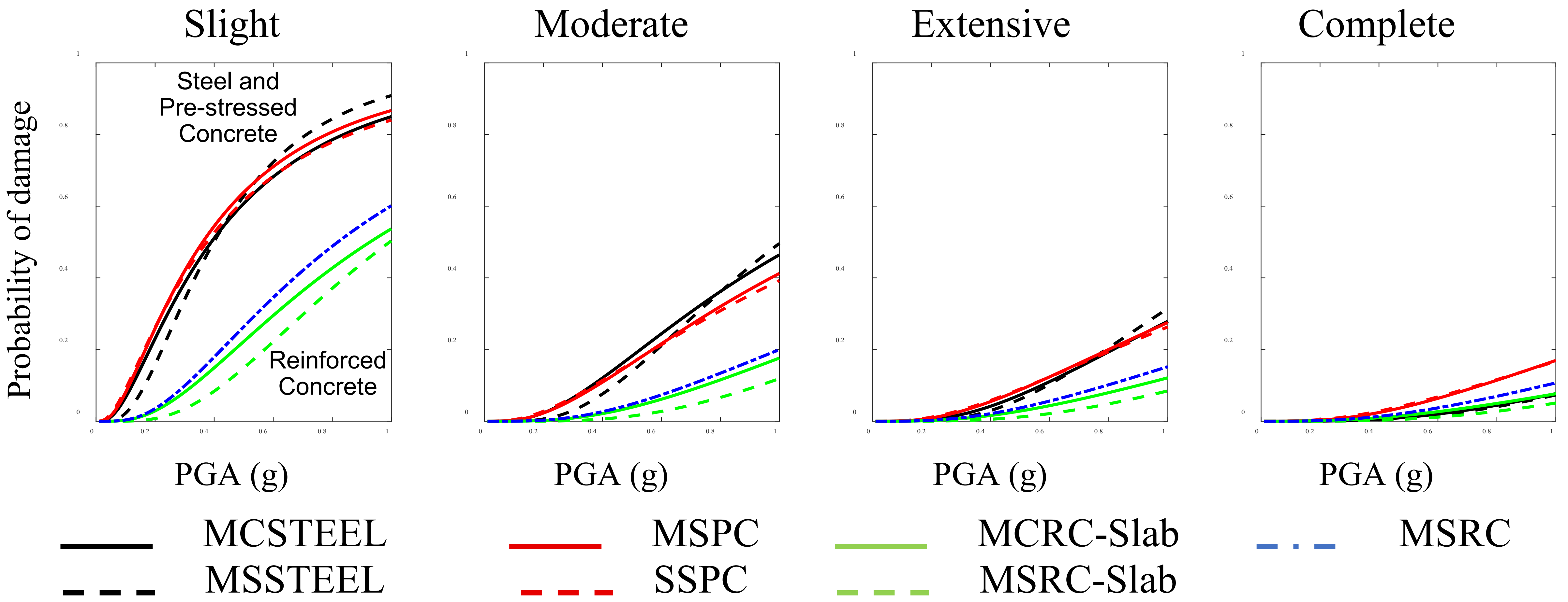
- ***Used computer models to simulate*:**
  - Different geometries (height, span length, etc.)
  - Different construction materials & designs
  - Wide range of ground motions



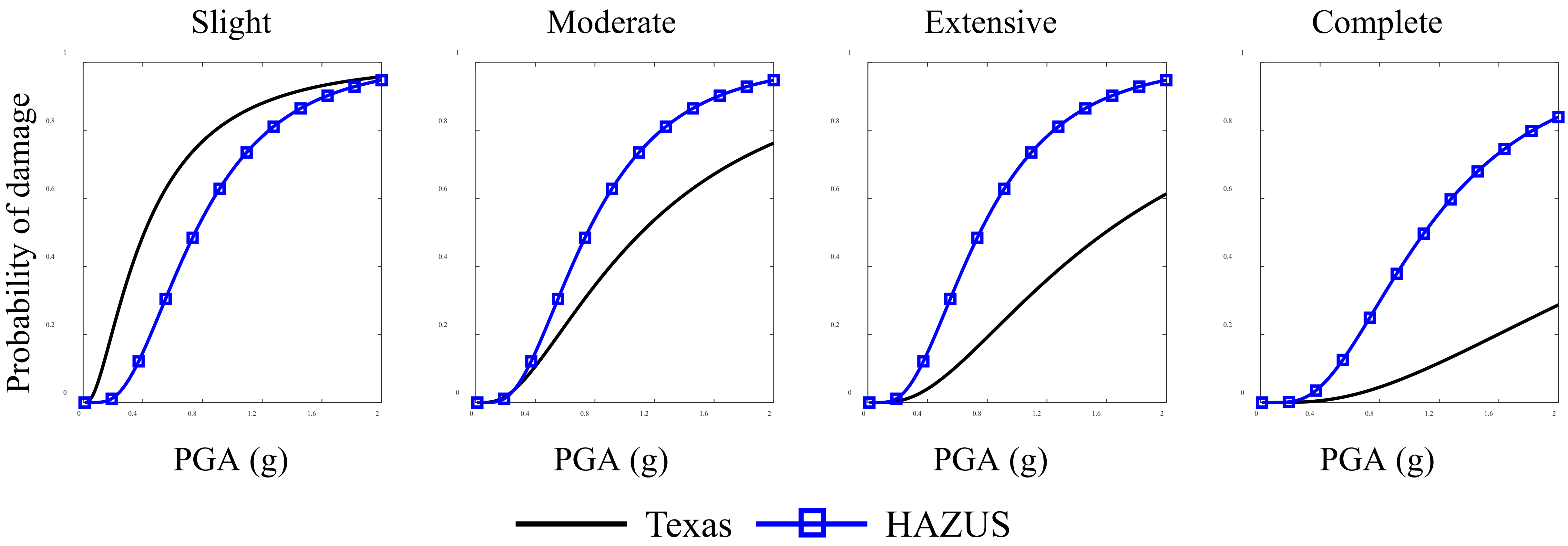


Developed in OpenSees Software

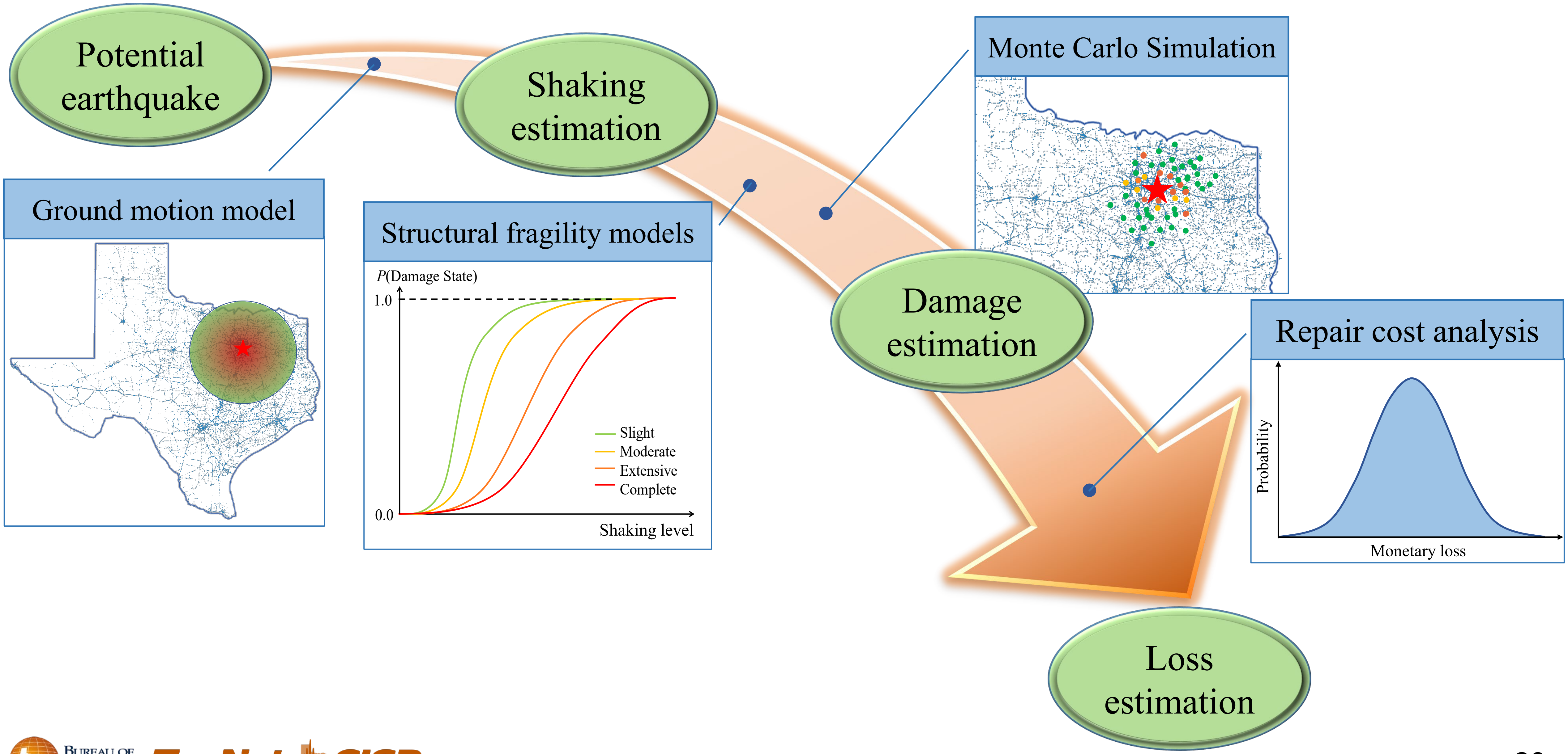
Bridge Fragility Curves in Texas



Continuous steel girder bridges



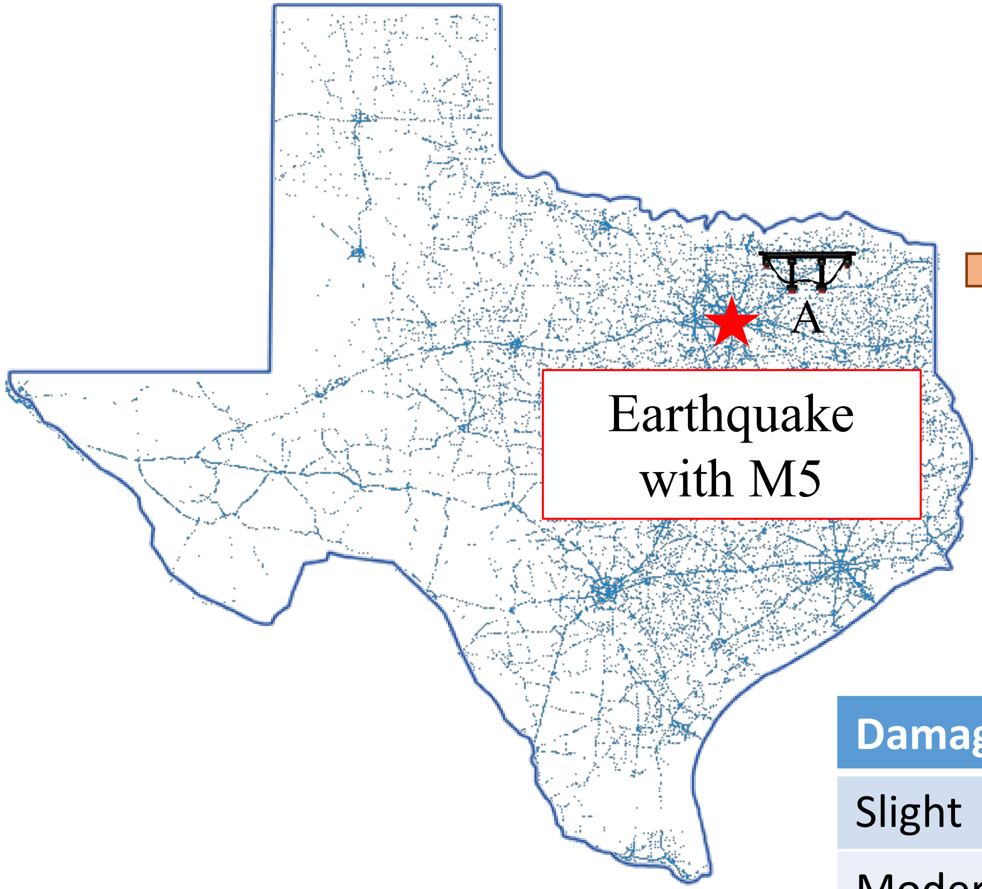
Risk Assessment Framework

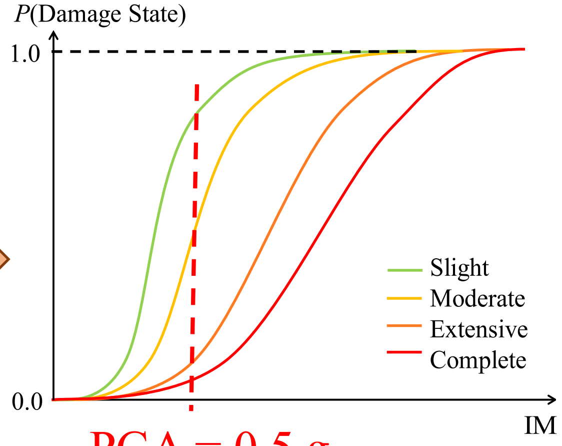


Bureau of Economic Geology TexNet CISR

Damage Estimation

Hypothetical Earthquake with M5 in Dallas, Texas





PGA = 0.5 g
From ground motion models

Damage	Probability
Slight	0.4
Moderate	0.2
Extensive	0.1
Complete	0.1
No damage	0.2

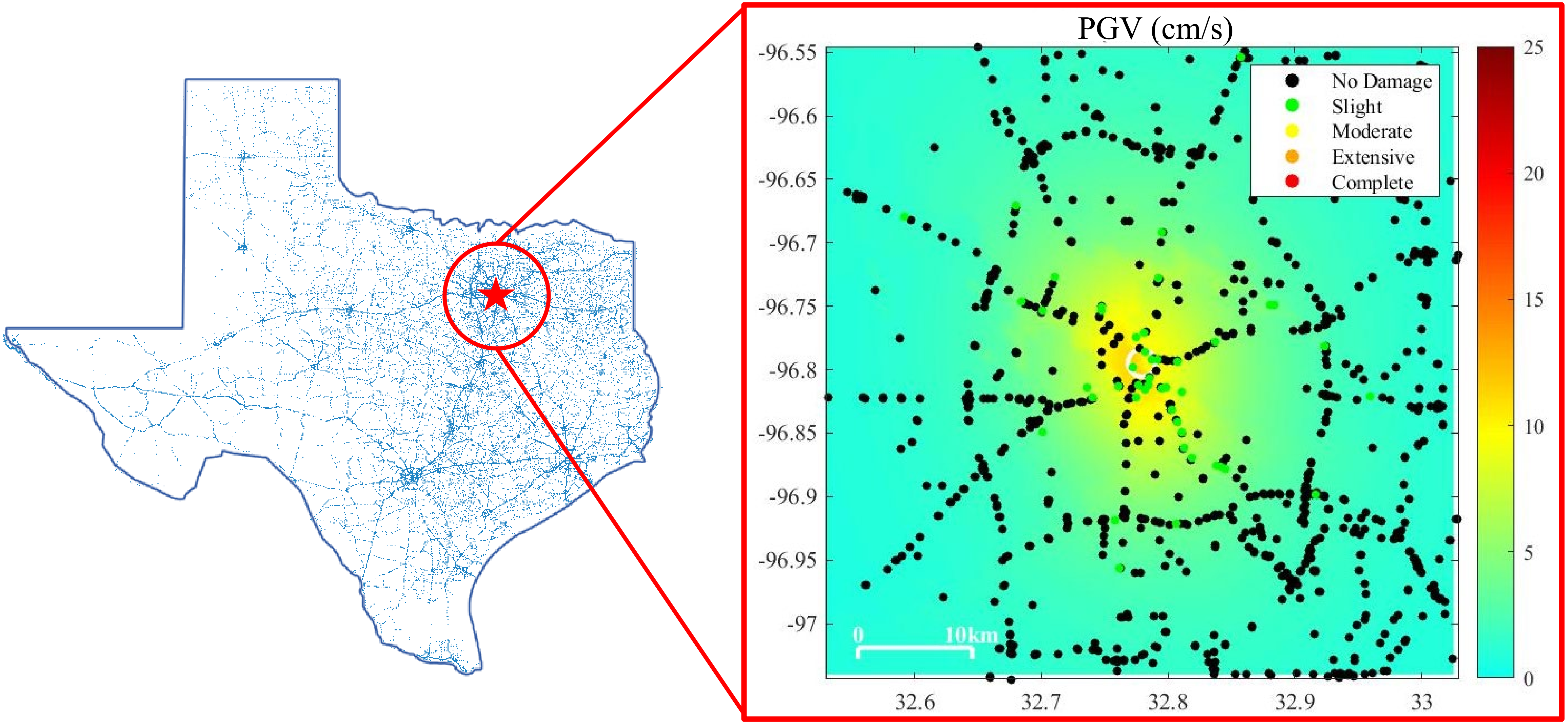
One Realization

Slight damage

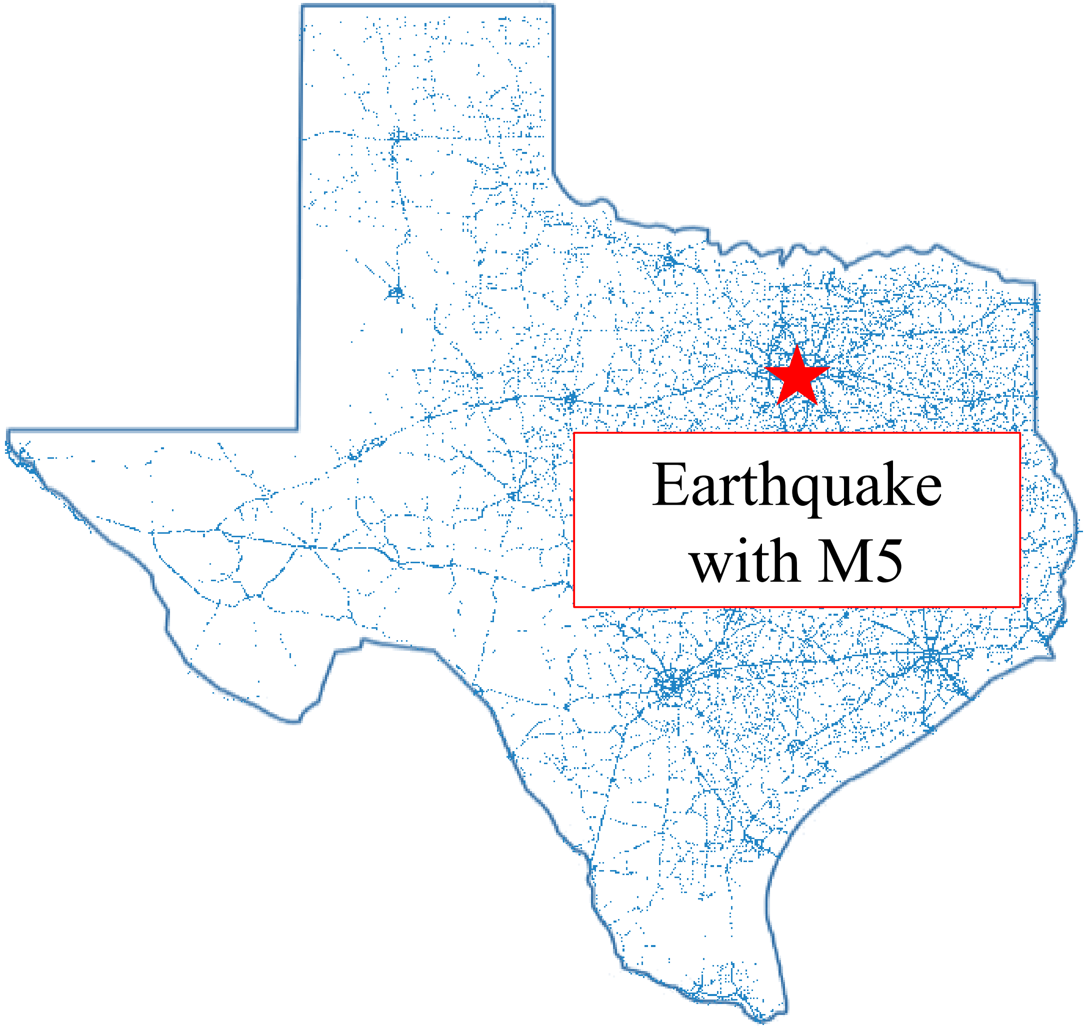
Damage	Repair Cost
Slight	0.03 x Construction Cost
Moderate	0.08 x Construction Cost
Extensive	0.25 x Construction Cost
Complete	1.00 x Construction Cost

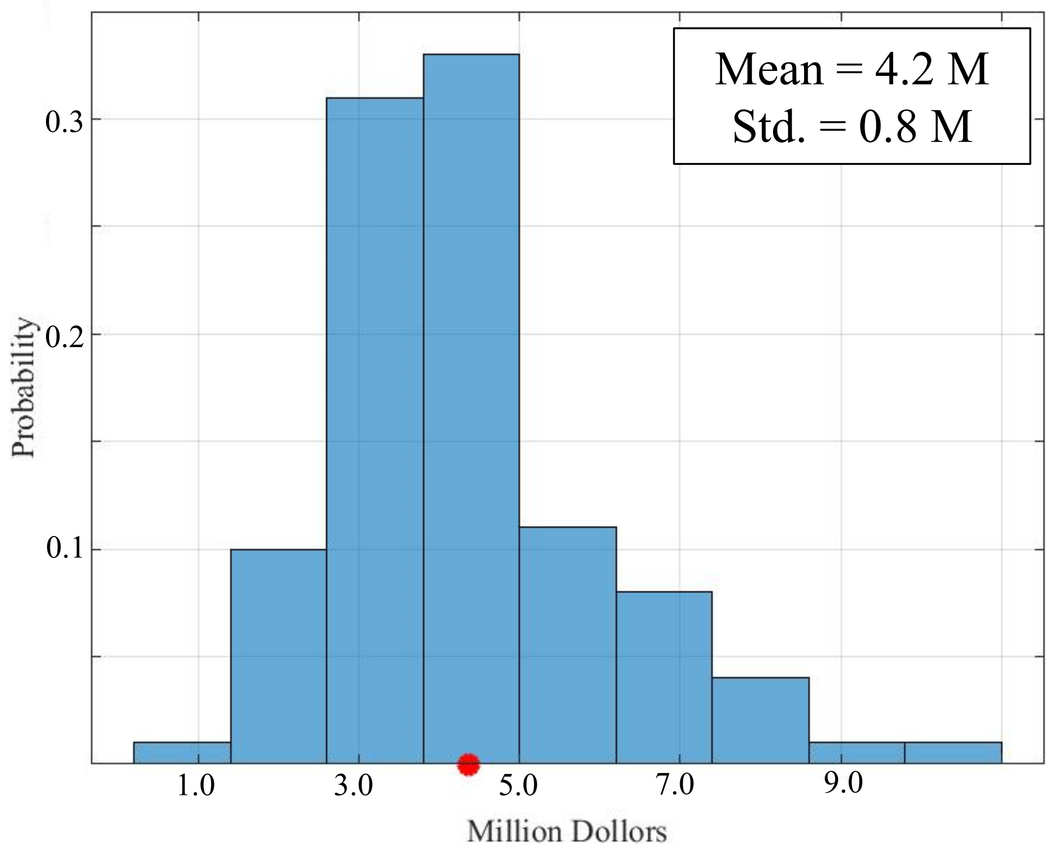
Damage Estimation

Hypothetical Earthquake with M5 in Dallas, Texas

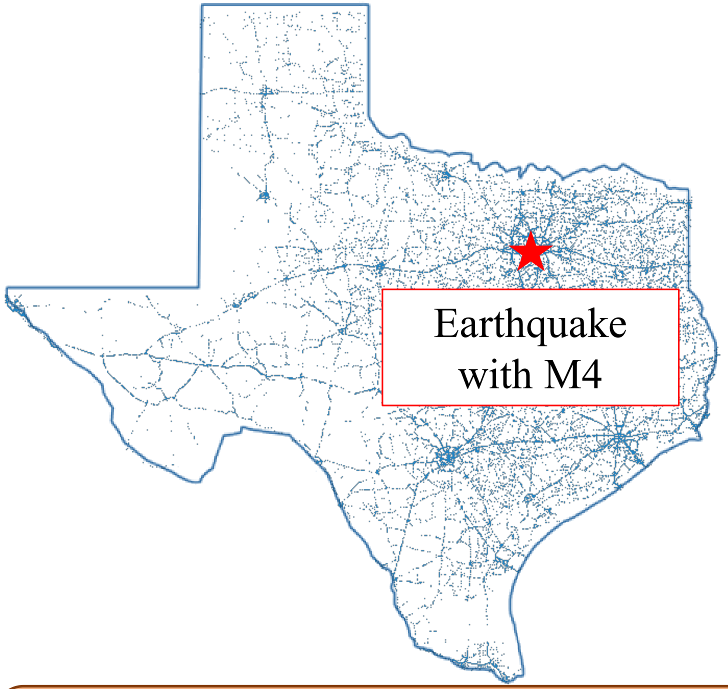


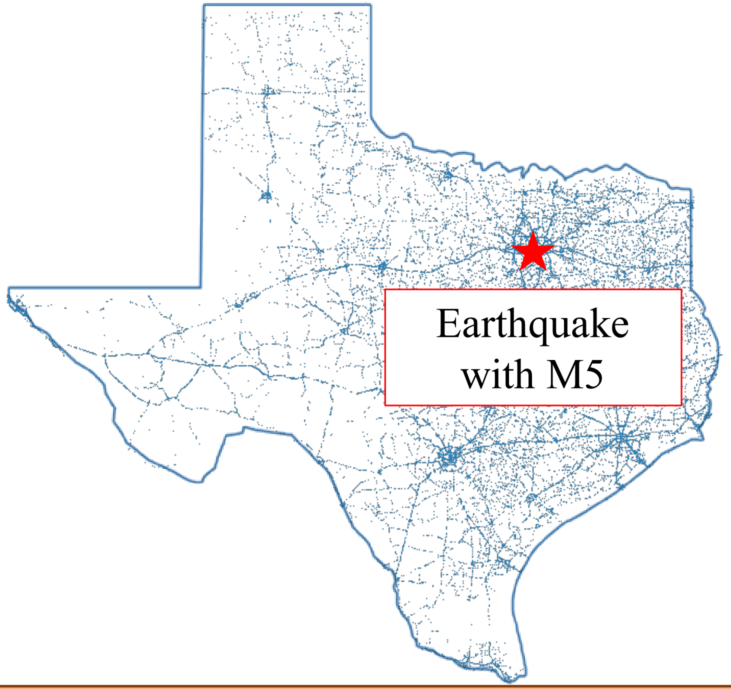
Loss Estimation

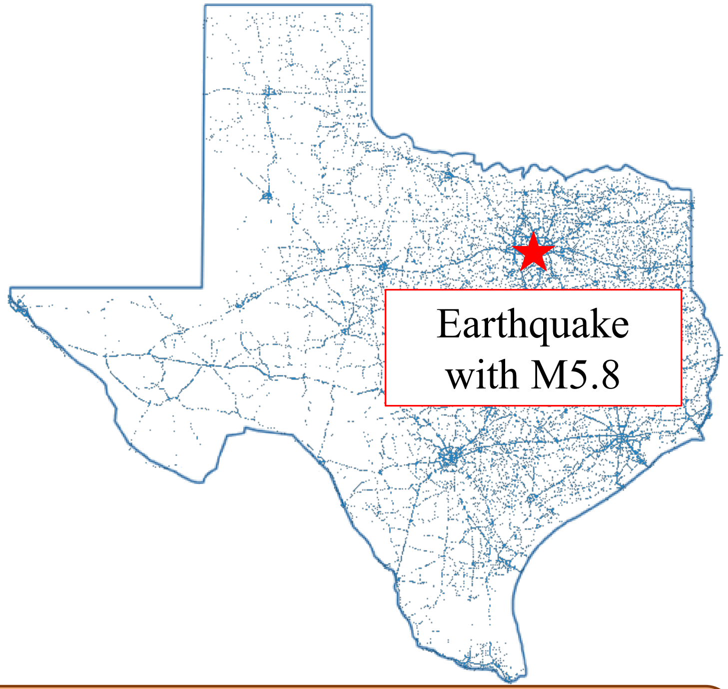




Scenario-based Loss Estimation







Mean of Monetary Loss

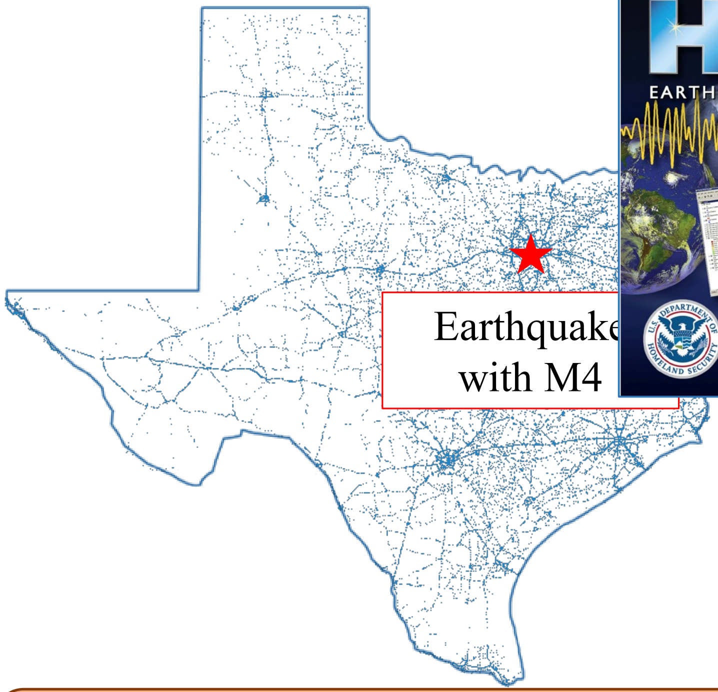
$ 0.04 M

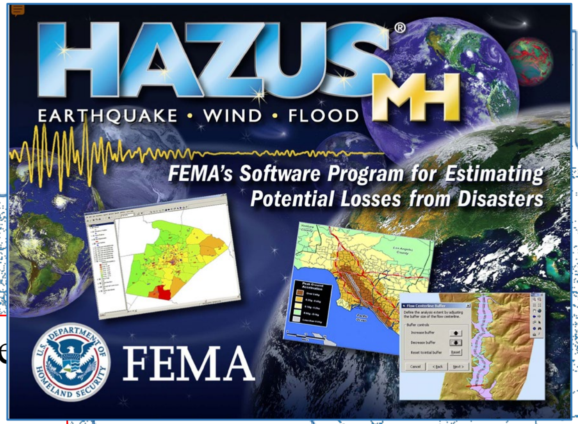
$ 4.2 M

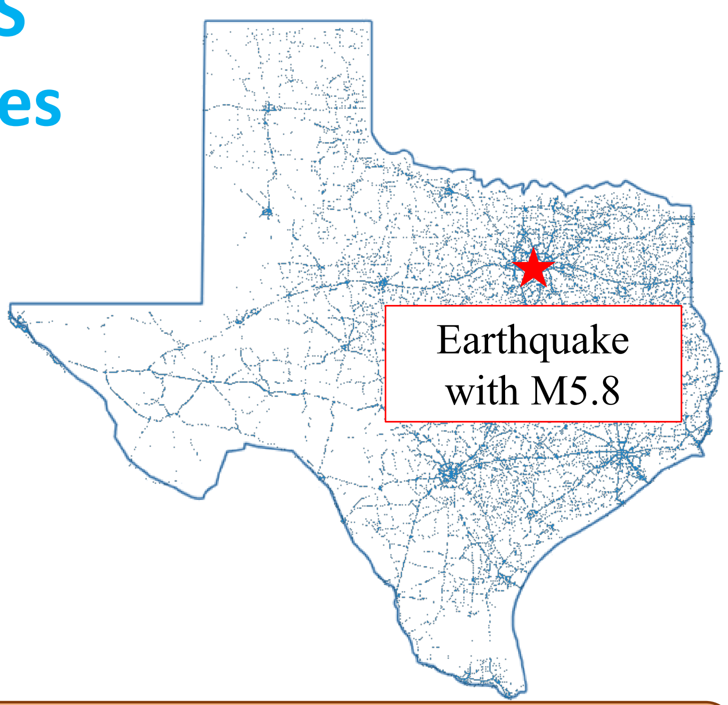
$ 16.2 M

Scenario-based Loss Estimation

Using HAZUS Fragility Curves



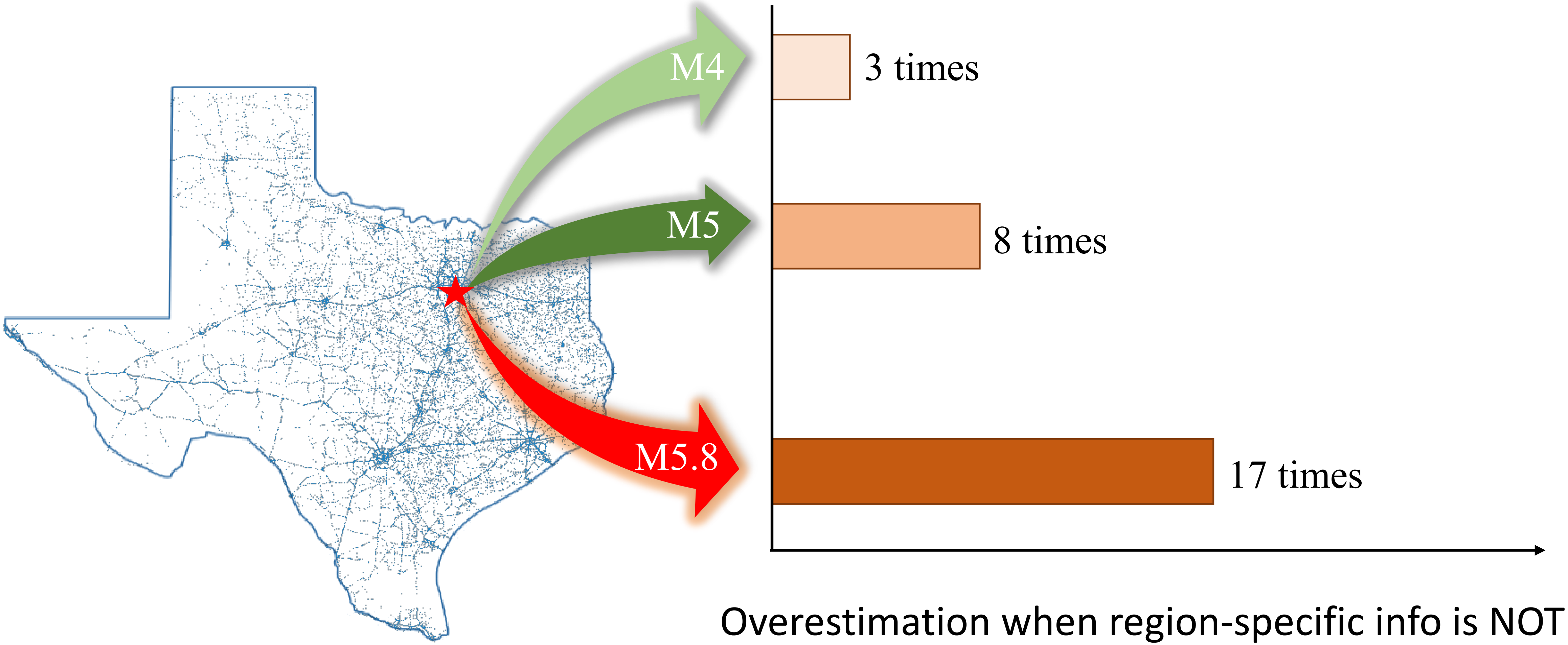




Mean ... s

Earthquake with M4	Earthquake with M5	Earthquake with M5.8
$ 0.09 M	$ 31.3 M	$ 284.3 M
$ 0.04 M	$ 4.2 M	$ 16.2 M

Scenario-based Regional Loss Estimates



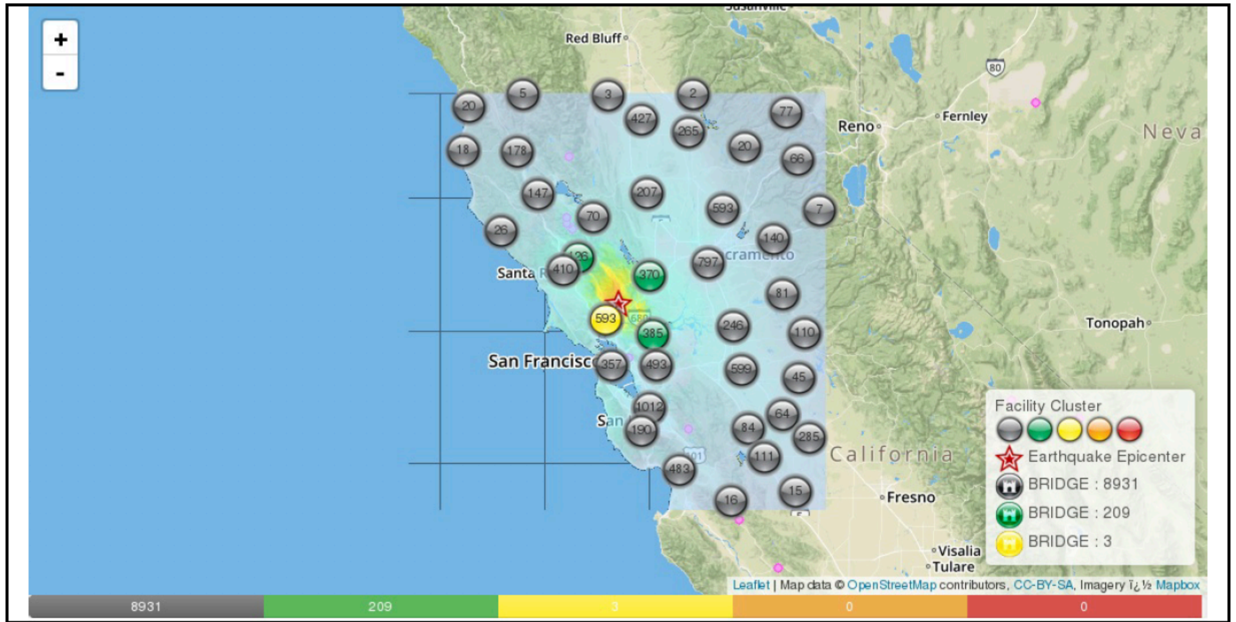
Overestimation when region-specific info is NOT used

Rapid Post-Event Consequence Assessment

ShakeCast Report
National Earthquake Information Center (NEIC)

Magnitude 6.02 - NORTHERN CALIFORNIA Version 1
Origin Time: 2014-08-24 10:20:44 GMT Created: 2018-06-15 20:39:34 GMT
Latitude: 38.21517 Longitude: -122.31233 Depth: 11.12 km

These results are from an automated system and users should consider the preliminary nature of this information when making decisions relating to public safety. ShakeCast results are often updated as additional or more accurate earthquake information is reported or derived.



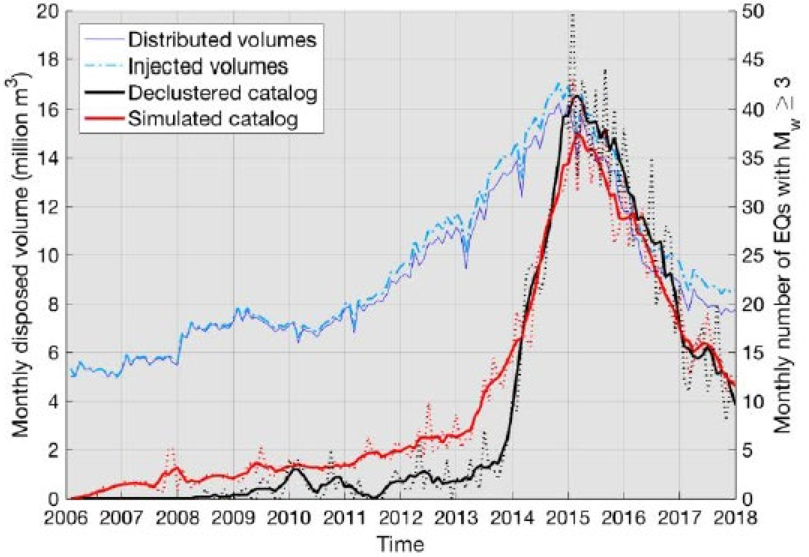
Type	ID	Name	Ep. Distance (km)	Inspection Priority	PGA (%g)	PGV (cm/s)	PSA 1s (%g)	MMI	Vs30 (m/s)
BRIDGE	06_21_0098	21_0098 - STANLEY CREEK	4.3	Moderate	40.62	39.65	39.14	VIII	269.477
BRIDGE	06_21_0087	21_0087 - STATE ROUTE 29	8.1	Moderate	39.75	40.02	41.09	VIII	323.411
BRIDGE	06_21C0006	21C0006 - SODA SPRINGS CREEK	15.97	Moderate	22.29	33.05	31.06	VII	331.11
BRIDGE	06_21C0081	21C0081 - CARNEROS CREEK	2.14	Low	41.86	45.24	44.84	VIII	293.382
BRIDGE	06_21C0047	21C0047 - FAGAN CREEK	3.48	Low	33.04	28.63	27.89	VII	298.697
BRIDGE	06_21C0078	21C0078 - HUICHICHA CREEK	3.76	Low	41.78	41.55	40.81	VIII	307.819
BRIDGE	06_21_0049	21_0049 - NVRR NAPA RIVER STANLY	4.06	Low	34.59	38.13	37.43	VIII	219.46

- *TxDOT implementation of ShakeCast software*
  - **Input TxDOT bridge inventory & vulnerability** (from research)
  - **Automatically retrieves ShakeMap from USGS** minutes after event
    - Integrate new GMM and Vs30 map
  - **Real-time report of inspection priorities**
  - **Sends notifications to personnel**

(ongoing project funded by TxDOT)

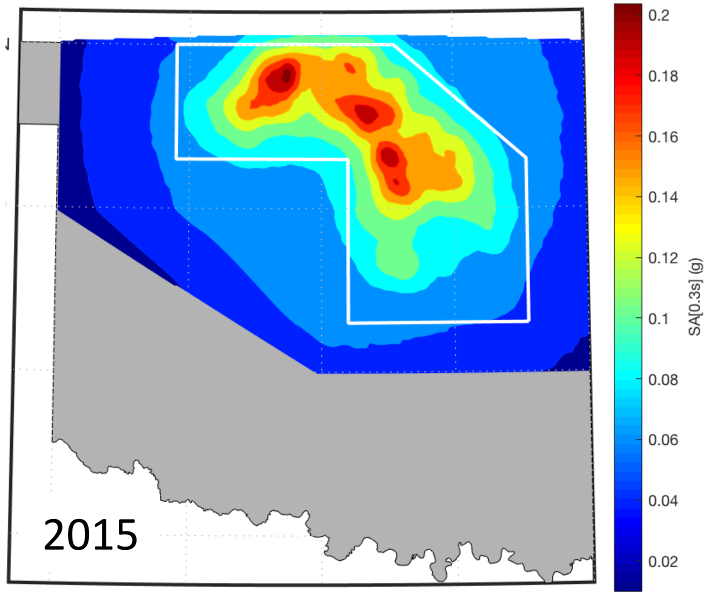
Probabilistic, Time-Dependent Risk Assessment: Oklahoma

Simulated Seismicity

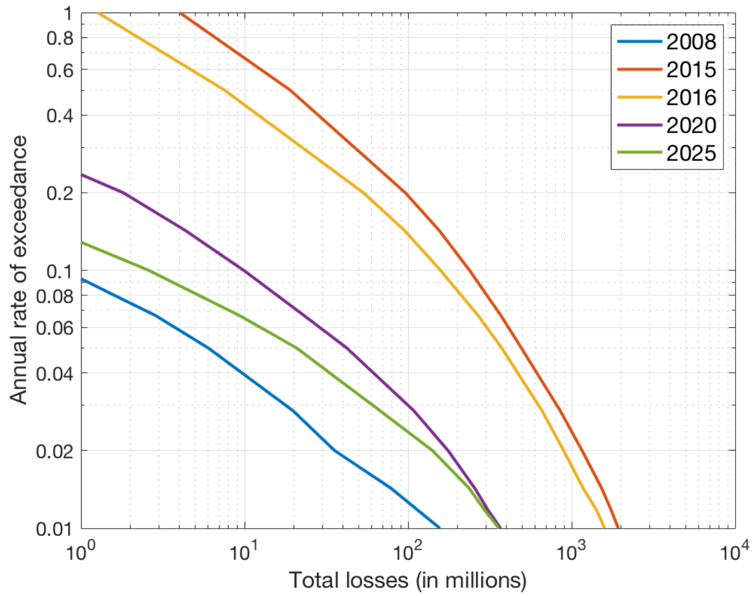


Ground Motion Hazard

10% Annual Probability of Exceedance



Monetary Loss Curves



- Annual seismicity rates from Grigoratos et al. *BSSA* model calibrated through 2017
- After 2017, injection rates assumed constant
- Ground shaking from Zalachoris and Rathje (2019, *EQS*) GMM
- Event-based annual PSHA from 10,000 simulations using OpenQuake (*GEM Foundation*)
- Building inventory from 2010 census and 2018 replacement costs
- Fragility curves for “low-code” buildings in the US (from *GEM/USGS*)

Conclusions

- Seismic hazard and risk approaches for tectonic earthquakes can be adapted for induced earthquakes
- Key improvements required:
  - Semi-empirical models to forecast spatial and temporal variations in seismicity
  - Ground motion models for induced earthquakes in the region of interest
  - Detailed Vs30 maps using regional/local data
  - Fragility models to predict infrastructure damage for the expected ground shaking characteristics and local construction practices