Recent Developments and Persistent Challenges in Seismic Hazard Assessment for Dams in the Central and Eastern United States

National Dam Safety Program Technical Seminar | February 2023

FEMA

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Outline

- Recent Developments
- Persistent Challenges

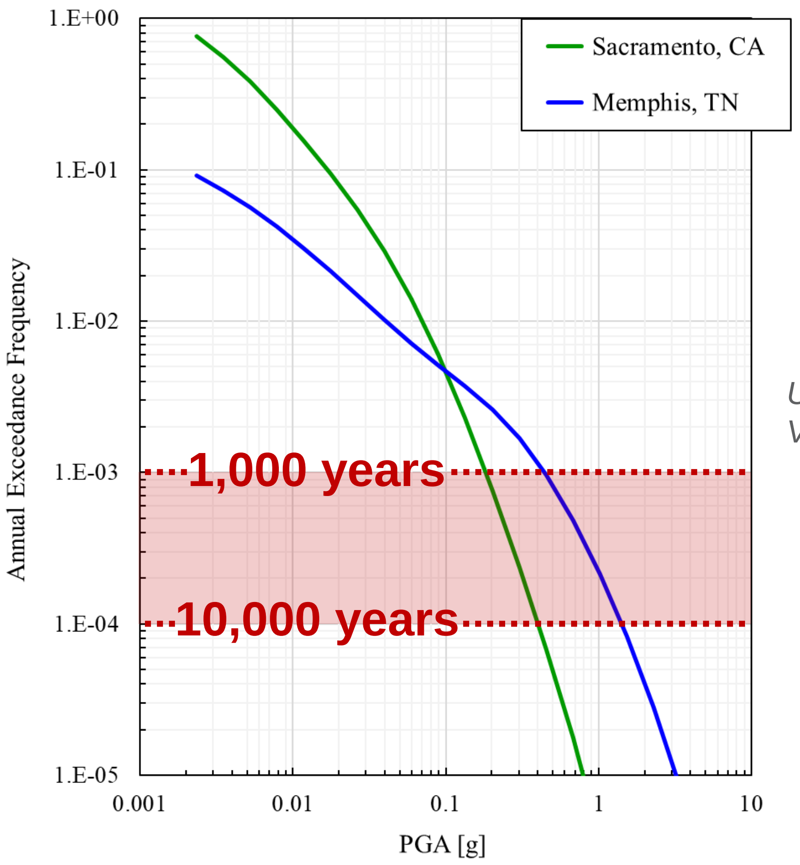
Recent Developments

Realization of Seismic Hazard in Central and Eastern U.S. (CEUS)

Largest Historical Earthquakes in Continental U.S.

Location	Date	Magnitude
Cascadia subduction zone	1700	~ 9
Fort Tejon, California	1857	7.9
San Francisco, California	1906	7.8
Imperial Valley, California	1892	7.8
New Madrid, Missouri	1811 (12/16)	7.7
New Madrid, Missouri	1812 (02/07)	7.7
New Madrid, Missouri	1812 (01/23)	7.5
Owens Valley, California	1872	7.4
Landers, California	1992	7.3
Hebgen Lake, Montana	1959	7.3
Kern County, California	1952	7.3
Eureka, California	1922	7.3
Charleston, South Carolina	1886	7.3
California – Oregon Coast	1873	7.3

National Earthquake Information Center



USGS 2018 NSHM
V_{S30} = 760 m/s

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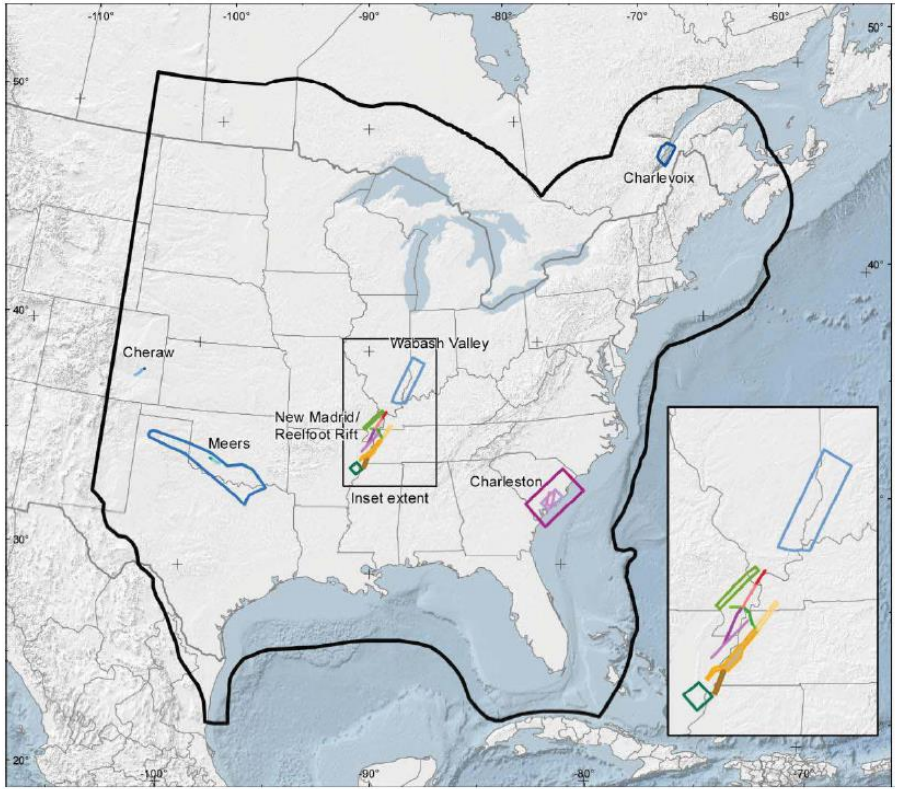
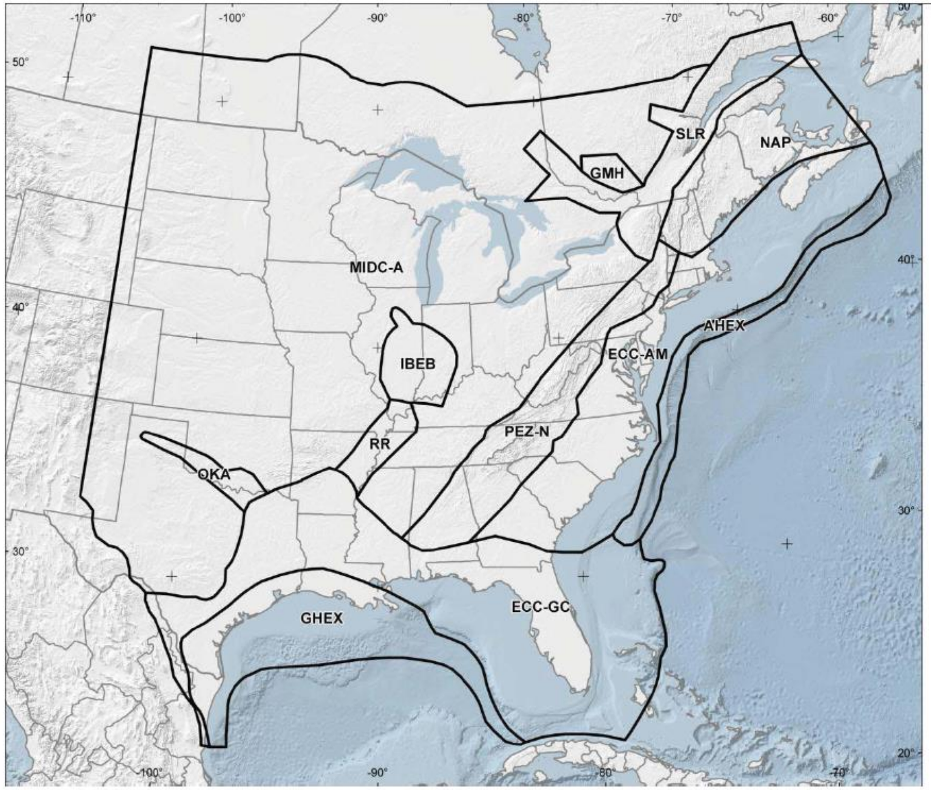
Seismic Source Characterization

Repeated Large Magnitude Earthquakes



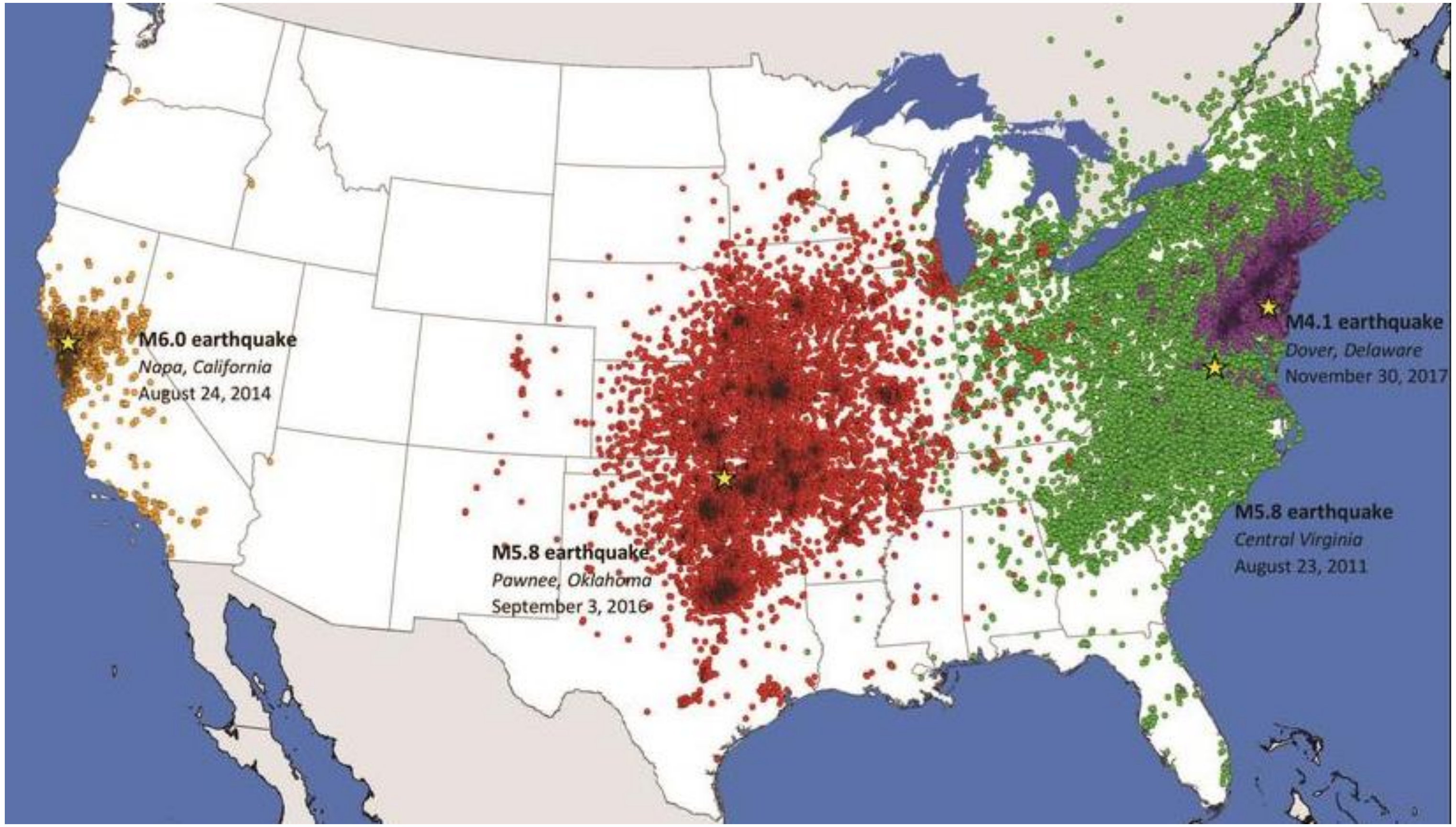
Distributed Seismicity Sources



EPRI / DOE / NRC (2012)

Ground Motion Characterization

Ground motions attenuate differently in CEUS



Eric Jones, USGS

Ground Motion Characterization

NGA-East (Goulet et al., 2018)

- 17 median models
- Frequency-dependent weights
- 3 ergodic standard deviation models
- 3 non-ergodic standard deviation models
- Magnitude and R_{RUP} dependent
- Reference site condition:
  - V_{S30} = 3,000 m/s
  - Kappa (κ) = 0.006 s

The B. John Garrick Institute for the Risk Sciences UCLA ENGINEERING

NGA-East: Central and Eastern North America Groun

Ground-Motion Model Tool developed by Silvia Mazzo

source: Report PEER 2018/08 - Central and Eastern North America Ground-Motio
Christine Goulet, Yousef Bozorgnia, Norman Abrahamson, Nicolas Kuehn, Linda
https://apps.peer.berkeley.edu/publications/peer_reports/reports_2018/

***Instruction**: Make selection in User-Input box. Some input values (Models and Types) are to be selected from a pull-down menu, others require numeric right). Model limits are given in the Model-Limits box. Values outside these limits are not allowed.*
The Median and Sigma (σ) models are described in the report. The WeightedAvg model for both the Median and Sigma (σ) uses the weights recommende

User Input:	
Median Model:	WeightedAvg
Magnitude:	6.2
Rrup (km):	25
σ Type:	Ergodic
σ Model:	WeightedAvg
N-sigma:	1

Model Limits	
Median Model:	(WeightedAvg, 1, 2,..., 16, 17)
Magnitude:	(4-8.2)
Rrup (km):	(0-1500)
σ Type:	(Erogodic, SingleStation)
σ Model:	(WeightedAvg, Central, High, Low)
N-sigma:	(>=0)

all values are for Vs30=3000m/s

Quantity	Period (sec)	Median (WeightedAvg) [M=6.2, Rrup=25km, Vs30=3000m/s]	σ (Ergodic WeightedAvg Model)	Median - 1*σ (Ergodic WeightedAvg Model)	Median + 1*σ (Ergodic WeightedAvg Model)	Frequency (Hz)
Response Spectrum PSA (g)	0.01	**0.2176**	*0.6150*	0.1177	0.4026	100
	0.02	**0.3069**	*0.6148*	0.1659	0.5675	50
	0.025	**0.3471**	*0.6197*	0.1868	0.6450	40
	0.03	**0.3702**	*0.6238*	0.1984	0.6907	33.33
	0.04	**0.3986**	*0.6411*	0.2099	0.7567	25
	0.05	**0.4052**	*0.6552*	0.2105	0.7803	20
	0.075	**0.3676**	*0.6523*	0.1915	0.7057	13.33
	0.1	**0.3293**	*0.6352*	0.1745	0.6214	10
	0.15	**0.2696**	*0.6247*	0.1444	0.5035	6.67
	0.2	**0.2191**	*0.6284*	0.1169	0.4107	5
	0.25	**0.1869**	*0.6326*	0.0993	0.3518	4
	0.3	**0.1634**	*0.6367*	0.0864	0.3088	3.33
	0.4	**0.1311**	*0.6429*	0.0689	0.2493	2.5
	0.5	**0.1080**	*0.6445*	0.0567	0.2058	2
	0.74	**0.0744**	*0.6414*	0.0392	0.1413	1.35
	0.75	**0.0735**	*0.6413*	0.0387	0.1395	1.33
	1	**0.0517**	*0.6328*	0.0275	0.0974	1
	1.5	**0.0297**	*0.6155*	0.0160	0.0549	0.67
	2	**0.0190**	*0.6014*	0.0104	0.0347	0.5
	3	**0.0090**	*0.5779*	0.0051	0.0161	0.33
	4	**0.0052**	*0.5646*	0.0030	0.0092	0.25
	4.5	**0.0041**	*0.5605*	0.0024	0.0073	0.22
	5	**0.0034**	*0.5569*	0.0019	0.0059	0.2
	7.5	**0.0016**	*0.5475*	0.0009	0.0027	0.13
	10	**0.0009**	*0.5433*	0.0005	0.0015	0.1
Peak Ground Acceleration (g)	*PGA*	***0.1860***	*0.6150*	*0.1005*	*0.3440*	*PGA*
Peak Ground Velocity (cm/s)	*PGV*	***6.8385***	*0.6112*	*3.7111*	*12.6015*	*PGV*

Release: March 2020

https://www.risksciences.ucla.edu/nhr3/gmtc

PEER / risksciences.ucla / Silvia Mazzoni, 2020

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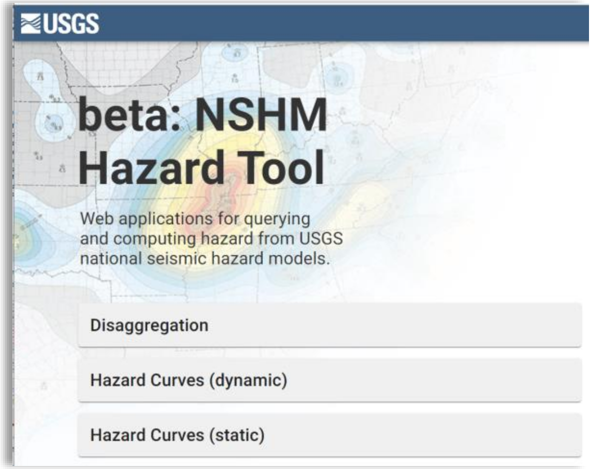
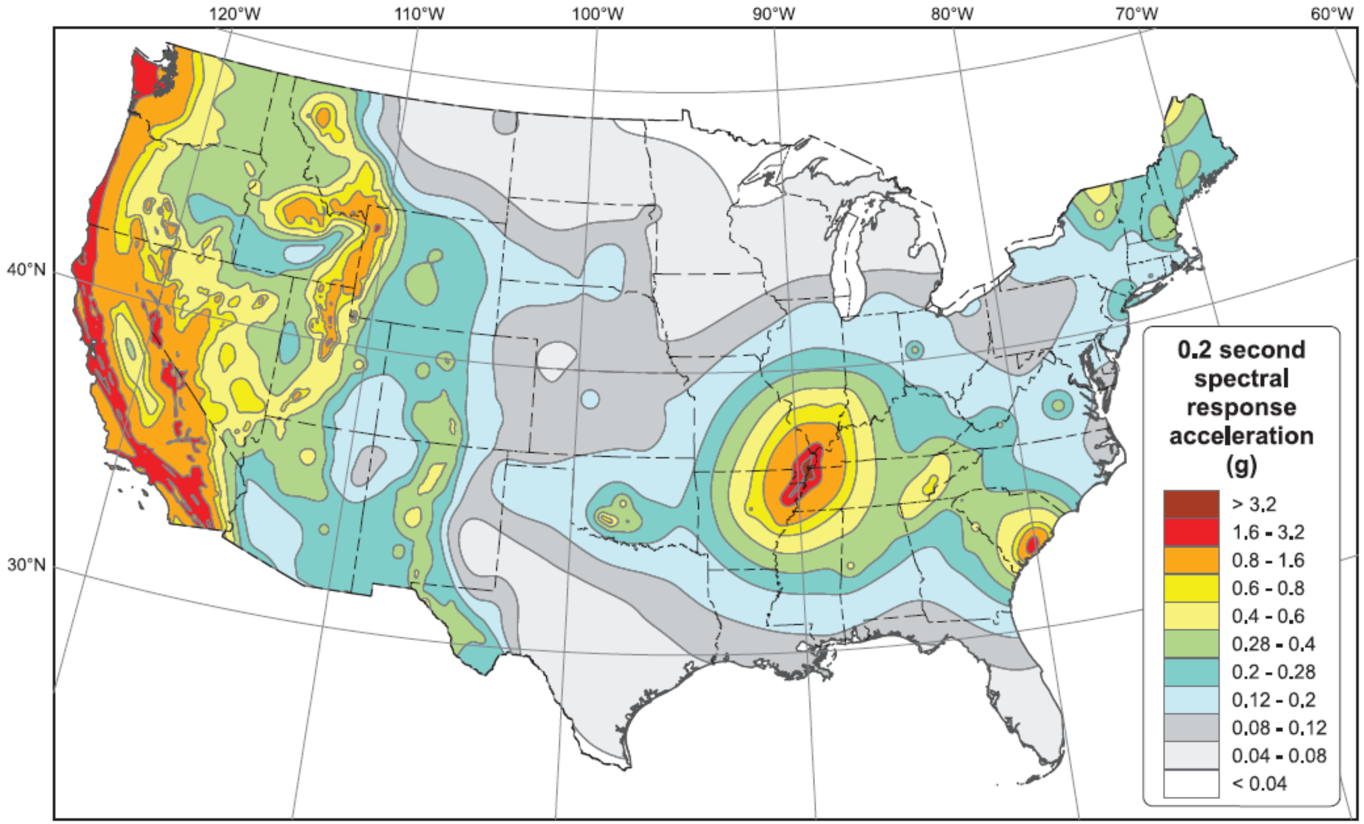
Regional Seismic Hazard Assessments

Latest USGS National Seismic Hazard Model is 2018

- EQ Catalog (2017)
- NGA-East
- Expanded V_{S30}
- Expanded periods





2018 NSHM, 2% in 50 years probability of exceedance, NEHRP site class B/C (V_{S30} = 760 m/s)

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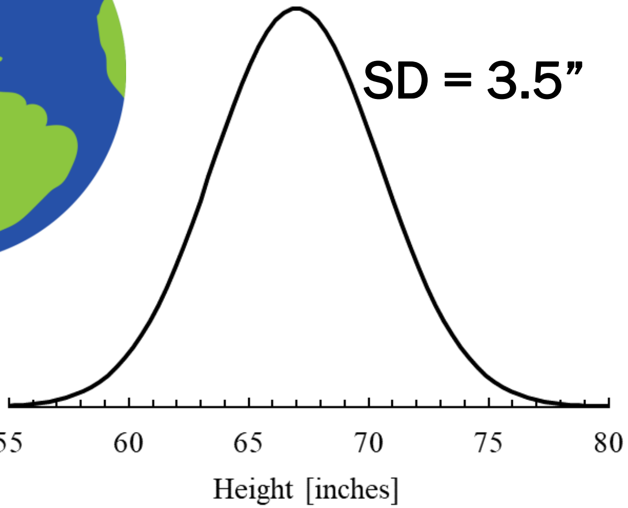
What’s coming?

Move from ergodic to non-ergodic ground motion models

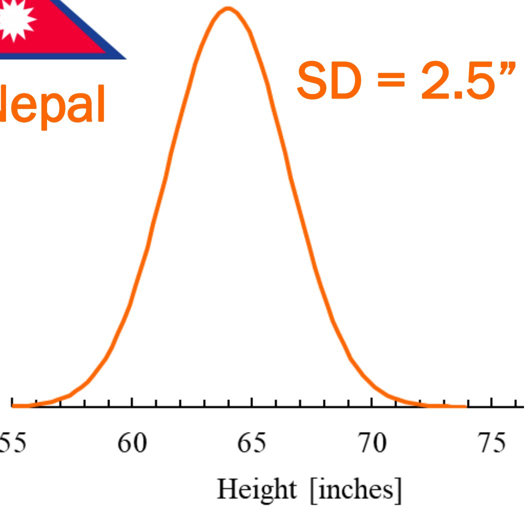
Analogy: Estimate height of a human

Ergodic = global

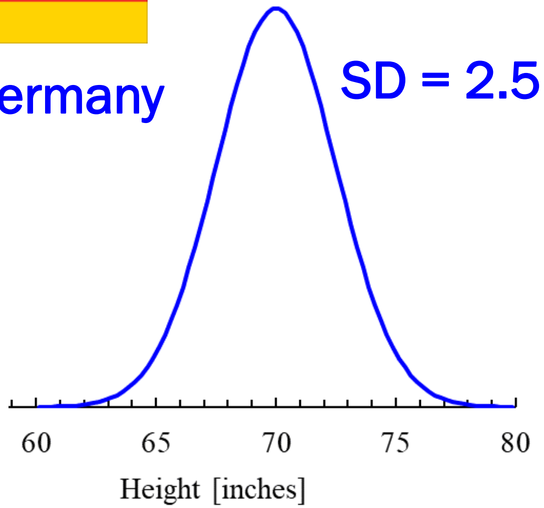
Non-ergodic = specific



Nepal



Germany



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Persistent Challenges

Primer on Deterministic Seismic Hazard Analysis (DSHA)

Methodology – Three Steps:

1. Identify and characterize seismic sources
2. For each source, define the deterministic scenario
    1. Magnitude (M_W)
    2. Distance (R_{RUP}, R_{JB}, R_X, etc.)
    3. Ground Motion Level (50^{th}, 84^{th}-percentile)
3. Calculate response spectra for each scenario

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Primer on DSHA for Fault Source

Example:

1. Identify and characterize seismic sources
2. For each source, define the deterministic scenario

Fault Name	Dip °	SOF	Mag (1)	R_{RUP} *km* (2)	R_{JB} *km*	R_X *km*	Slip Rate *mm/yr*	GM Level (3)
Fault 1	88	SS	7.2	21.3	20.8	22.1	2.00	84th
Fault 2	71	RV	6.4	10.2	5.9	9.5	0.10	50th
Fault 3	90	SS	6.6	6.2	6.2	-6.2	0.15	50th
Fault 4	50	RVO	6.7	18.2	15.9	22.6	0.25	50th

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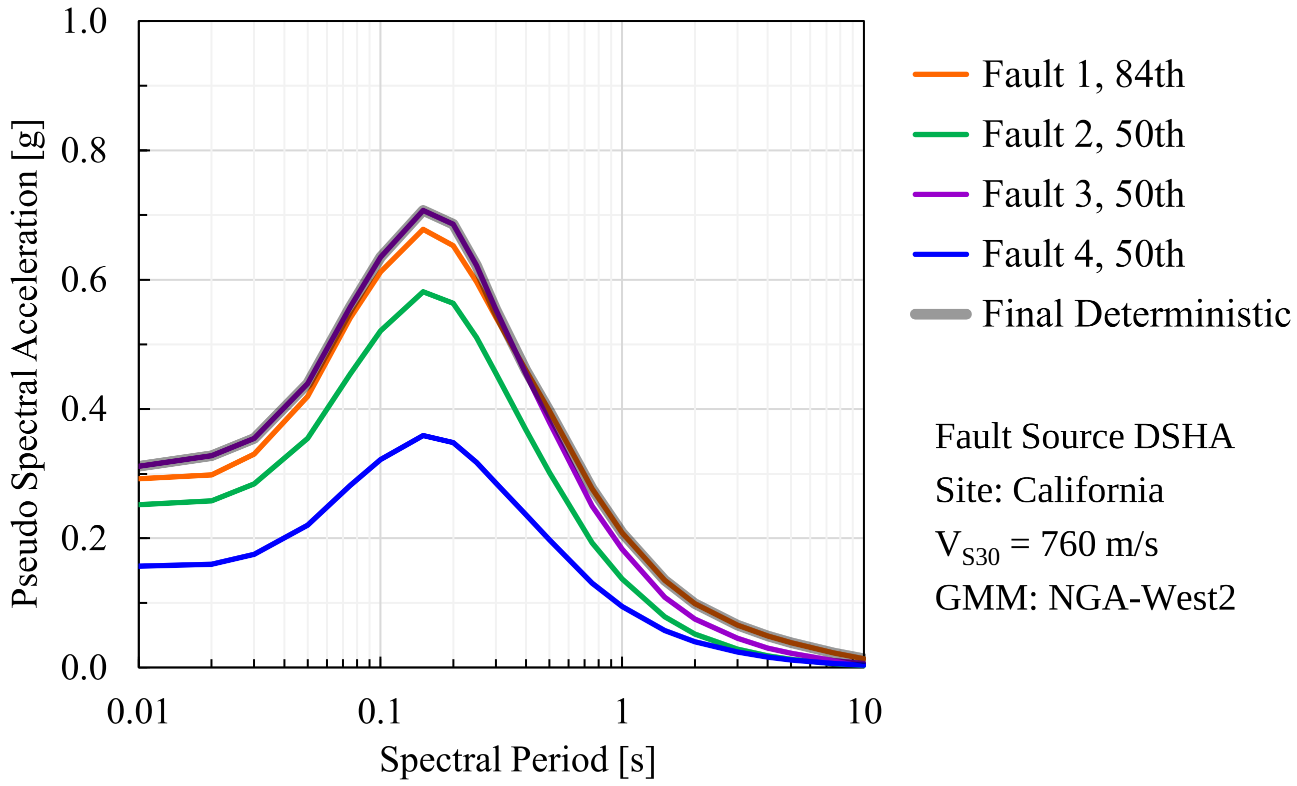
Primer on DSHA for Fault Source

Example: 3. Calculate the response spectra



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Guidance Documents

Recommend or require a deterministic seismic hazard analysis (DSHA):

- FERC Chapter 13 (2018)

6.0 GUIDELINES

These guidelines are provided in this section to establish the requirements for a seismic hazard evaluation at a particular site. The seismic design criteria for that site are then to be based on the results of such an evaluation.

6.3 Deterministic Development of Earthquake Ground Motions

A deterministic evaluation should always be conducted for the site to obtain the target spectrum for each source (identified in the geologic/seismologic studies) significant to the site. As noted in

6.4 Probabilistic Development of Earthquake Ground Motions

If sufficient information, or if a logic tree can be reasonably constructed, for the seismic sources that can affect the site, then a probabilistic seismic hazard analysis (PSHA) may be completed for the site. It is essential that the seismologic as well as the geologic data pertinent to each source be

Guidance Documents

Recommend or require a deterministic seismic hazard analysis:

- FERC Chapter 13 (2018)

6.0 GUIDELINES

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- California DSOD (2018)
- USACE ER 1110-2-1806 (2016)

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Guidance Documents

Criteria assume the source is characterized as a known fault

- Use area of fault → Magnitude
- Use location of fault → Distance
- Use slip rate of fault → Ground Motion Level

In many areas of the Central and Eastern U.S., don't know where the faults are, but know that there is seismic hazard

Distributed seismicity sources are a significant contributor to the hazard

How do you perform a DSHA for a distributed seismicity source?

Distributed Seismicity Source DSHA

Issues

- Cannot use source geometry to calculate magnitude
- Cannot use location to calculate distance
- Cannot use slip rate to calculate ground motion level

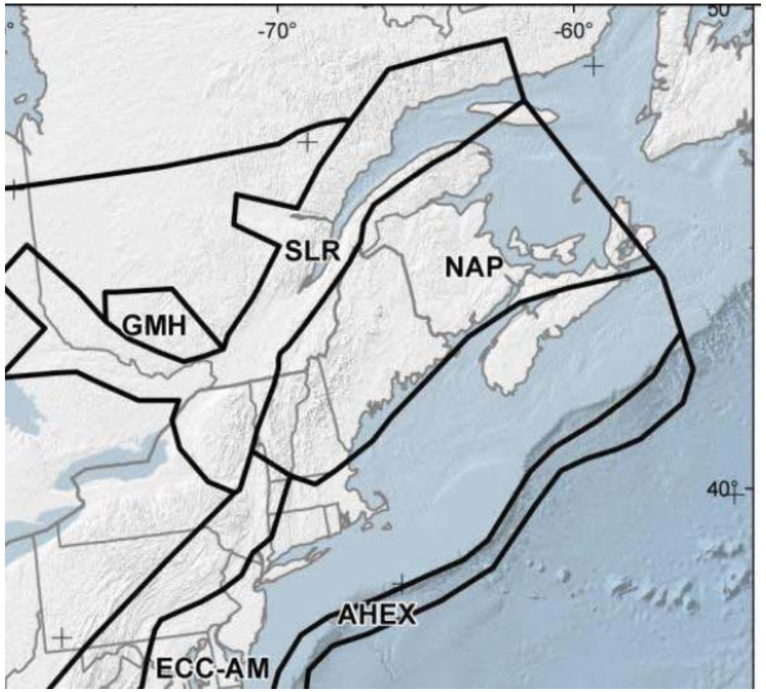
Three Different Approaches:

1. Purely deterministic approach
2. Purely probabilistic approach
3. Probabilistically-informed DSHA approach

Distributed Seismicity Source DSHA

1. *Purely Deterministic Approach*

- Site is in the Northeast region of the United States



EPRI/NRC/DOE 2012

Source Name	Type	Mag	R_{RUP} *km*	GM Level
NAP	Distributed	?	?	?

How do you define the scenario?

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Distributed Seismicity Source DSHA

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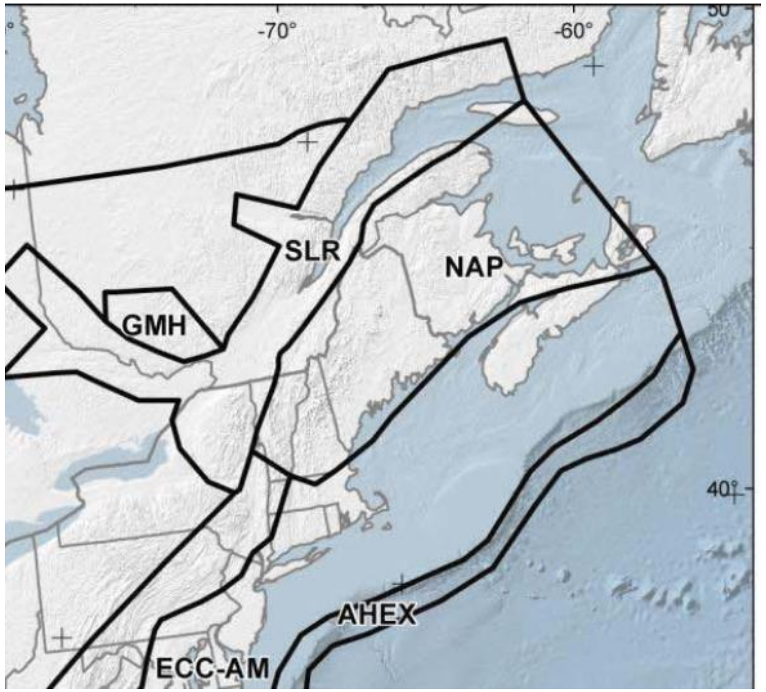


EPRI/NRC/DOE 2012

Source Name	Type	Mag	R_{RUP} *km*	GM Level
NAP	Distributed	7.18	0	50^{th}

NAP Mag = M_{max} from CEUS 2012

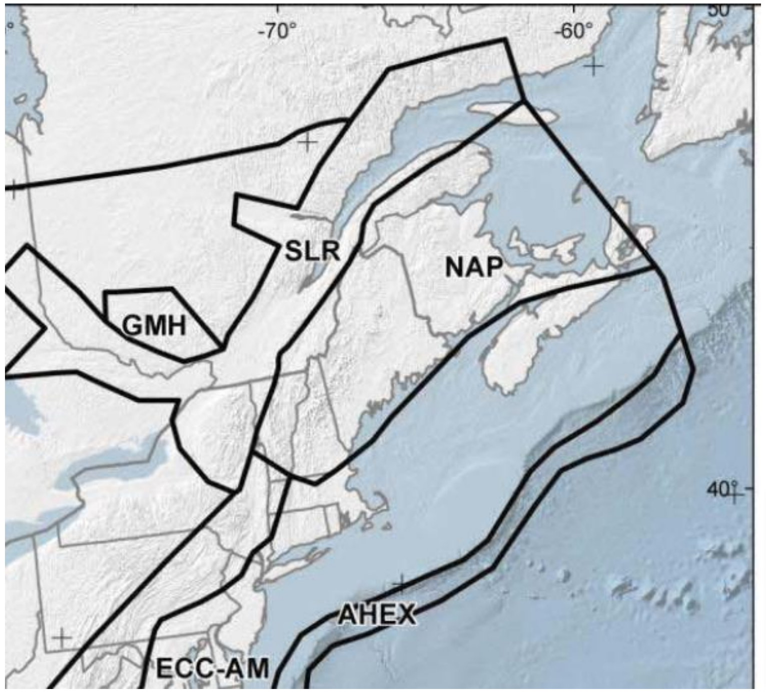
Most practitioners would agree M 7.18 at 0 km is too conservative.

Question becomes: how far do you back off of M 7.18 at 0 km?

Distributed Seismicity Source DSHA

1. *Purely Deterministic Approach*

- One option: arbitrarily consider a M 6 – 6.5 at 10 – 15 km



EPRI/NRC/DOE 2012

Source Name	Type	Mag	R_{RUP} *km*	GM Level
NAP	Distributed	6	15	50^{th}

FERC Chapter 13 Section 3 (2018)

The distance from the site to such areal seismic sources is usually assigned as a "depth" below the site and typically varies from 5 to 15 km. Data from instrumental seismicity (which would include the depth of each event) are necessary for assigning this depth. The maximum moment magnitude considered for such zones is typically M = 6½ ± ¼.

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Distributed Seismicity Source DSHA

1. Purely Deterministic Approach

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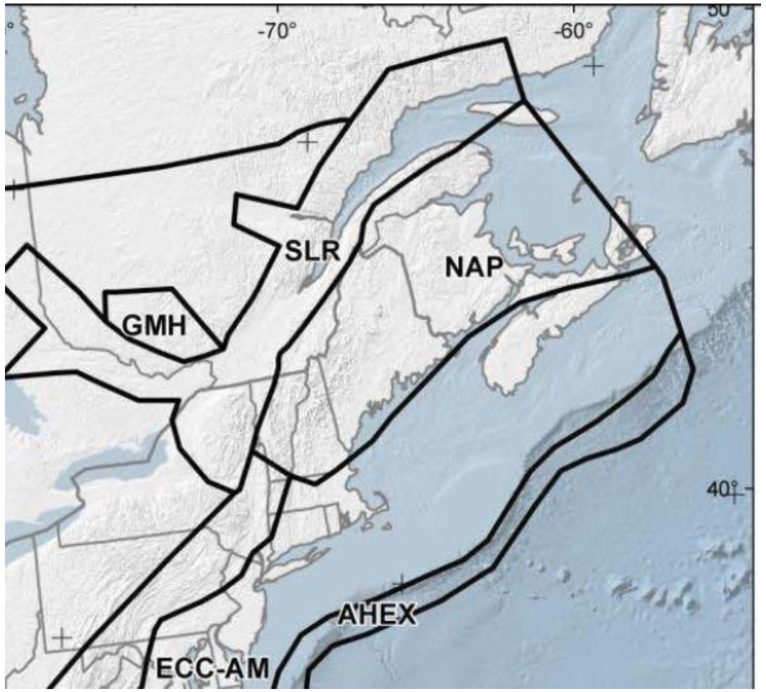

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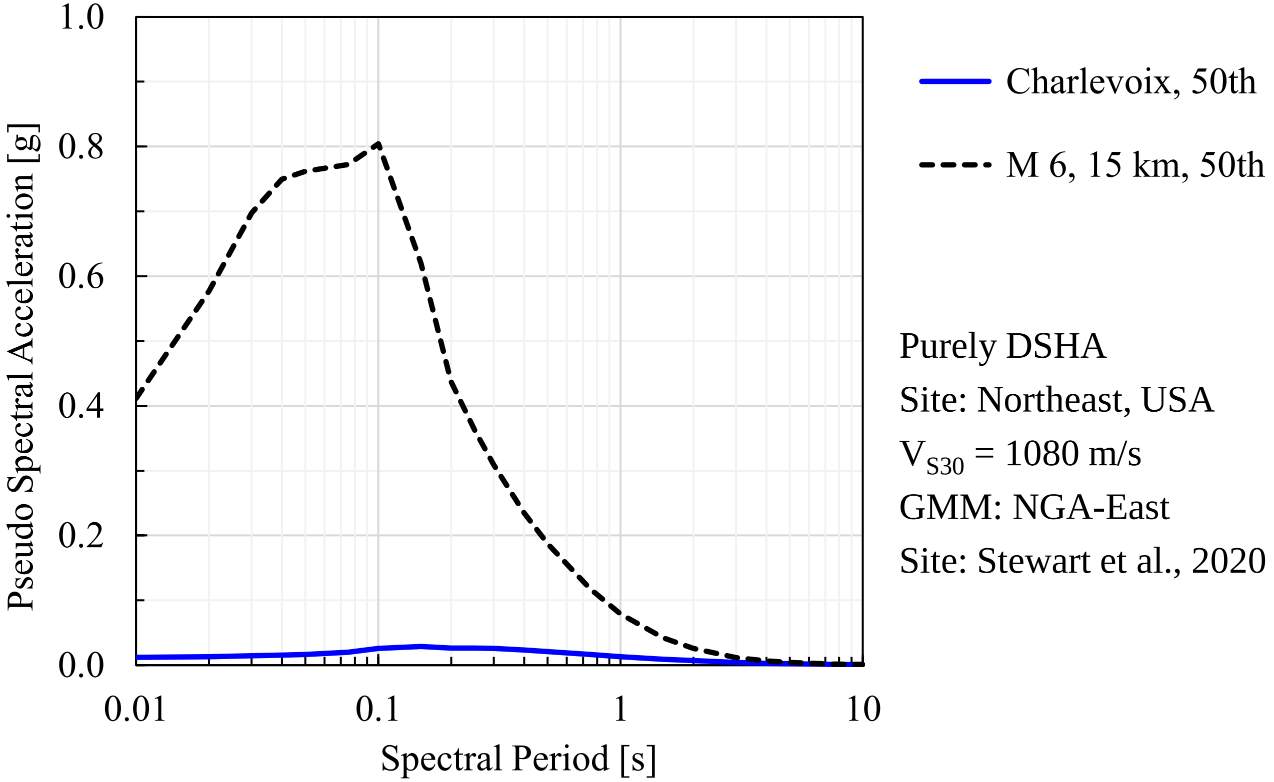

Distributed Seismicity Source DSHA

2. Purely Probabilistic Approach

- Forgo DSHA all together
- Perform Probabilistic Seismic Hazard Analysis (PSHA)
- No longer need to select a single Magnitude, Distance, and Ground Motion Level
- Critical decision: return period of the ground motion

Distributed Seismicity Source DSHA

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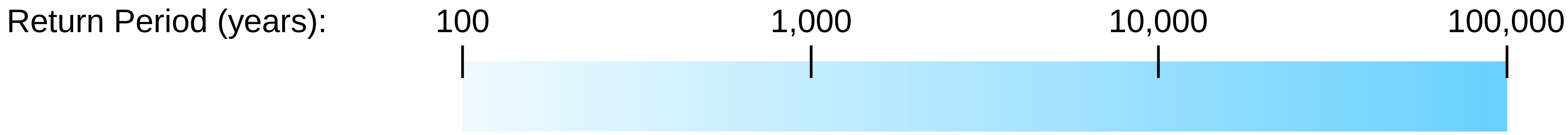

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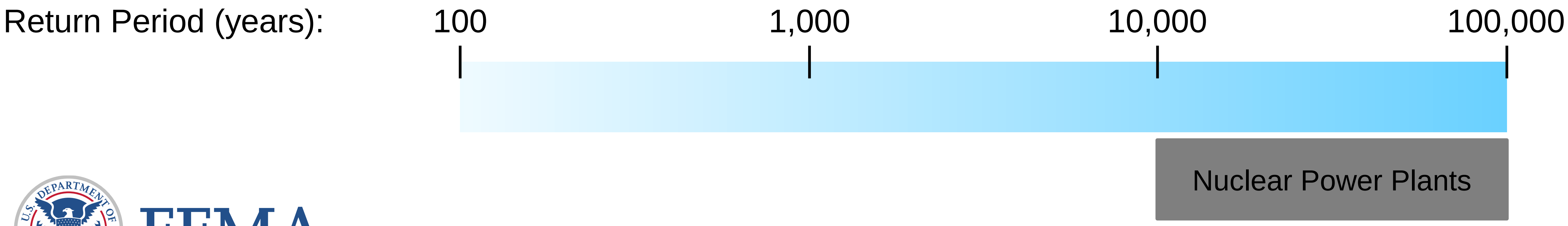

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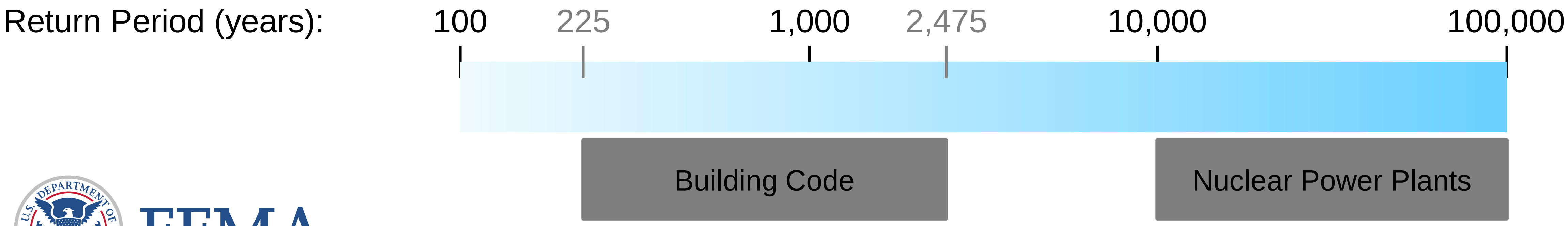

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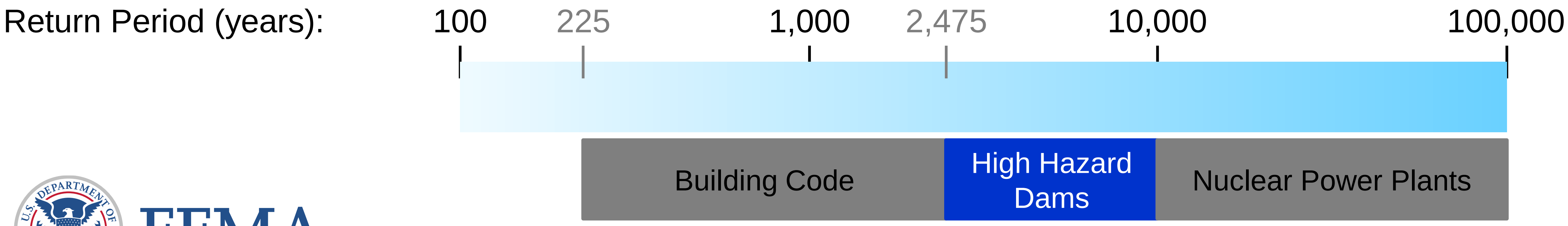


Distributed Seismicity Source DSHA

2. *Purely Probabilistic Approach*

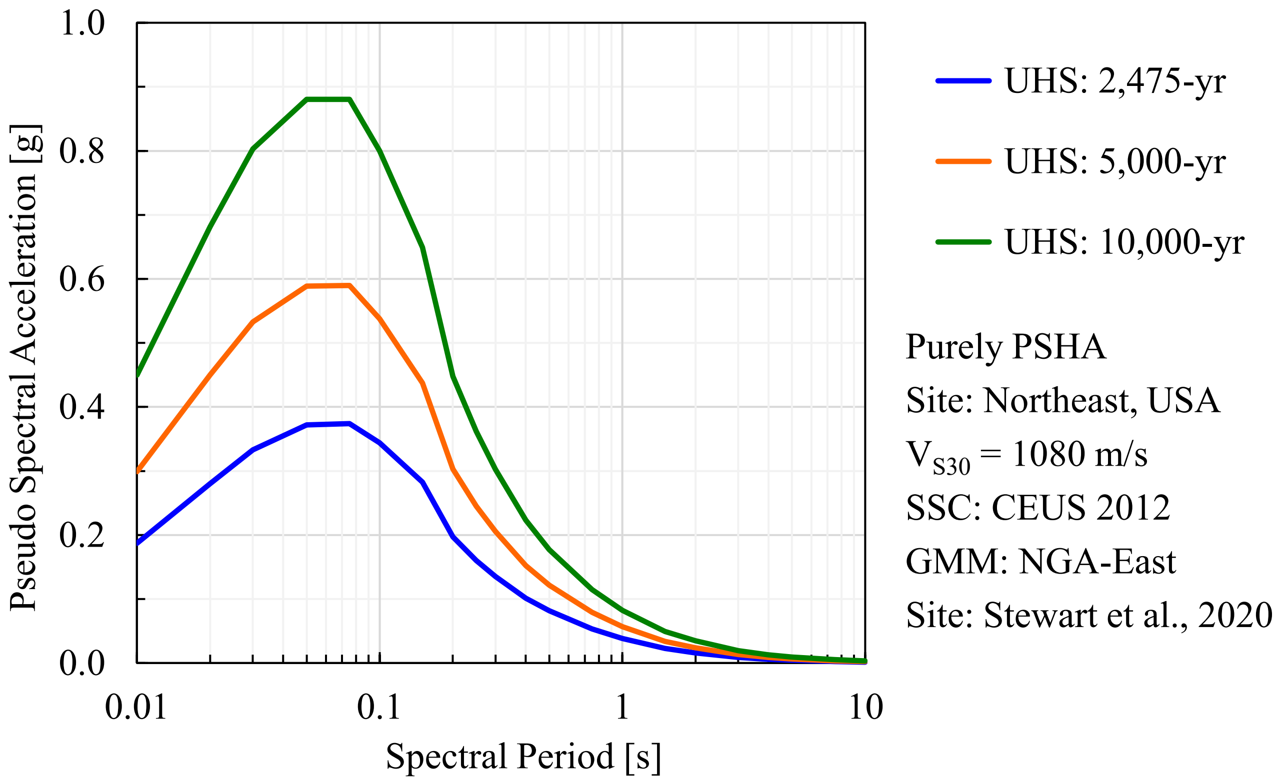
- Guidance document summary – return period of ground motion

Guidance Document	Hazard Classification	Return Period (years)
FERC Chapter 13 (2018)	Deterministic based - no explicit guidance	Deterministic based - no explicit guidance
California DSOD (2018)	Deterministic based - no explicit guidance	Deterministic based - no explicit guidance
USACE (2016)	Deterministic based - no explicit guidance	Deterministic based - no explicit guidance
CDA Dam Safety Guidelines (2013)	High - Extreme	2,475 - 10,000
USDA NRCS (2019)	High	10,000
Montana DNRC (2020)	High	5,000 - 10,000
ICOLD Bulletin 72 (2010)	Moderate - High	3,000 - 10,000
Global Standard – Tailings (2020)	High - Extreme	2,475 - 10,000
U.S. Bureau of Reclamation (2015)	Risk based - all return periods	Risk based - all return periods

Distributed Seismicity Source DSHA

2. Purely Probabilistic Approach

- Perform PSHA, construct Uniform Hazard Response Spectra (UHS)



Purely PSHA
Site: Northeast, USA
V_{S30} = 1080 m/s
SSC: CEUS 2012
GMM: NGA-East
Site: Stewart et al., 2020

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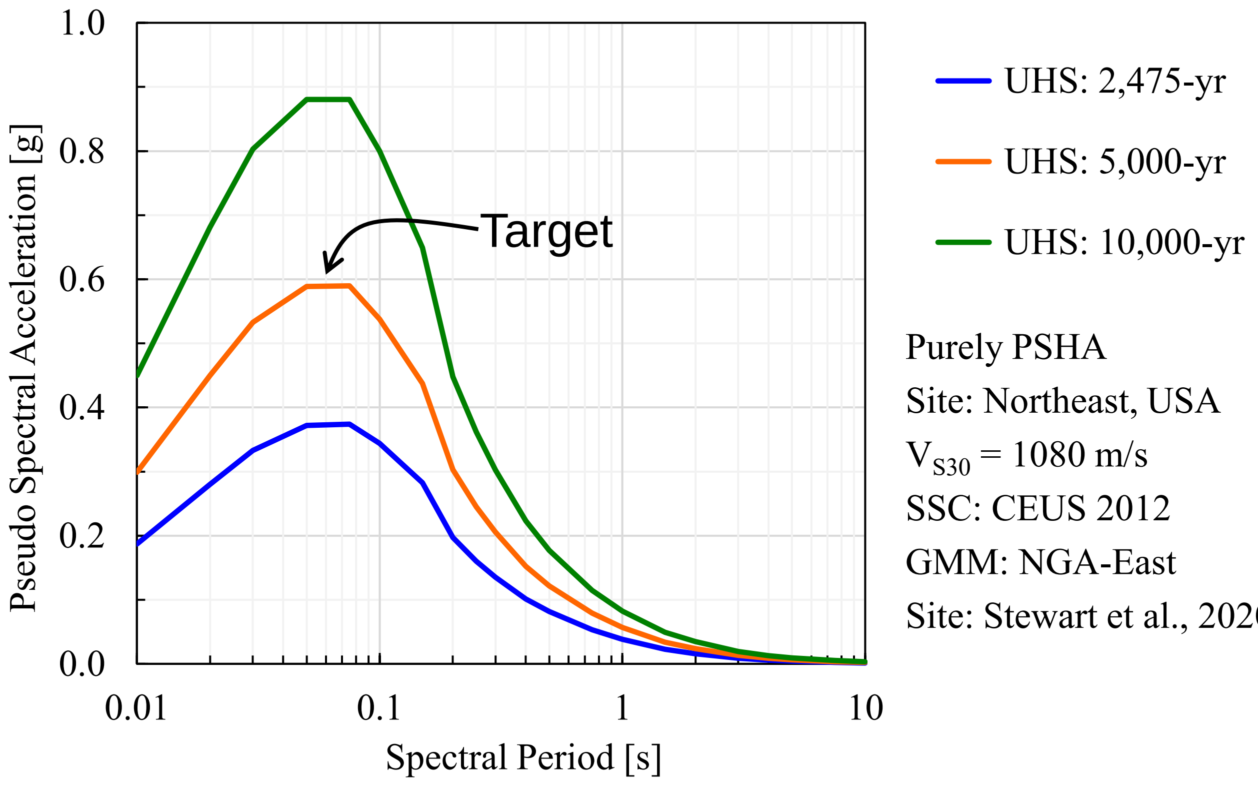
Distributed Seismicity Source DSHA

3. Probabilistically-Informed DSHA Approach

- Select a deterministic scenario that approximates a target UHS from a PSHA



Purely PSHA

Site: Northeast, USA

V_{S30} = 1080 m/s

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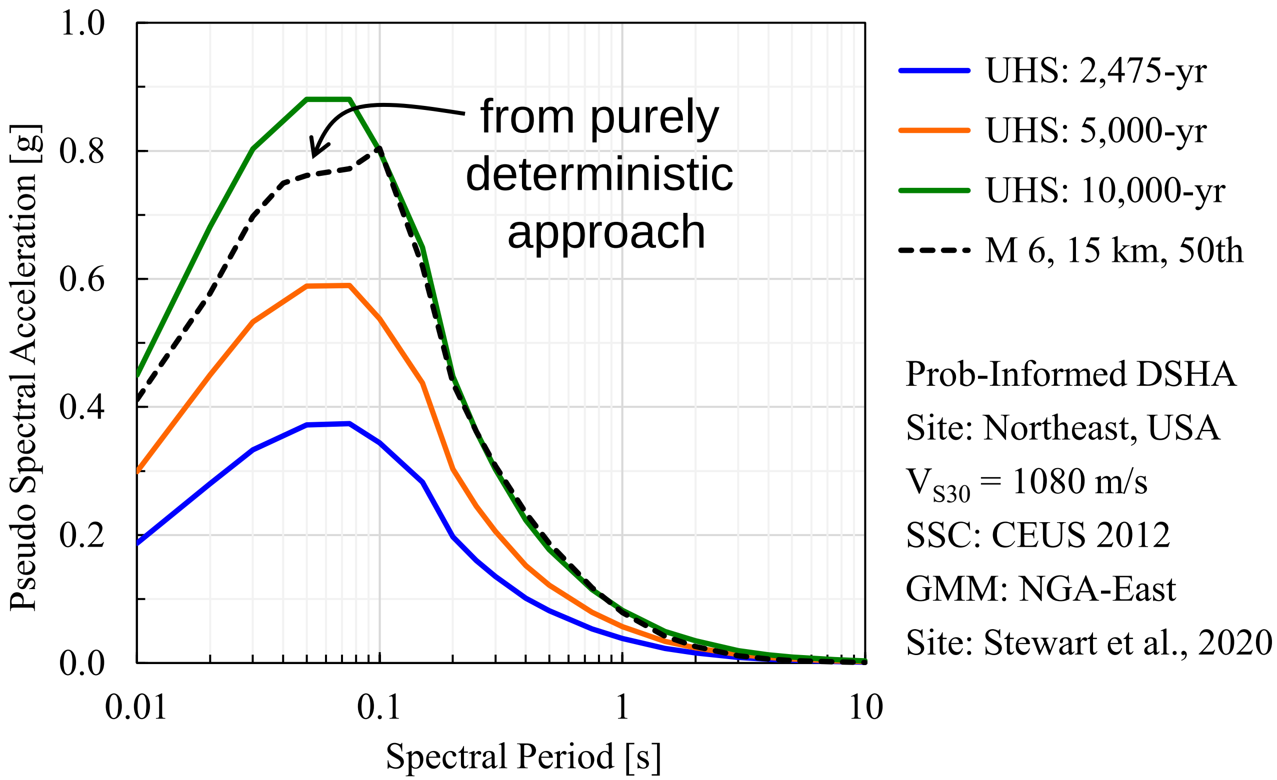
Site: Stewart et al., 2020

Distributed Seismicity Source DSHA

3. *Probabilistically-Informed DSHA Approach*

- Comparison with purely deterministic approach



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Site: Northeast, USA
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SSC: CEUS 2012
GMM: NGA-East
Site: Stewart et al., 2020

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Distributed Seismicity Source DSHA

3. *Probabilistically-Informed DSHA Approach*

- Evaluate results from a deaggregation analysis

What magnitude and distance are appropriate for the distributed seismicity source?

Distance [km]	Magnitude 5.0 - 5.2	5.2 - 5.4	5.4 - 5.6	5.6 - 5.8	5.8 - 6.0	6.0 - 6.2	6.2 - 6.4	6.4 - 6.6	6.6 - 6.8	6.8 - 7.0	7.0 - 7.2	7.2 +	Distance Percentile
0 - 10	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	100%
10 -20	5%	5%	4%	3%	2%	2%	1%	1%	0%	0%	0%	0%	92%
20 - 30	3%	3%	3%	3%	2%	2%	1%	1%	1%	0%	0%	0%	68%
30 - 50	2%	2%	2%	2%	2%	2%	2%	2%	1%	1%	1%	0%	49%
50 - 70	0%	0%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	31%
70 - 90	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	23%
90 - 120	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	0%	1%	19%
120 - 150	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	14%
150 - 200	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	10%
200 - 250	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	6%
250+	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%	4%
Magnitude Percentile	12%	24%	35%	46%	55%	64%	71%	78%	84%	89%	93%	100%	

Observation: A broad range of magnitude and distance pairs contribute to the ground shaking hazard at the site

Distributed Seismicity Source DSHA

3. Probabilistically-Informed DSHA Approach

- Evaluate results from a deaggregation analysis

What magnitude and distance are appropriate for the distributed seismicity source?

Distance [km]	Magnitude: 5.0 - 5.2	5.2 - 5.4	5.4 - 5.6	5.6 - 5.8	5.8 - 6.0	6.0 - 6.2	6.2 - 6.4	6.4 - 6.6	6.6 - 6.8	6.8 - 7.0	7.0 - 7.2	7.2 +	Distance Percentile
0 - 10	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	100%
10 -20	5%	5%	4%	3%	2%	2%	1%	1%	0%	0%	0%	0%	92%
20 - 30	3%	3%	3%	3%	2%	2%	1%	1%	1%	0%	0%	0%	68%
30 - 50	2%	2%	2%	2%	2%	2%	2%	2%	1%	1%	1%	0%	49%
50 - 70	0%	0%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	31%
70 - 90	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	23%
90 - 120	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	0%	1%	19%
120 - 150	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	14%
150 - 200	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	10%
200 - 250	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	6%
250+	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%	4%
Magnitude Percentile	12%	24%	35%	46%	55%	64%	71%	78%	84%	89%	93%	100%	

Trying to do something in line with the fault source approach

Looking for an above average magnitude, closer than average distance

Distributed Seismicity Source DSHA

3. *Probabilistically-Informed DSHA Approach*

- Evaluate results from a deaggregation analysis

What magnitude and distance are appropriate for the distributed seismicity source?

Distance [km]	Magnitude 5.0 - 5.2	5.2 - 5.4	5.4 - 5.6	5.6 - 5.8	5.8 - 6.0	6.0 - 6.2	6.2 - 6.4	6.4 - 6.6	6.6 - 6.8	6.8 - 7.0	7.0 - 7.2	7.2 +	Distance Percentile
0 - 10	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	100%
10 -20	5%	5%	4%	3%	2%	2%	1%	1%	0%	0%	0%	0%	92%
20 - 30	3%	3%	3%	3%	2%	2%	1%	1%	1%	0%	0%	0%	68%
30 - 50	2%	2%	2%	2%	2%	2%	2%	2%	1%	1%	1%	0%	49%
50 - 70	0%	0%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	31%
70 - 90	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	23%
90 - 120	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	0%	1%	19%
120 - 150	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	14%
150 - 200	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	10%
200 - 250	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	6%
250+	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%	4%
Magnitude Percentile	12%	24%	35%	46%	55%	64%	71%	78%	84%	89%	93%	100%	

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0 - 10	2%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	100%
10 - 20	5%	5%	4%	3%	2%	2%	1%	1%	0%	0%	0%	0%	92%
20 - 30	3%	3%	3%	3%	2%	2%	1%	1%	1%	0%	0%	0%	68%
30 - 50	2%	2%	2%	2%	2%	2%	2%	2%	1%	1%	1%	0%	49%
50 - 70	0%	0%	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%	31%
70 - 90	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	23%
90 - 120	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	0%	1%	19%
120 - 150	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	14%
150 - 200	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	1%	10%
200 - 250	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	6%
250+	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%	4%
Magnitude Percentile	12%	24%	35%	46%	55%	64%	71%	78%	84%	89%	93%	100%	

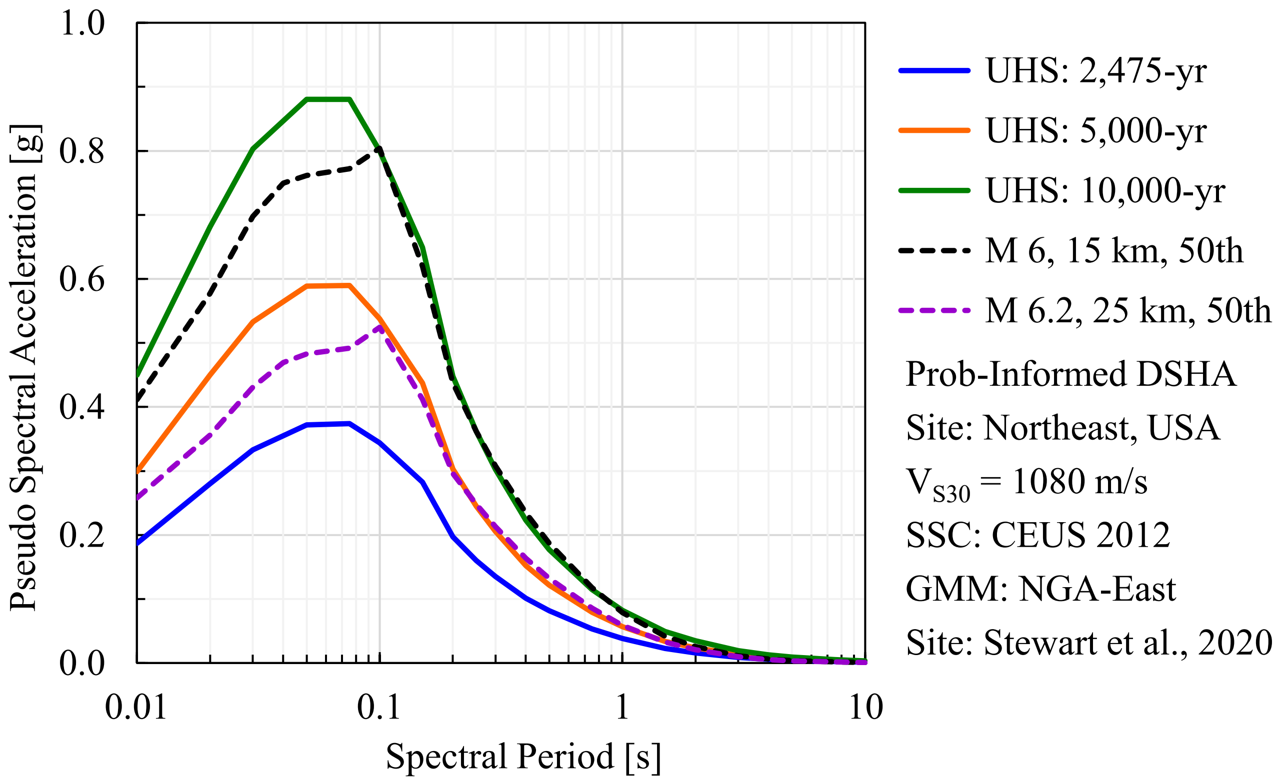
Trying to do something in line with the fault source approach

Looking for an above average magnitude, closer than average distance

Distributed Seismicity Source DSHA

3. Probabilistically-Informed DSHA Approach

- Select a deterministic scenario that approximates a target UHS from a PSHA



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Discussion

Challenges and considerations for each approach

- Purely deterministic
  - Arbitrarily selecting a M 6 – 6.5 at 10 – 15 km does not recognize the widely varying seismic environments of different regions
  - Ground motions from DSHA associated with a wide range of return periods
- Purely probabilistic
  - Advantage of accounting for broad distribution of scenarios
  - This approach, by itself, does not meet the current regulatory requirements
- Probabilistically-informed DSHA
  - Inconsistency between fault and distributed seismicity sources
  - Why not just use the UHS that you're targeting?

Conclusions

Selection of a magnitude and distance for a distributed seismicity source is a major challenge and practitioners are almost always looking at insights from a PSHA to make this decision.

When a DSHA is required by regulations, a probabilistically-informed DSHA with a carefully selected return period is a reasonable approach.

When a DSHA is not required, a PSHA with a carefully selected return period is preferred because of the ability to account for the broad distribution of magnitudes, distances, and ground motion levels that contribute to the ground shaking hazard at the Site.

Conclusions (2)

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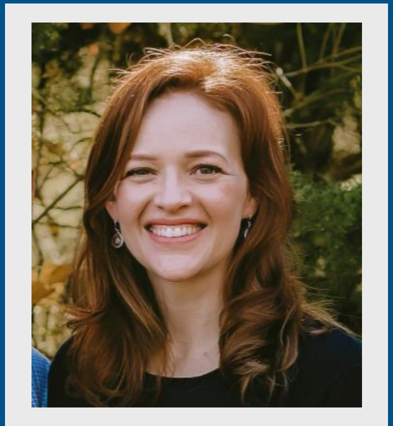
THANK YOU



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