Seismic Loading and Performance Criteria for Design and Evaluation of Dams: A Comparison of International and U.S. Guidance

National Dam Safety Program Technical Seminar | 2023

U.S. DEPARTMENT OF HOMELAND SECURITY

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Primary Building Blocks for Evaluation of Earthquake Effects in Our Dams

1. Seismic hazard (loading) assessment at the project site
2. Geological and geotechnical site characterization
3. Parameter development for potentially liquefiable and non-liquefiable soils and rock
4. Earthquake analyses of dams with proper implementation of concepts, analytical models, and engineering relationships.
5. Assessment of consequences of potential damage to dams.
6. Implementation of engineered solutions to improve safety and prevent human loss of life and property loss, if needed.

We will discuss seismic loading and performance criteria from international dam agencies and USA

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How a Flood Differs from An Earthquake? Focus on Dams and Levees in USA

▪ **Frequency:** Floods (or highwater) are more frequent events. →	▪ Earthquakes are rare events.
▪ **Warning:** Weather forecast can provide warning for flood events. →	▪ Earthquakes occur without warning.
▪ **Geography of Risk:** Floods are risks in most of the country. →	▪ Earthquakes are higher risks in a more limited number of states (not a uniform 50-state issue from an immediate effects standpoint).
▪ **Awareness:** Flood awareness due to hydrologic flooding may be higher. →	▪ Earthquake awareness is poor, except some isolated pockets in California.
▪ **Response Preparedness:** During flood, close monitoring and responses may be available for dams and levees. Operations are part of emergency preparedness. →	▪ After an earthquake, all infrastructure including the emergency response resources may be affected and not available to respond to dams and levee emergencies.
▪ **Engineering knowledge and skills:** Improved engineering knowledge and skills across the country (with regional specialties to address regional concerns) regarding flood-related PFMs. →	▪ Engineering knowledge and skills on seismic related PFMs may be inadequate.

World Map Showing Pacific Northwest in 1700

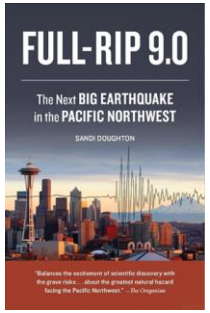
Void North of California in 1700

In 1700, world maps showed a void north of California.

- *In the Cascadia subduction zone 13 megathrust events have been identified in the last 6,000 years.*
- *Some have been as close together as 200 years and some have been as far apart as 800 years. The last one was 300 years ago.*

[Reference:https://earthquakescanada.nrcan.gc.ca/zones/cascadia/qa-en.php]

37% probability that a Mw = 7.1 or greater event will occur in the Cascadia subduction zone **within the next 50 years**.



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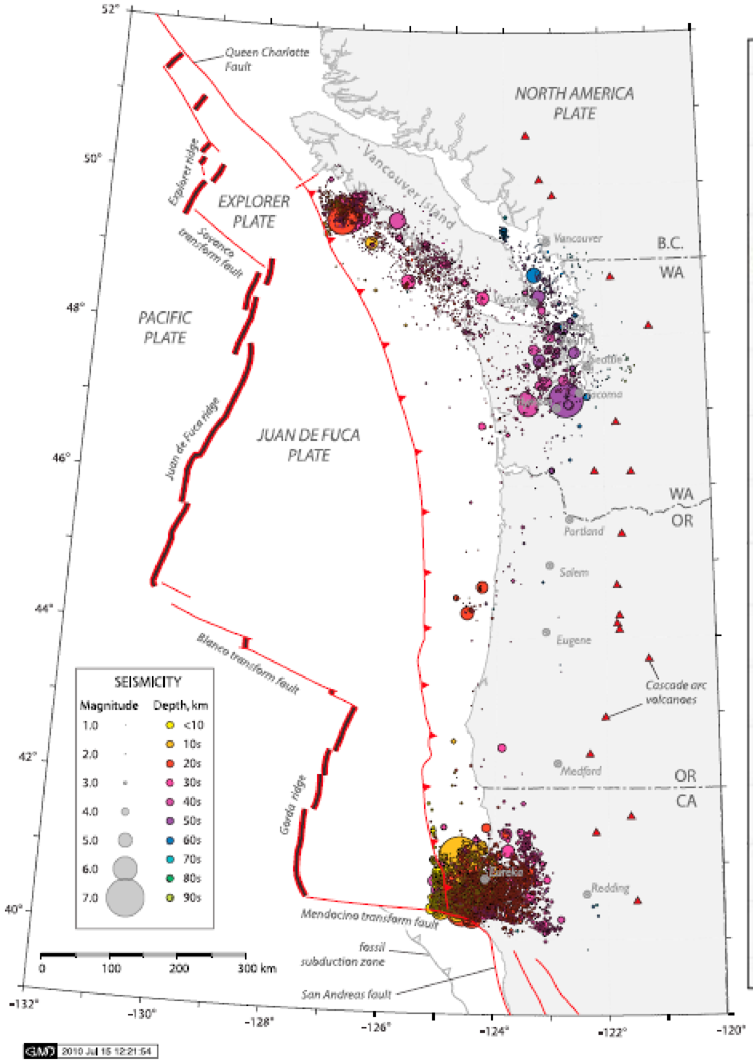
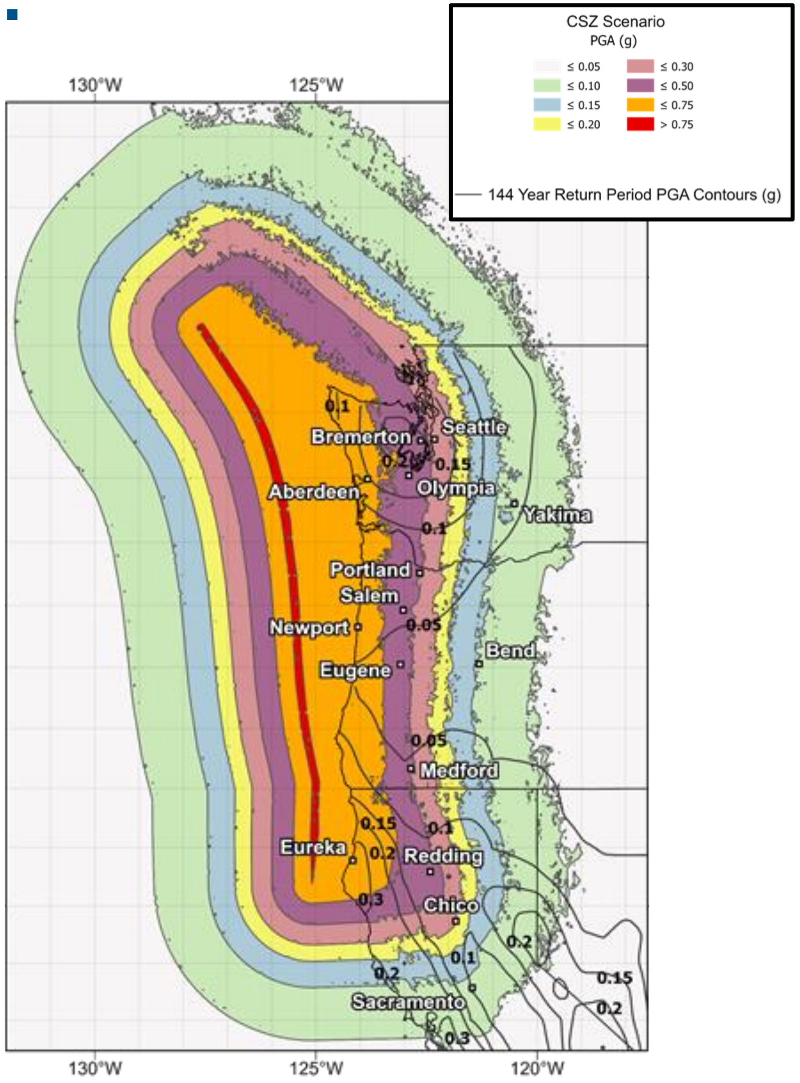
Fast Forward ~ 323 Years ……………………

- 12 Million People in WA and OR.
- Seattle and Portland metropolitan area GDP exceeds $556B annually.
- 42 Ports in WA and OR
- 2,012 Dams in WA and OR
- 542 miles of USACE levees in WA and OR
- Affects CA and Canada also





New Madrid Earthquake Sequence – Fast Forward 212 Years.............

Three Mainshocks:

December 16, 1811 M=7.7
January 23, 1812 M=7.5
February 7, 1812 M=7.7

Population:

Affected area in 1812: 5,700

Current Population:
>11-12M in St. Louis-Memphis region

River Bank Failure:

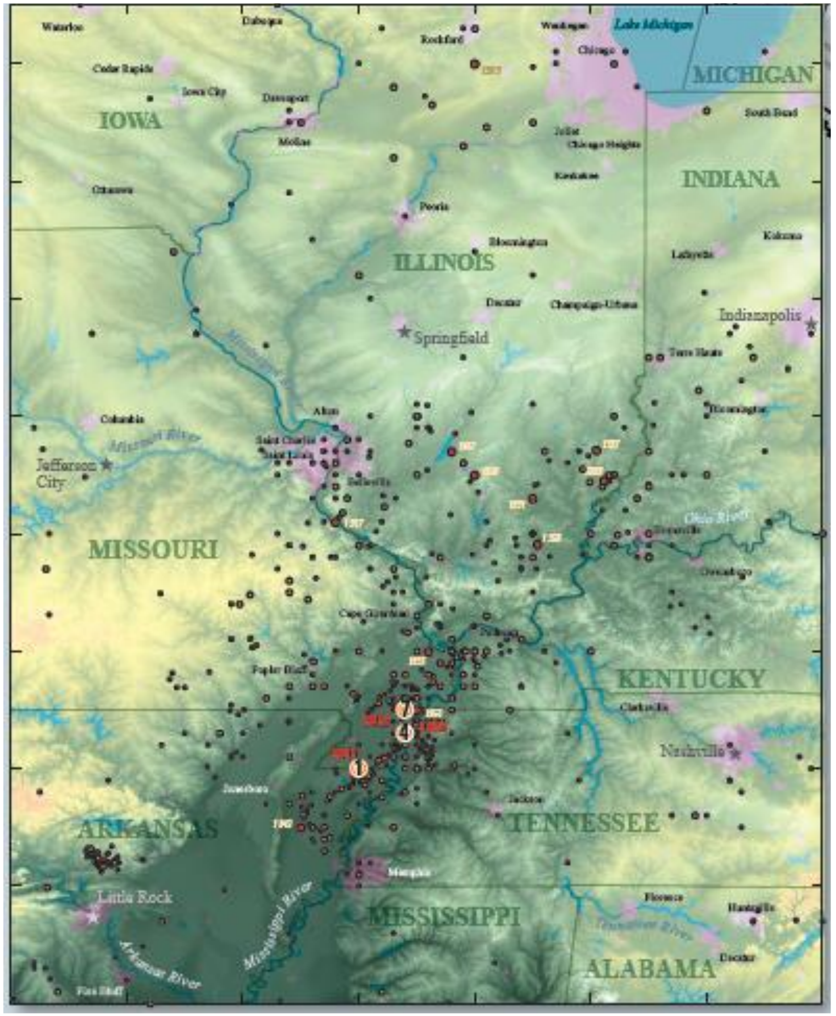
Landslides along 125 miles of bluffs on the east side of the Mississippi River north of Memphis.

Current Conditions:

a. Levees along the river with narrower bank due to erosion.

b. Many dams designed and constructed without considering seismic performance

c. Navigation through Mississippi River may get disrupted



Williams, R.A., McCallister, N.S., and Dart, R.L., 2011, 20 cool facts about the New Madrid Seismic Zone—Commemorating the bicentennial of the New Madrid earthquake sequence, December 1811–February 1812 [poster]: U.S. Geological Survey General Information Product 134

By March 15, 1812, an estimated 2,000 aftershocks had been felt including three aftershocks ranging from M=6.0 to 6.5

Many visible features including Reelfoot Lake in Tennessee were formed

7–10% probability of a M_w = 7.0 or greater will occur in the New Madrid region within the **next 50 years**.

28–46% probability of a M_w = 6.0 or greater will occur in the New Madrid region within the **next 50 years**.

Let’s go to the Movies

Questions?

- How many dams were retrofitted for seismic PFMs in WA and OR after discovery of Cascadia Subduction Zone earthquake risk (~20 to 30 years)?

- How many dams were retrofitted for seismic PFMs when we have celebrated 200th anniversary of the New Madrid event (or since then)?

- What about thousands of miles of levees?

Review of International and US Guidelines and Criteria

- Definitions of Operating Basis Earthquake Ground Motion (OBE-GM) and Maximum Design Earthquake Ground Motion (MDE-GM) or Maximum Credible Earthquake Ground Motion (MCE-GM)
- Seismic loading criteria for OBE-GM and MDE-GM/MCE-GM
- How existing OBE-GM criteria compare with scenario Cascadia subduction zone and New Madrid events
- Coincident pool elevation for seismic analysis
- Seismic freeboard requirement

Definition and Performance Requirements of Operating Basis Earthquake Ground Motion (OBE-GM)

- The Operating Basis Earthquake Ground Motion (OBE- GM) is a ground motion that can reasonably be expected to occur within the service life of the project.

- The purpose of the OBE-GM is to protect against economic losses from damage or loss of service.

- The associated performance requirement is that the project functions with little or no damage and without interruption of function.

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Why is the OBE-GM so important for new dam design and for existing dam evaluation?

BY DEFINITION: Interruptions of dam functions are allowed:

(1). Flood control

(2). Water supply for drinking and agriculture

(3). Hydroelectric

(4). Environmental purpose, and

(5). Recreation and all other activities.

There is no limit on how long this disruption would exist and how expensive that disruption would be (disruptions such as pool restriction, loss of hydroelectric, loss of water supply, etc.).

Definition and Performance Requirements of Maximum Design Ground Motion (MDE-GM)

- The Maximum Design Earthquake Ground (MDE-GM) **is the maximum level of ground motion for which a structure is designed or evaluated**.

- The associated performance requirement is that the **project performs without loss of life or catastrophic failure (such as an uncontrolled release of a reservoir) although severe damage or economic loss may be tolerated.**

- Maximum Credible Earthquake Ground Motion (MCE-GM) for a given project site is defined as the largest earthquake that can reasonably be expected to be generated by a specific source or zone and is based on seismological and geological characterization of both nearby and more distant potentially active seismic sources. Used mainly for critical features, for which MDE-GM is equal to MCE-GM.

Significance of Maximum Design Ground Motion (MDE-GM)

BY DEFINITION:
If the dam barely stands and no catastrophic failure happens, it is acceptable.

POTENTIAL CONSEQUENCES:

As MDE/MCE loadings correspond to rare events, it is easy to justify major damages, as long as no uncontrolled release of impounded water. However, the rebuilding of the dam may be very cost prohibitive, and the loss of function may be extensive.

Dams with extensive or moderate damage have been taken out of service after an earthquake (for example, both Lower and Upper San Fernando Dams were permanently removed from service).

Existing Seismic Loading for OBE-GM (USACE Regulations and Guidance)

USACE ER 1110-2-1806 (**Regulation**)

c. Operating Basis Earthquake (OBE). The OBE is an earthquake that can reasonably be expected to occur within the service life of the project, typically a 50% probability of exceedance in 100 years (average return period of 144 years) assessed using a PSHA informed by the results of a site-specific DSHA. The associated performance requirement is that the project functions with little or no damage and without interruption of function. The purpose of the OBE is to protect against economic losses from damage or loss of service, therefore, alternative choices of return periods for the OBE may be based on economic considerations.

Economic perspective is missing when we interpreted regulation to guidance

USACE EM 1110-2-2100 (**Guidance** for concrete structures)

4-7. Earthquake Loading Conditions

a. Seismic Load Conditions. Earthquake loads are used to represent the inertial effects attributable to the structure mass, the surrounding soil (dynamic earth pressures), and the surrounding water (hydrodynamic pressures). Design earthquakes shall comply with requirements of ER 1110-2-1806, based on the following seismic events.

- *Operational basis earthquake (OBE).* The OBE is considered to be an earthquake that has a 50 percent chance of being exceeded in 100 years (or a 144-year return period).

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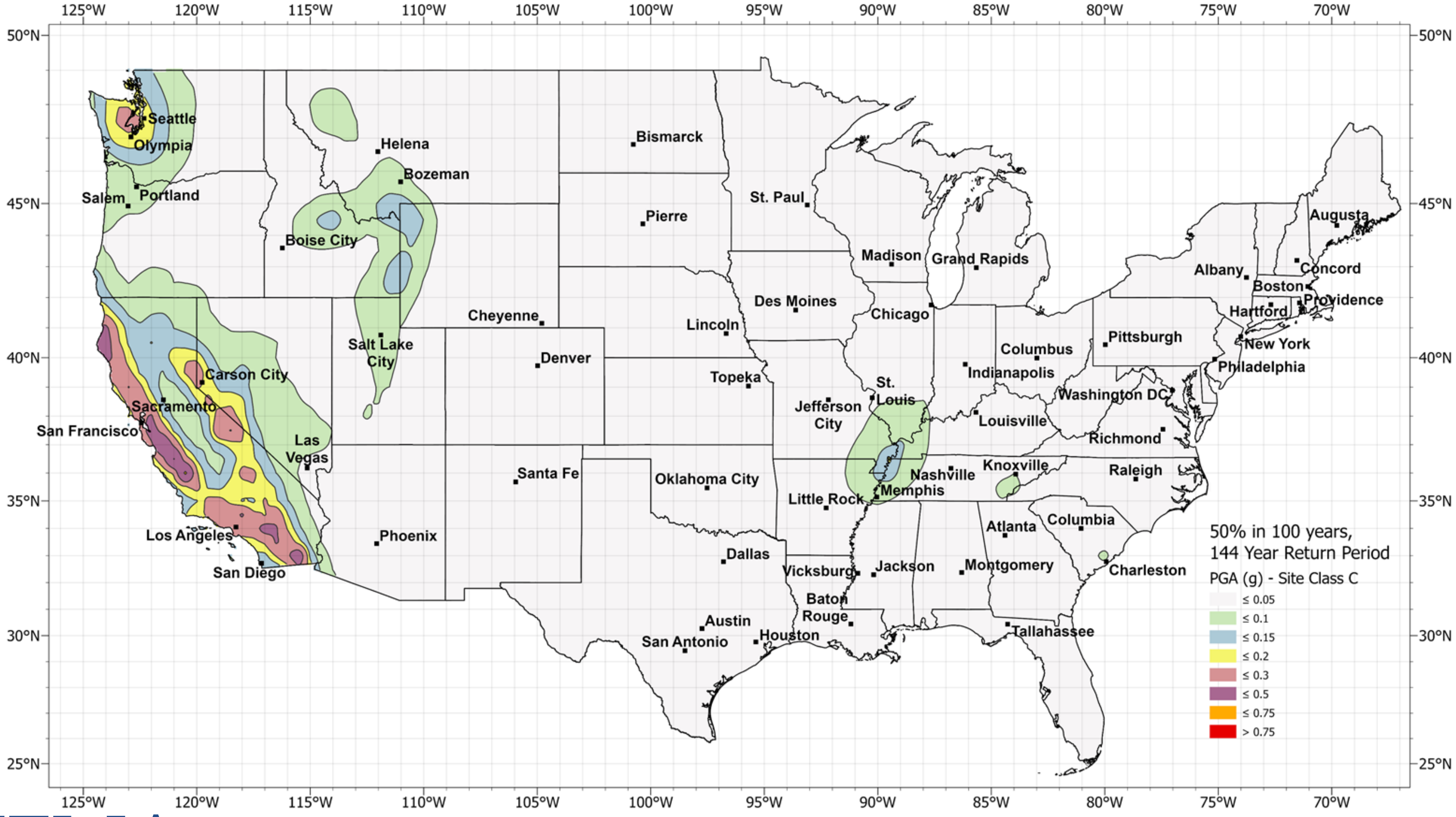
Peak Ground Acceleration (PGA) Variation in CONUS for 144-Year EQ Return Period



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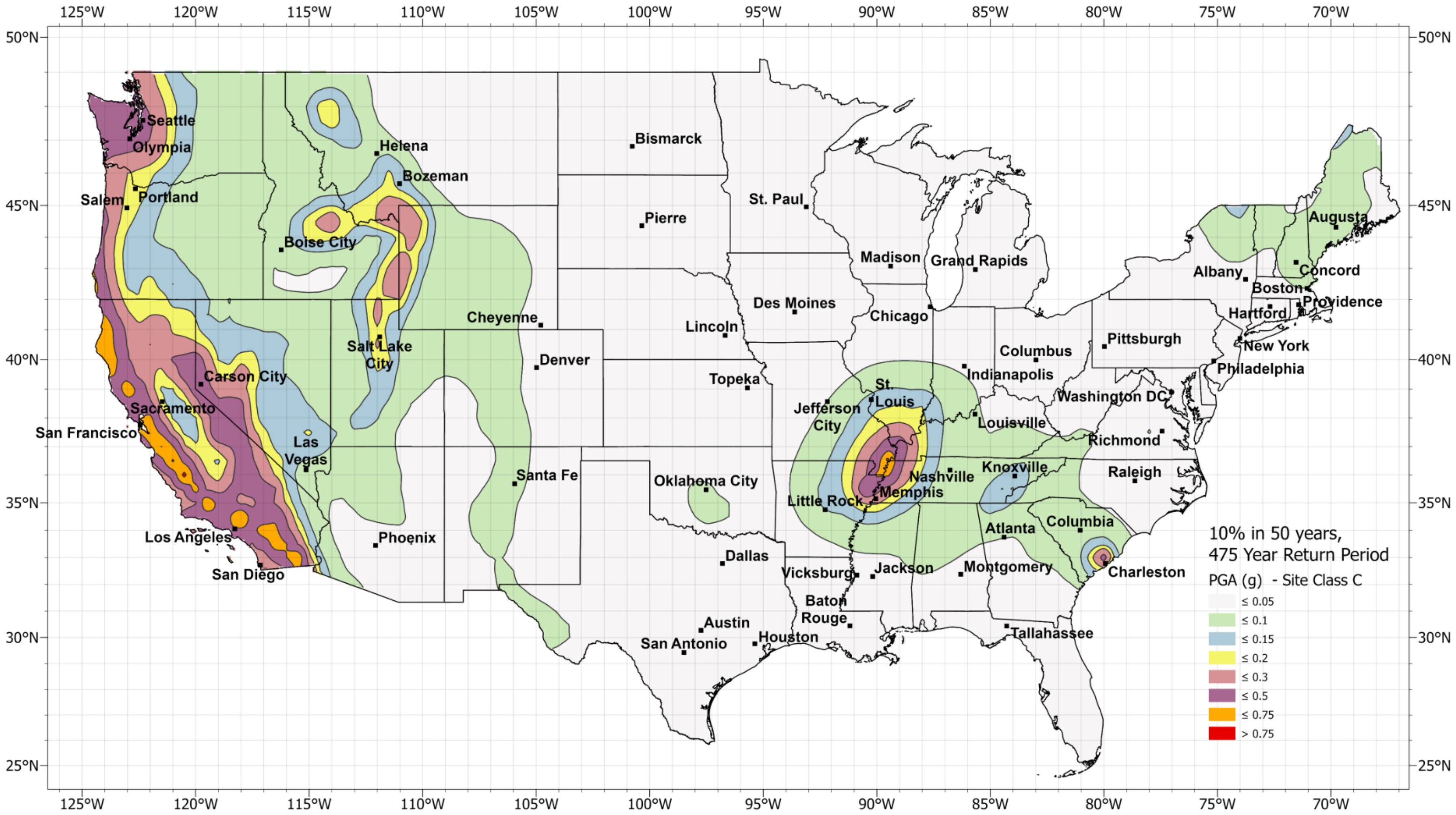
Peak Ground Acceleration (PGA) Variation in CONUS for 475-Year EQ Return Period



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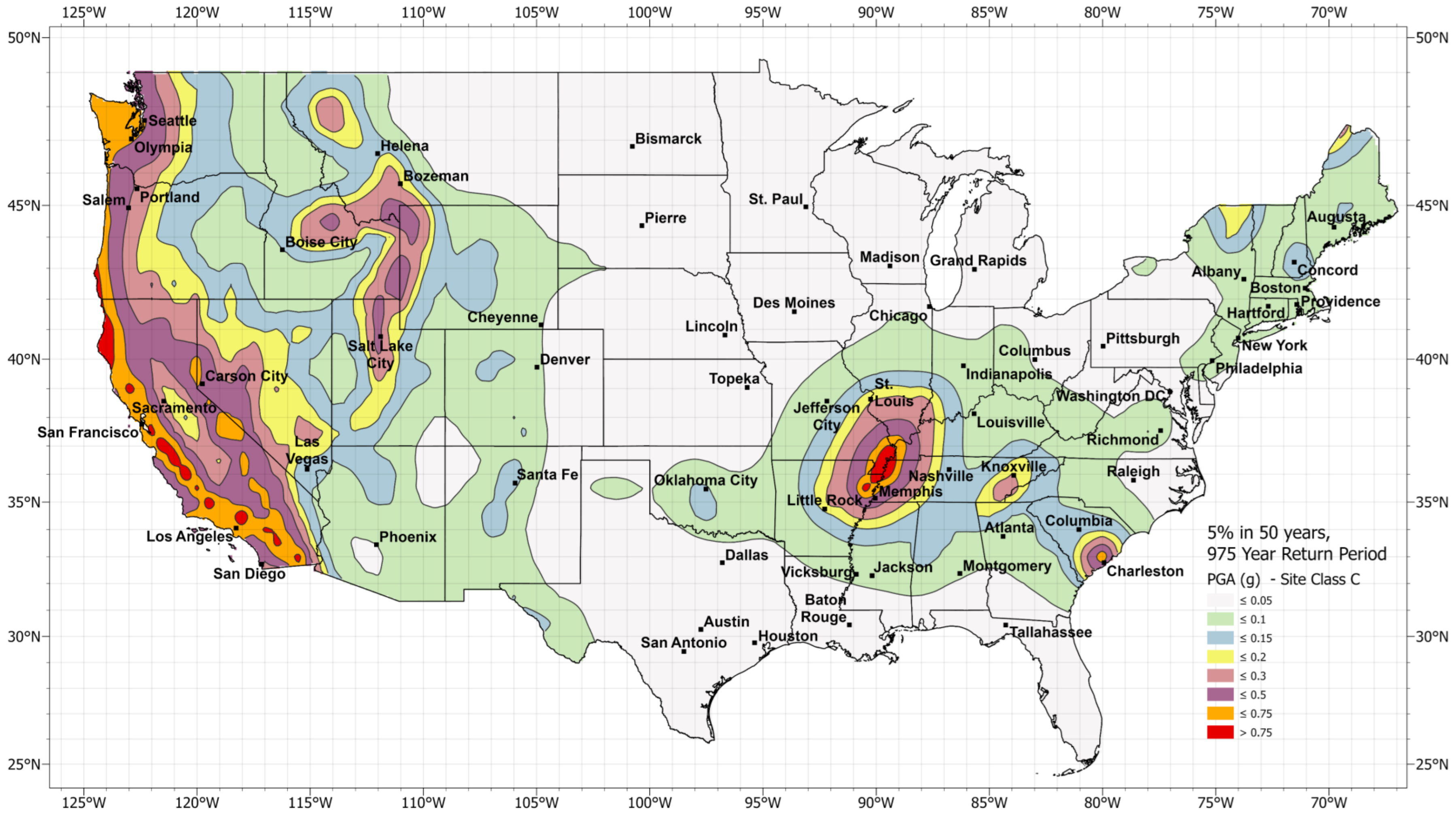
Peak Ground Acceleration (PGA) Variation in CONUS for 975-Year EQ Return Period



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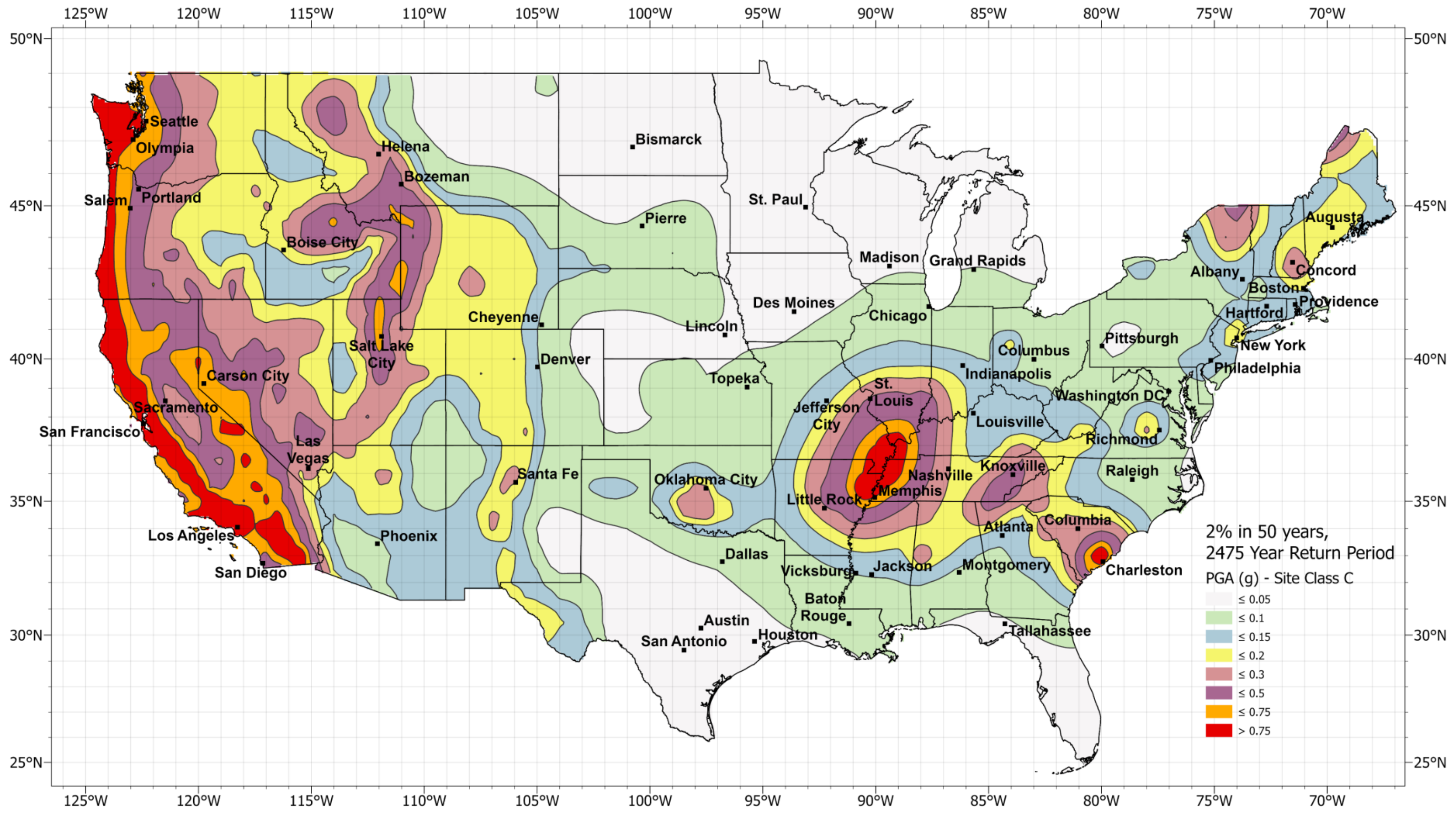
Peak Ground Acceleration (PGA) Variation in CONUS for 2,475-Year EQ Return Period



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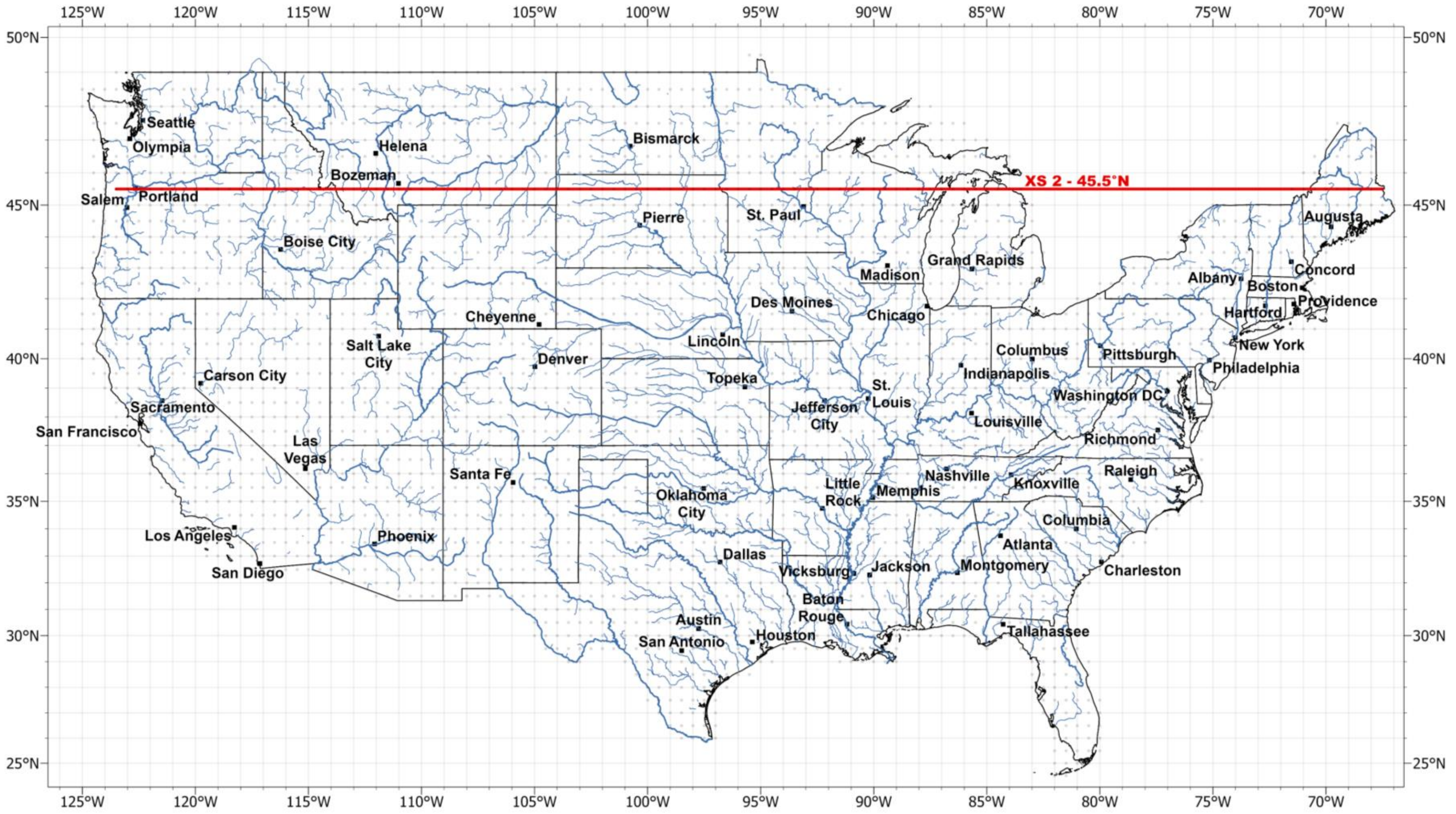
XS 2 – PGA Variation Across CONUS by Cross-Section, Site Class C [Major City – Portland]



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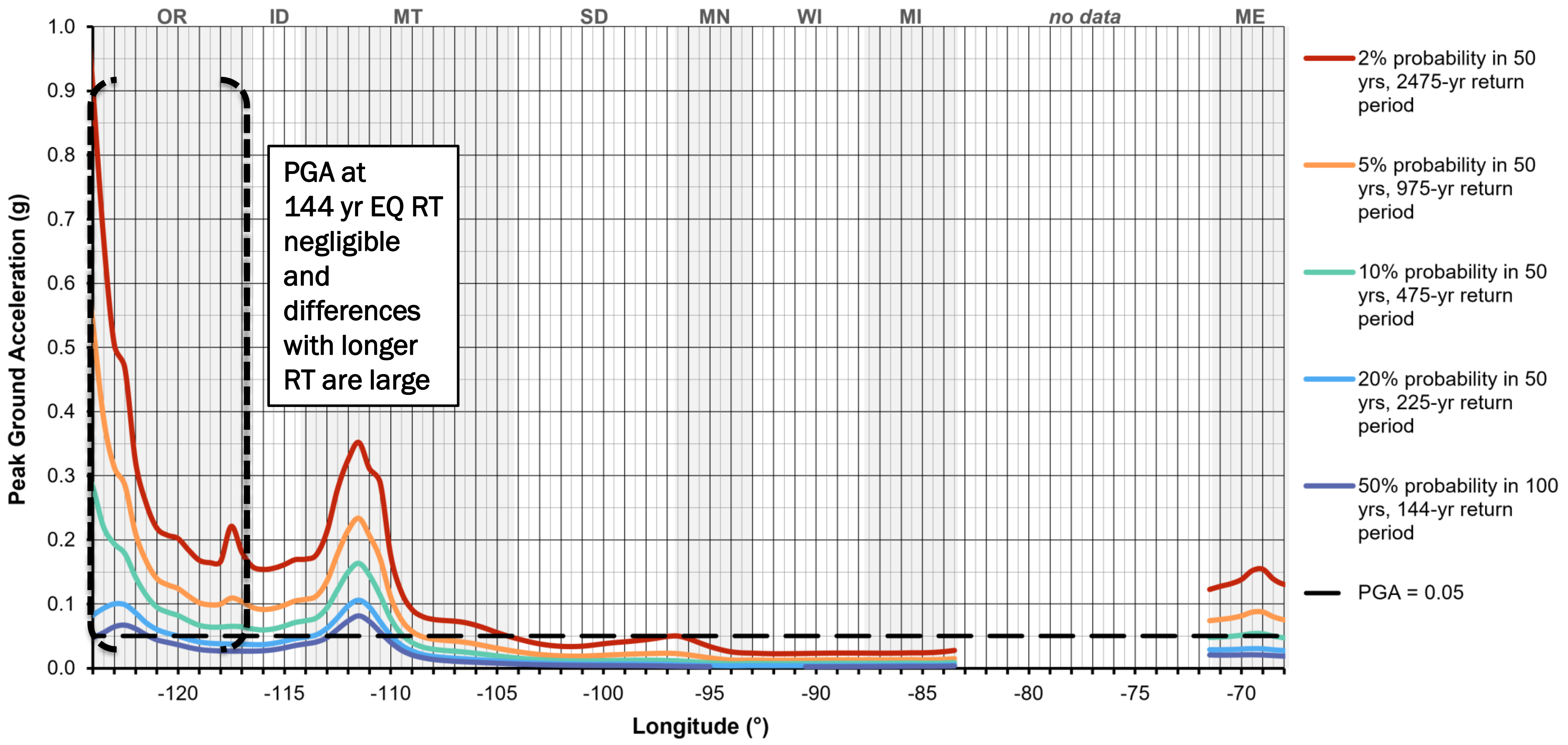
XS 2 – PGA Variation Across CONUS by Cross-Section, Site Class C [Major City – Portland] (2)



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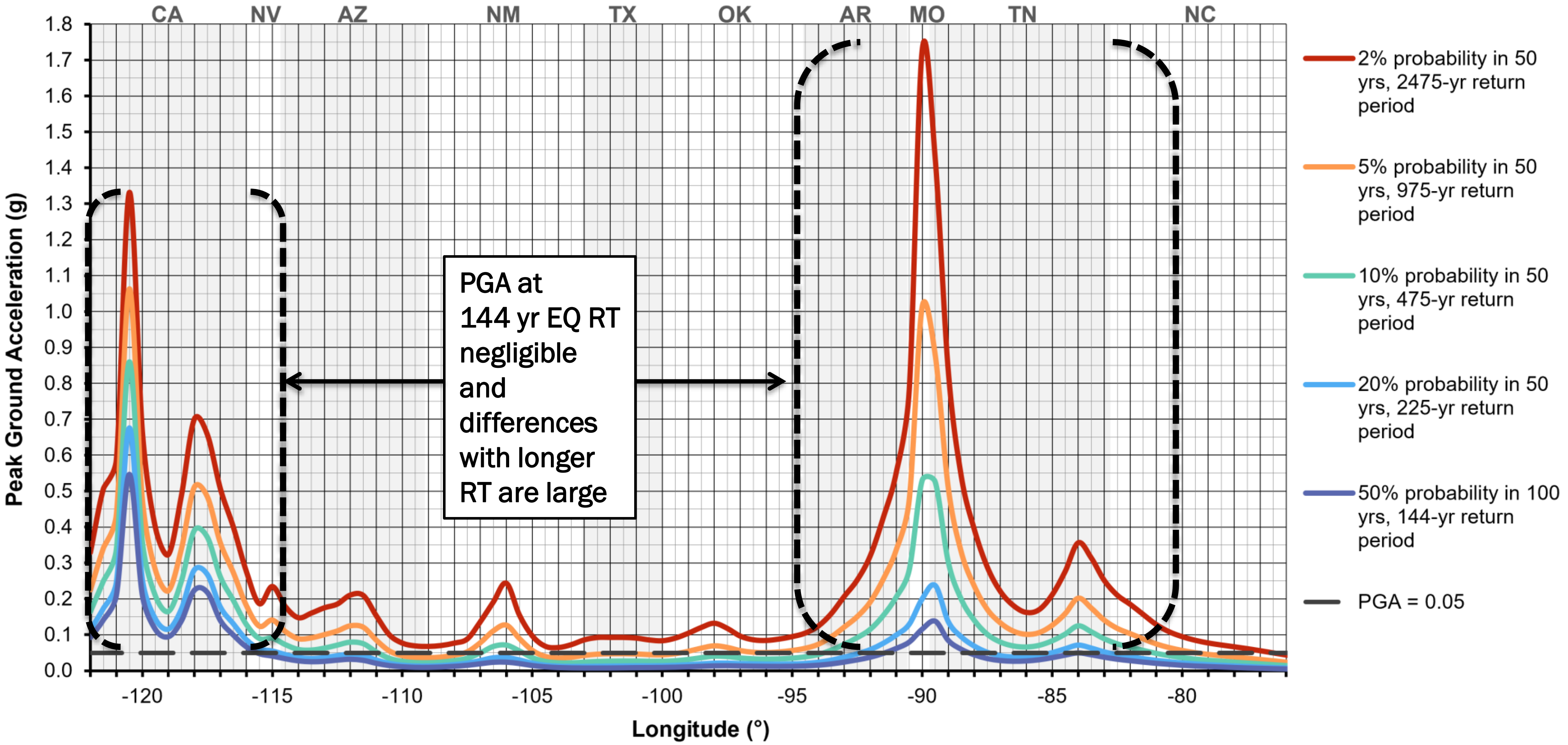
XS 5 – PGA Variation Across CONUS by Cross-Section, Site Class C [Major Cities – Memphis and Nashville]

XS 5 – PGA Variation Across CONUS by Cross-Section, Site Class C [Major Cities –Memphis and Nashville]



A Review of International and U.S. Federal and State Guidelines

International Dam Organization Guidelines

1) Australian National Committee on Large Dams (ANCOLD), 2019. Guidelines for Design of Dams and Appurtenant Structures for Earthquake.
2) Canadian Dam Association (2007) (2013 Edition). Dam Safety Guidelines 2007 (2013 Edition).
3) Japan River Bureau, Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) (2005). Dam Safety Performance Verification Guidelines for Large-Scale Earthquakes (Draft).
4) International Commission on Large Dams (ICOLD) (2010). Bulletin 148 – Selection Seismic Parameters for Large Dams.

U.S. Federal and State Dam Agency Guidelines

1) Federal Energy Regulatory Commission (FERC) (2018). Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 13 – Earthquake Ground Motions.
2) Natural Resource Conservation Service (2019). Technical Release 210-60, Earth Dams and Reservoirs.
3) California Natural Resources Agency Department of Water Resources Division of Safety of Dams (CA DSOD) (2019). Division of Safety of Dams Inspection and Reevaluation Protocols. September, 2018.
4) Montana Department of Natural Resources and Conservation (2020). Technical Note 5 – Simplified Seismic Analysis Procedure for Montana Dams. Prepared by HDR Engineering.

US Building Codes, Bridge Codes, and LNG Industry (US and International)

1) Building Code - American Society of Civil Engineers (ASCE) (2022). Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE 7-22.
2) Bridge Code - American Association of State Highway and Transportation Officials (AASHTO) (2020). Load-and-Resistance Factor Design (LRFD) Bridge Design Specifications (BDS), LRFDBDS-9.
3) Liquefied Natural Gas Industry [National Fire Protection Association (NFPA), Canada Standards Association (CSA), and European Standards (EN).

ANCOLD (Australian National Committee of Large Dams) Guidelines [2019]

Seismic Loading Criteria	Performance Requirements Consideration for Consequence Category	Comment
Extreme Consequence Category Dams: **OBE: Commonly 1 in 475 AEP up to 1 in 1,000 AEP** SEE: The greater of: Ground motion from the MCE on known active faults or Probabilistic ground motion Extreme: 1 in 10,000 AEP	**Operating Basis Earthquake (OBE):** The OBE is that level of ground motion at the dam site for which only minor damage is acceptable. The dam, appurtenant structures, and equipment should remain functional, and damage from the occurrence of earthquake shaking not exceeding the OBE should be easily repairable. **Safety Evaluation Earthquake (SEE):** The SEE is the recommended maximum level of ground motion for which the dam should be designed or analyzed. Damage can be accepted, but there should be no uncontrolled release of water from the reservoir or tailing dams.	▪ There is no separation between the dam, appurtenant structures, and critical equipment or "works" in a system. Unlike "normal" and "critical" features we analyze separately in USA. ▪ Definitions of OBE and SEE in ANCOLD are somewhat similar to USA regulations and guidance.
High A, B, and C Consequence Category Dams: **OBE: Commonly 1 in 475 AEP up to 1 in 1,000 AEP** SEE: Probabilistic ground motion High A: 1 in 10,000 AEP High B: 1 in 5,000 AEP High C: 1 in 2,000 AEP	The considerations for consequence category are: (a). Total infrastructure costs (residential, commercial, community infrastructure, dam repair or replacement cost), (b). Impact on dam owner's business (important of the system (need to replace the dam), effect on services provided by owner, effect on continuing credibility, community reaction and political implications, impact on financial viability, value of water in storage), (c). Health and social impacts (human health, loss of services to community, dislocation of people, dislocation of business, employment affected, loss of heritage, loss of recreational facility), (d). Environmental impacts (area of impact, duration of impact, stock and fauna, ecosystems, rare and endangered species).	▪ **OBE is 1 in 475 years to 1 in 1,000 years AEP, which is higher than what most US agencies use.** ▪ Probabilistic motions up to the MCE or 1 in 10,000 years AEP
Significant Consequence Category Dams: **OBE: Commonly 1 in 475 AEP** SEE: Probabilistic ground motion 1 in 1,000 AEP		
Low Consequence Category Dams: **OBE: Commonly 1 in 475 AEP** SEE: Probabilistic ground motion 1 in 1,000 AEP		

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CDA (Canadian Dam Association) Safety of Dam Guidelines

Seismic Loading Criteria	Performance Criteria	Comment
Dam Class: Low 1 in 100 AEP **Dam Class: Significant** Between 1 in 100 AEP and 1 in 1,000 AEP **Dam Class: High** 1 in 2,475 AEP **Dam Class: Very High** Traditional Standard Based Approach: 1/2 between 1 in 2,475 AEP and 1 in 10,000 AEP or MCE Risk Informed Approach: 1 in 10,000 AEP **Dam Class: Extreme** Traditional Standard Based Approach: 1 in 10,000 AEP or MCE Risk-Informed Approach: 1 in 10,000 AEP	**For Risk-Informed Approach:** For Dam Classifications: High, Very High, and Extreme Societal risk target $(1/N) \times 10^{-3}$ [N, number of fatalities] **For Traditional Standard Based Approach:** For geotechnical: Pseudo-static: Minimum Factor of Safety = 1.0 Post-earthquake Minimum Factor of Safety = 1.2-1.3 For concrete gravity dam: Criteria for position of resultant force, normal compression stress, sliding factor safety, etc.	(1). **There is no distinction between OBE and MDE.** Requirements vary based on dam classes, which are based on population at risk, loss of life, environmental and cultural values, infrastructure and economics. (2). **Manual differentiates between traditional standard-based approach and risk informed approach for dam safety evaluations.** The seismic loading and performance requirements for the traditional standard based approach and risk-informed approach are different. (3). **Infrastructure and economics loss are well defined with examples.** For example, infrastructure such as ***highway, industrial facility, storage facilities for dangerous substances are in 'Very High" dam class, whereas hospital, major industrial complex, major storage facilities for dangerous substances are in "Extreme" dam class.***

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CDA (2013) Consequence-based Dam Classifications

Dam Class	Population at risk [note 1]	Incremental Losses		
		Loss of life	Environmental and cultural values	Infrastructure and economics
Low	None	0	Minimal short-term loss. No long-term loss.	Low economic losses; area contains limited infrastructure or services.
Significant	Temporary only	Unspec-ified	No significant loss or deterioration of fish or wildlife habitat. Loss of marginal habitat only. Restoration or compensation in kind highly possible.	Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes.
High	Permanent	**10 or fewer**	Significant loss or deterioration of important fish or wildlife habitat. Restoration or compensation in kind highly possible.	**High economic losses affecting infrastructure, public transportation, and commercial facilities.**
Very High	Permanent	**100 or fewer**	Significant loss or deterioration of critical fish and wildlife habitat. Restoration or compensation in kind possible but impractical.	**Very high economic losses affecting important infrastructure or services** (**e.g. highway, industrial facility, storage facilities for dangerous substances**).
Extreme	Permanent	**More than 100**	Major loss of critical fish or wildlife habitat Restoration or compensation in kind impossible	**Extreme losses affecting critical infrastructure or services** (**e.g. hospital, major industrial complex, major storage facilities for dangerous substances**).

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Japan River Bureau, Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) Guidelines for Dam Safety Verification [2005 draft]

<table>
<tr><th>Seismic Loading Level</th><th>Performance Requirements</th><th>Comment</th></tr>
<tr><td>Level 1 Earthquake
Level 1 seismic ground motions are those that have a high probability of occurring during the service life of a structure. They are specified to follow the level of seismic motion considered in conventional seismic design using the seismic intensity method.</td><td>The dam or levee can maintain the same function before and after the earthquake without any repairs to restore the function being necessary.</td><td rowspan="2">(1). No earthquake return period is associated with the Level 1 and Level 2 earthquakes.

(2). Performance requirements for Level 2 earthquake are higher standards than many US standards. US regulations and guidance allow significant damage at the MDE level, as long as no uncontrolled release is ensured.

▪ Therefore, controlled release or lowering of pool elevation or a non-functioning dam for an unlimited period post-earthquake is allowed (unknown duration of non-performing water storage function).

▪ The Japanese criteria requires maintenance of water storage function. Requirement that the damage caused remains within the repairable range ensures limited damage during the Level 2 earthquake (potentially comparable earthquake intensity level with MCE in US standards).</td></tr>
<tr><td>Level 2 Earthquake
Level 2 seismic ground motions having the maximum-scale level of intensity conceivable at the dam site, at the present and in the future.</td><td>1). Maintaining Water Storage Function [note A].

2). The Damage caused remains within the Repairable Range. [note B].</td></tr>
</table>

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Commentary on Objectives of the Japan MLIT Level 2 Earthquake Performance

(1) Maintaining Water Storage Function.

The dam may cause enormous damage to the downstream area if an uncontrollable outflow of water occurs due to significant damage. "Maintaining the water storage function" is the seismic performance that should be secured against Level 2 earthquake motion.

(2). The Damage caused remains within the Repairable Range.

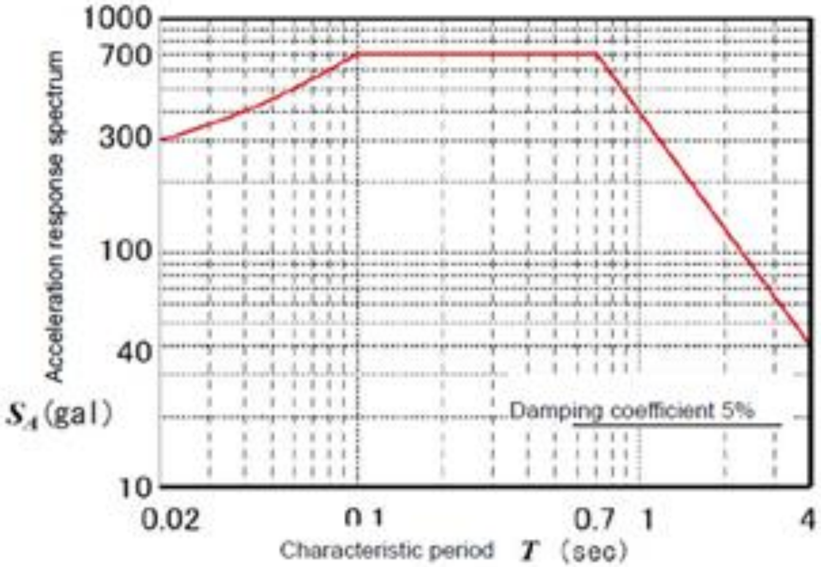
A dam is a structure that has an extremely important function for hydraulic control and water utilization in basin. It is difficult to replace its function with another structure or rebuild promptly if an earthquake causes damage that makes it difficult to repair for continued use with applicable technology and within reasonable cost and time period. "The damage remains within the repairable range" is set as the seismic performance that should be ensured against Level 2 seismic motion to confirm that there is no such risk.

Procedure for Level 2 Ground Motions Are Estimated in MLIT (2005)

(a) The largest seismic motion actually observed in the past at or near the dam site

(b) Seismic ground motion with the lower limit acceleration response spectrum for verification listed in Table-1.

Period, T (sec)	Acceleration Response Spectra, S_A (gal)
$0.02 \leq T < 0.1$	$S_A = 400/0.08*(T-0.02)+300$
$0.1 \leq T \leq 0.7$	$S_A = 700$
$0.7 \leq T \leq 4.0$	SA = 700*(T/0.7)-1.642
Note: 100 gal ~ 0.1g	



At T = 0.02 sec., $S_A = 0.3g$

T = 0.1 sec., $S_A = 0.7g$

T = 0.7 sec., $S_A = 0.7g$

T = 1 sec., $S_A = 0.4g$

T = 4 sec., $S_A = 0.04g$

Note: Sa at 1 sec period is very important for embankment dam performance. A minimum Sa=0.4g ensures higher level of performance.

Essential Buildings and Bridges Required to be Functional After A Design Level Earthquake

Building Codes (ASCE 7-22)	AASHTO – LRFD Bridge Design Specifications (2020)
Risk-Targeted Maximum Considered Earthquake (MCE_R) USGS developed MCER map for use with ASCE 7-22. Risk category, Seismic Importance Factor, Seismic Design Category, Response Modification Factors, etc. are used for developing design seismic loading.	This design basis earthquake (DBE) of 7% probability of exceedance refers to earthquake return period of 1,033 years. It can be increased to larger earthquake return periods considering different operational (critical, essential, or other) classification-based response modification factors.
Risk Category IV shall be designed with reasonable probability to have adequate structural strength and stiffness to limit deflections, lateral drift, or other deformations such that their behavior would not prevent function of the facility immediately following any of the design-level environmental hazard events specified in this standard.	Essential bridges are generally those that should, as a minimum, be open to emergency vehicles and for security/defense purposes immediately after the design earthquake, i.e., a 1,000-yr return period event. However, some bridges must remain open to all traffic after the design earthquake and be usable by emergency vehicles and for security/defense purposes immediately after a large earthquake, e.g., a 2,500-yr return period. The basis of classification shall include social/survival and security/defense requirements. In classifying a bridge, consideration should be given to possible future changes in conditions and requirements.

BY DEFINITION: An Essential Building or a Bridge will be functional at higher seismic load than a critical dam (that may interrupt functions such as flood control, water supply, hydroelectric).

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Seismic Freeboard Requirements

Available Freeboard Criteria	Seismic Freeboard Criteria
Currently, there is no criteria for freeboard. Usually, arbitrary. Sometimes hydrologic considerations (fetch length, etc.) Example, 1 to 2% available freeboard in 300 to 500 feet tall dams.	Seismic freeboard is not the same as hydrologic freeboard. For an Embankment Dam, available freeboard should be greater than ▪ Seismic Deformations (deviatoric) ▪ Volumetric Settlement ▪ Potential Crack Depth ▪ Reservoir Seiches

CA Division of Safety of Dams: **Freeboard requirements for new dams considering seismic loading**

Adequate total freeboard must account for potential seismic deformation in areas subject to high seismic loading; this freeboard will, in theory, accommodate seismically induced deformations and cracking that cannot be fully estimated to a high level of certainty by analyses. Thus, **a criterion of 5 feet plus 5 percent of the dam height is typically to be used in determining minimum freeboard for new dams subject to high seismic loads.**

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Coincident Pool (An Often-Overlooked Criteria) for Seismic Analysis

Coincident pool is very important from at least two aspects:

(1). For seismic analyses of embankment dams, a higher coincident pool indicates higher saturation level and higher potential for liquefaction in shell, etc. and higher downstream phreatic surface due to poor drainage.

(2). A higher coincident pool results in less freeboard and higher consequences in the event of breach.

Excerpt from a USACE Guidance

- c. Coincident pool. The coincident pool represents temporal average pool conditions, which are used for load combinations that include seismic loads. The pool elevation that is equaled or exceeded 50-percent of the time is the temporal average pool. An estimate of temporal average headwater and tailwater pools can be obtained based on existing project operations data (providing sufficient data exists), or by using inflow data in combination with planned project operating procedures. A plot of this information is shown in Figure B-1. This figure was developed under the assumption the project is operated for a year under mean annual pool conditions, with project inflows varying from month to month due to seasonal variations. The mean monthly pool elevation from Figure B-1 can then be used to develop a pool-duration plot showing the percent of time a particular pool elevation will be equaled or exceeded. The pool elevation that is equaled or exceeded 50-percent of the time (or 182 days per year) is the temporal average pool. This is illustrated by Figure B-2.

Interpretation of 50 Percentile Coincident Pool Elevation for seismic analysis

For 6 months of the year, if an earthquake results in extreme damage including downstream flooding , it will be within our guidance requirement!

When we talk about probability of a rare earthquake and a rare flood event being extremely low,

6 months out of 12 months is not that type of rare flood event!

Coincident Pool (An Often-Overlooked Criteria)

Agency	Criteria for Coincident Pool for Seismic Analyses
CDA (Canadian Dam Association) Safety of Dam Guidelines	Coincident Pool for Concrete Dam Analysis: One of the loads that needs to be considered in the design and assessment of concrete structures is as below: Maximum normal headwater level, combined with the most critical concurrent tailwater level
Japan River Bureau, Ministry of Land, Infrastructure, Transport, and Tourism (MLIT)	The water storage level to be considered for the verification is based on the normal full water level. This is the water level that has a large effect on the dam structure in the event of an earthquake within the usual water level of the dam in service.
Federal Energy Regulatory Commission (FERC) Guidelines	For Embankment Dams: Normal/Static Loading PFMs with added seismic loads For concrete gravity and arch dams: Normal/Static and Hydrologic/Flood Loading PFMs with added seismic loads. [Reference: Chapter 17: Potential Failure Mode Analysis]
Natural Resources Conservation Service – USDA Guidelines	For seismic analyses, assume that the reservoir is at the highest normal pool elevation. Base the extent of saturation of embankment and foundation materials on the steady-state seepage conditions prior to earthquake loading resulting from the same pool elevation. Initial embankment and foundation properties used in the analyses must represent existing conditions prior to earthquake loading. Consider both upstream and downstream failure.

We Work With An Assumption: Joint Probability of a Rare Earthquake and a Flood Event is Very Low

- If a dam is built in accordance with the modern techniques to meet static/hydrologic criteria, it should have high likelihood to meet seismic criteria or at least provide resistance to a higher seismic loading.
- When we say a dam cannot handle a seismic loading, if a flood condition exists, we categorically acknowledge poor condition of a dam. If potential of a dam failure is high during an earthquake, it reflects poor conditions of the dam for static/hydrologic PFMs also.
- In a changing climate and forecast-informed reservoir operations (FIRO), durations of high pool is likely to be longer. These are not flood conditions, rather normal higher pool conditions for longer durations.

Summary

- Current regulations and guidelines in USA are not appropriately capturing the seismic risks in existing dams. Focus is mostly on life loss; however, potential functionality loss could be very expensive.
- The seismic loading and performance criteria in US practice are somewhat weaker than international guidelines.
- The seismic loading and performance criteria for dams are weaker than other infrastructures (buildings and bridges) in US practice, when it comes to functionality.
- The differences between OBE-GM shaking levels and potential shaking levels from major scenario earthquakes such as Cascadia subduction zone earthquake, New Madrid earthquake, and Maximum Credible earthquakes in major CA faults are very large and potential for functionality loss in our dams is high from such earthquake events.
- Importance of coincident pool in seismic analysis is often overlooked in guidance.
- Importance of seismic freeboard is regularly overlooked in US dam operations.

Thank you

Acknowledgement: USACE PDT and ATR Team Members
for ER 1110-2-1806 Update

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