# Wanapum Left Embankment Seismic Risk Assessment

May 1, 2025

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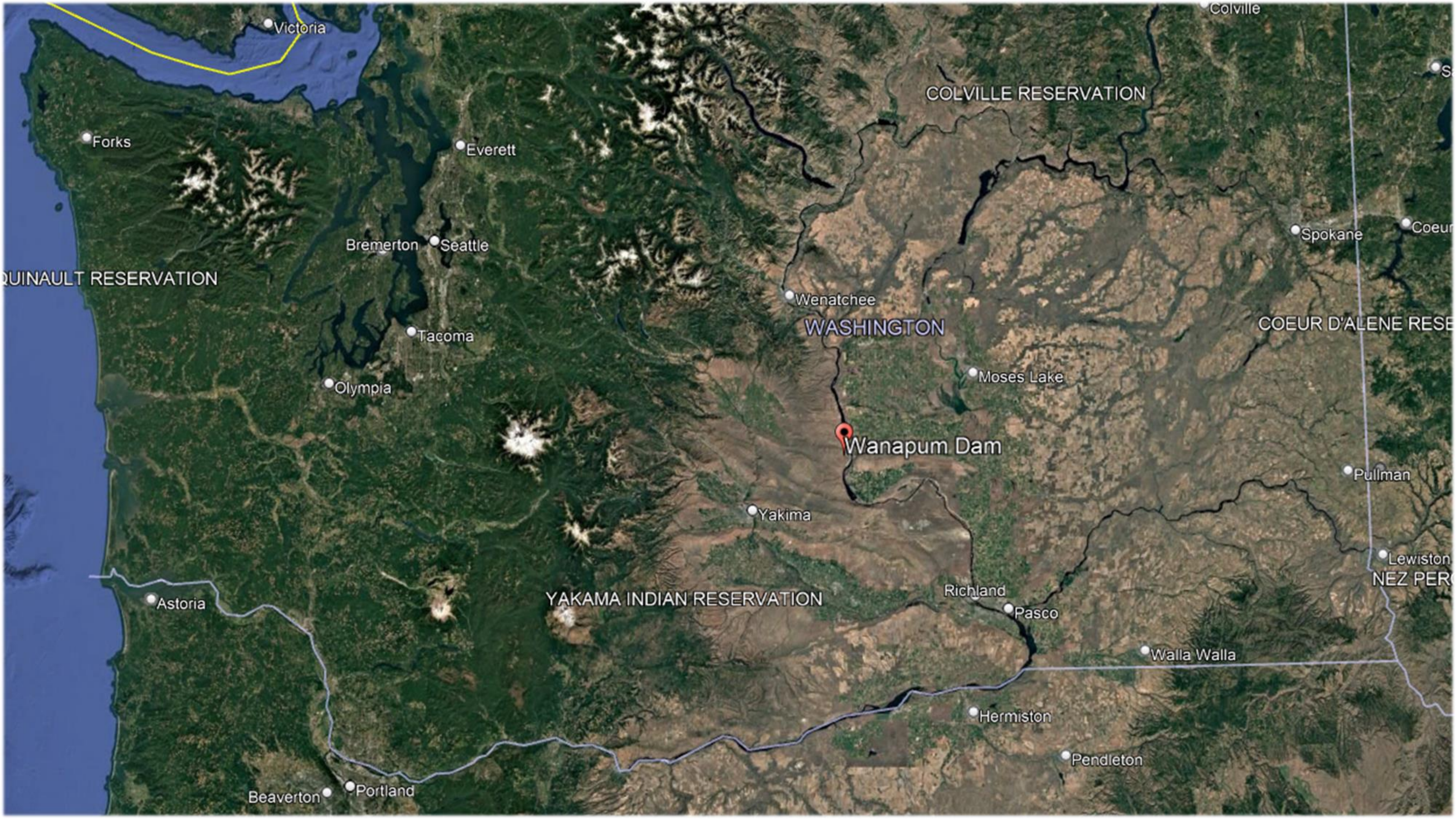
Grant PUD

# Overview

- Project Background
- Risk-Informed Decision-Making Approach
- Fragility Analysis
- Risk Analysis

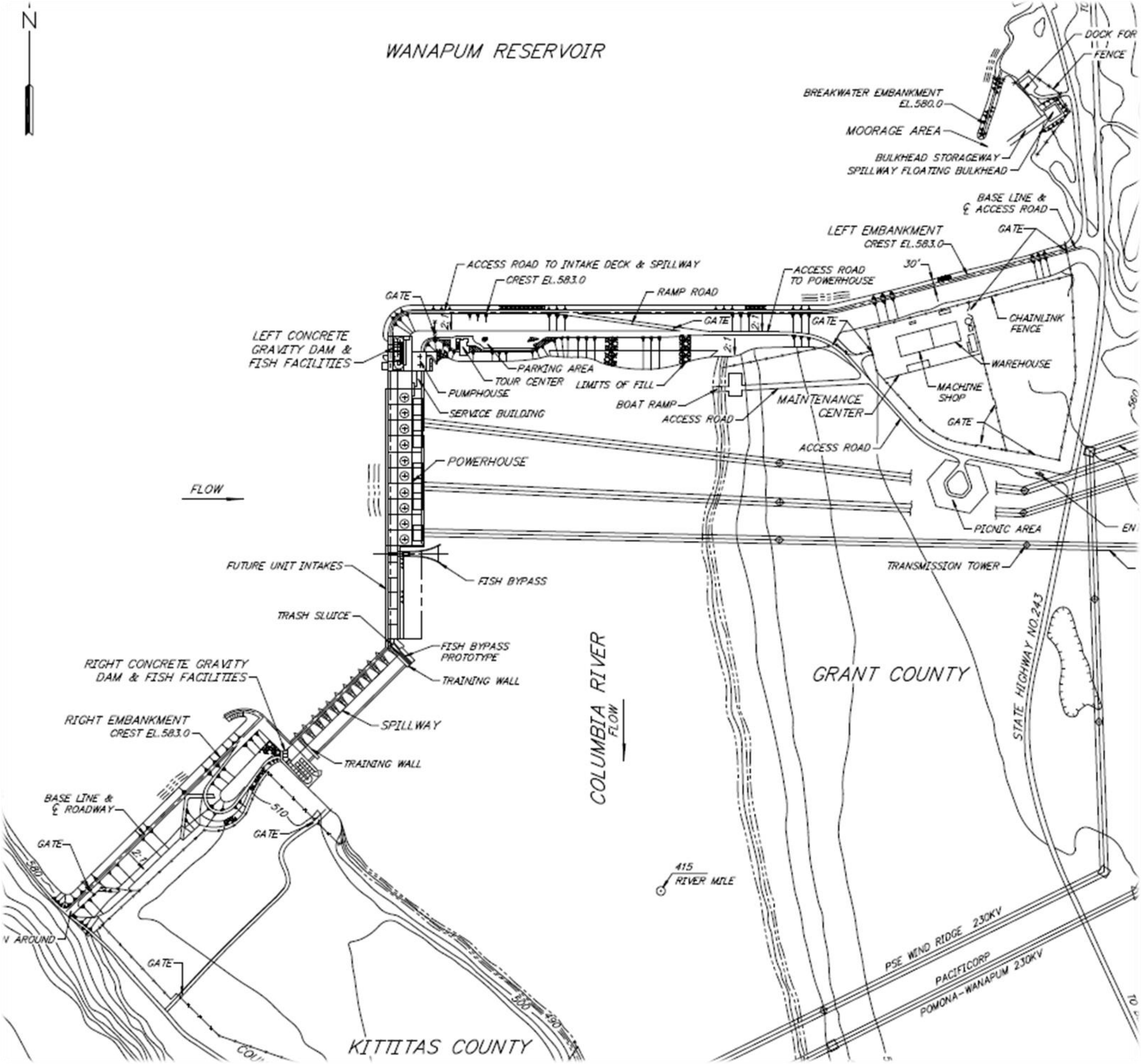
# Project Background

Wanapum Left Embankment Seismic Risk Assessment



Victoria
Colville
COLVILLE RESERVATION
Forks
Everett
Bremerton
Seattle
Spokane
Coeur
QUINAULT RESERVATION
Wenatchee
WASHINGTON
COEUR D'ALENE RESE
Tacoma
Moses Lake
Olympia
Wanapum Dam
Pullman
Yakima
Lewiston
NEZ PERC
Richland
Pasco
YAKAMA INDIAN RESERVATION
Astoria
Walla Walla
Hermiston
Pendleton
Beaverton
Portland


WANAPUM

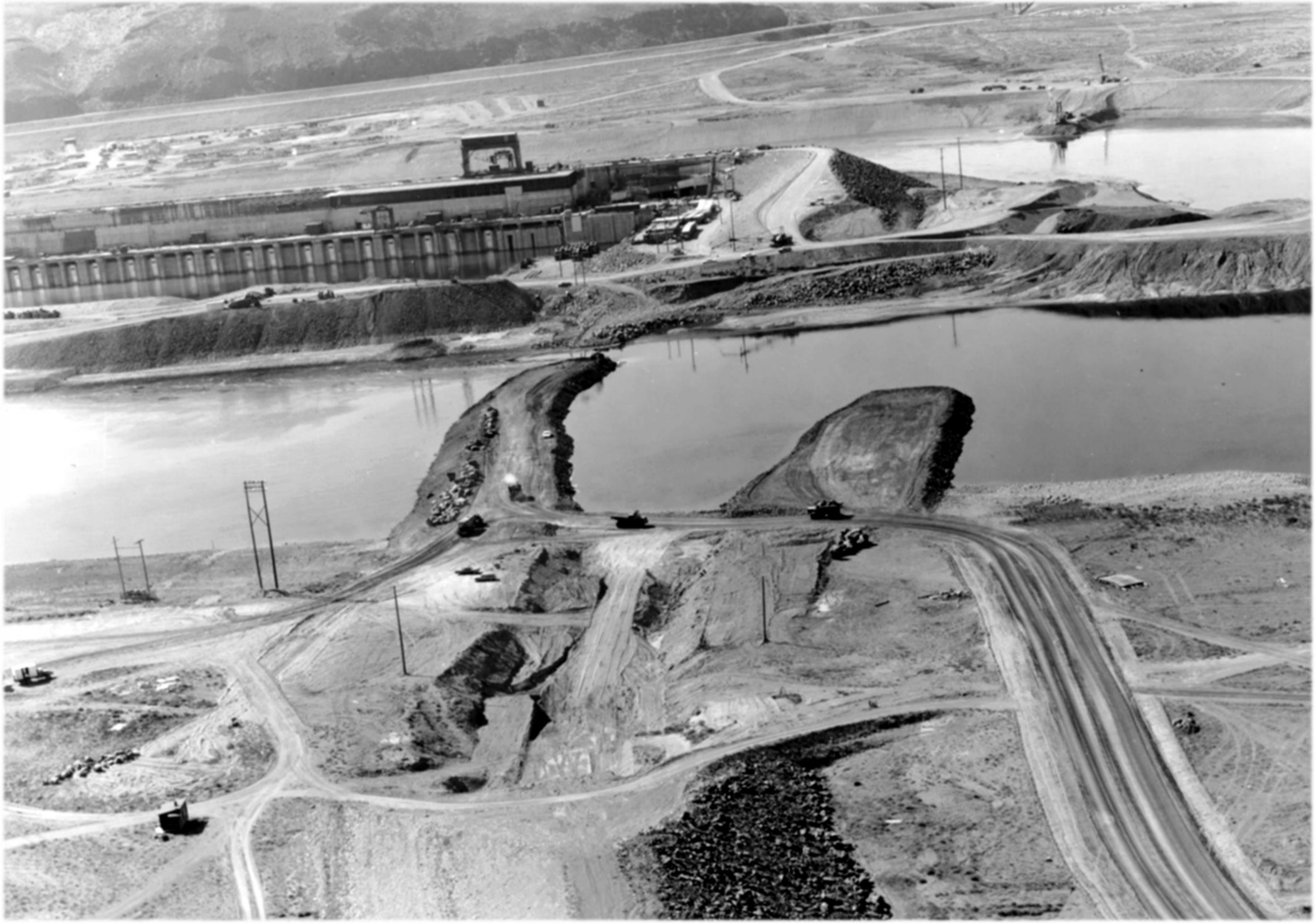

N
WANAPUM RESERVOIR
DOCK FOR
FENCE
BREAKWATER EMBANKMENT EL.580.0
MOORAGE AREA
BULKHEAD STORAGEWAY
SPILLWAY FLOATING BULKHEAD
BASE LINE & ℄ ACCESS ROAD
LEFT EMBANKMENT CREST EL.583.0
GATE
30'
ACCESS ROAD TO INTAKE DECK & SPILLWAY
CREST EL.583.0
RAMP ROAD
ACCESS ROAD TO POWERHOUSE
CHAINLINK FENCE
WAREHOUSE
MACHINE SHOP
LEFT CONCRETE GRAVITY DAM & FISH FACILITIES
PARKING AREA
TOUR CENTER
LIMITS OF FILL
PUMPHOUSE
SERVICE BUILDING
BOAT RAMP
ACCESS ROAD
MAINTENANCE CENTER
ACCESS ROAD
POWERHOUSE
FLOW
PICNIC AREA
TRANSMISSION TOWER
FUTURE UNIT INTAKES
FISH BYPASS
TRASH SLUICE
FISH BYPASS PROTOTYPE
TRAINING WALL
RIGHT CONCRETE GRAVITY DAM & FISH FACILITIES
COLUMBIA RIVER
FLOW
GRANT COUNTY
STATE HIGHWAY NO.243
RIGHT EMBANKMENT CREST EL.583.0
SPILLWAY
TRAINING WALL
BASE LINE & ℄ ROADWAY
GATE
GATE
415 RIVER MILE
N AROUND
GATE
PSE WIND RIDGE 230KV
PACIFICORP
POMONA-WANAPUM 230KV
KITTITAS COUNTY

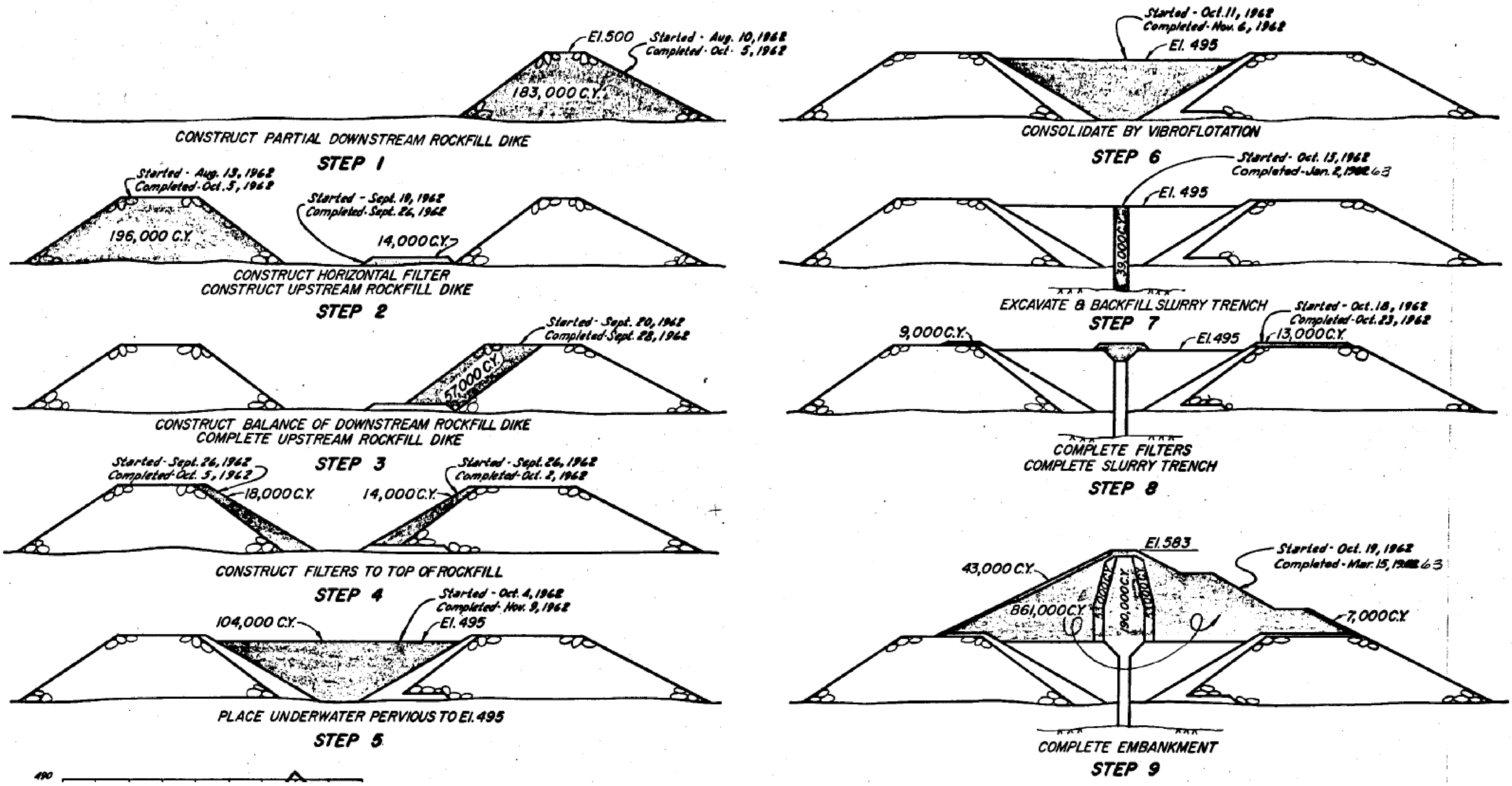
# Wanapum Dam

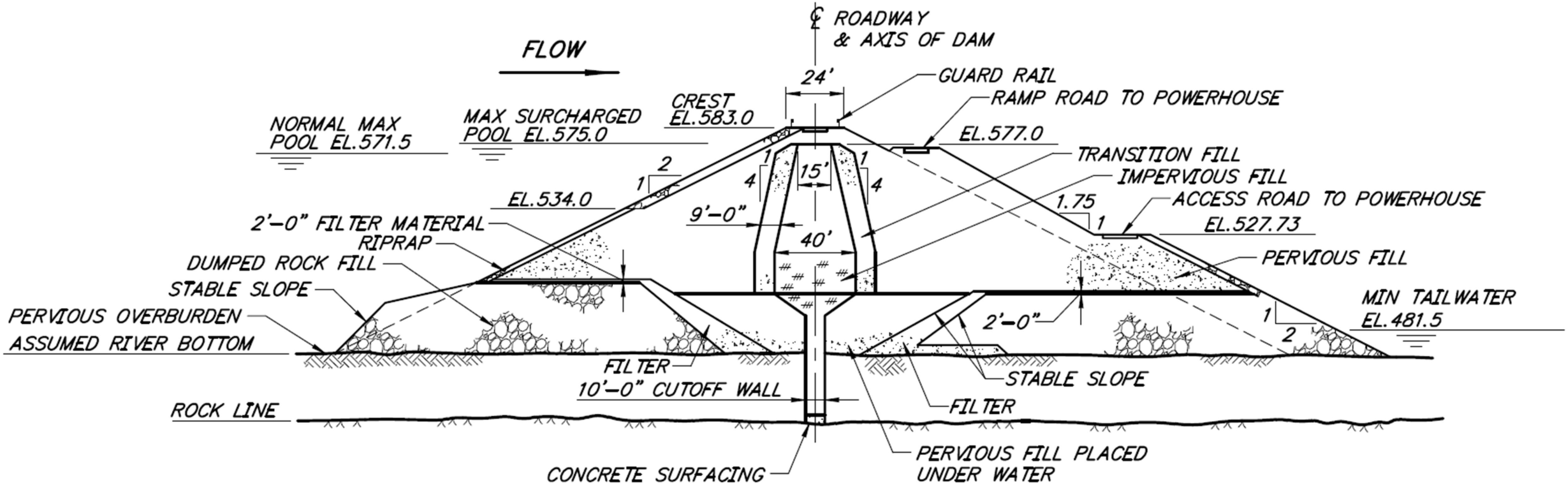
- Total length: 8,637 feet (1.6 miles)
- Maximum height: 186.5 feet
- Constructed: July 1959 – October 1963
- Concrete Gravity Sections
  - Powerhouse and Erection Bay
  - Future Unit Intake
  - Spillway – 12 Radial Gates
  - Fishways
- Zoned Earth and Rockfill Embankment Sections

# River Closure Section (RCS)

- Portion of left embankment constructed in existing river channel
- Material placed to divert river through spillway dumped in and through water — lower density and strength
- Native foundation material beneath dumped fill has low density zones




El.500
Started - Aug. 10, 1962
Completed - Oct. 5, 1962
183,000 C.Y.
CONSTRUCT PARTIAL DOWNSTREAM ROCKFILL DIKE
STEP 1
Started - Aug. 13, 1962
Completed - Oct. 5, 1962
196,000 C.Y.
Started - Sept. 19, 1962
Completed - Sept. 26, 1962
14,000 C.Y.
CONSTRUCT HORIZONTAL FILTER
CONSTRUCT UPSTREAM ROCKFILL DIKE
STEP 2
Started - Sept. 20, 1962
Completed - Sept. 28, 1962
57,000 C.Y.
CONSTRUCT BALANCE OF DOWNSTREAM ROCKFILL DIKE
COMPLETE UPSTREAM ROCKFILL DIKE
STEP 3
Started - Sept. 26, 1962
Completed - Oct. 5, 1962
18,000 C.Y.
Started - Sept. 26, 1962
Completed - Oct. 2, 1962
14,000 C.Y.
CONSTRUCT FILTERS TO TOP OF ROCKFILL
STEP 4
104,000 C.Y.
Started - Oct. 4, 1962
Completed - Nov. 9, 1962
El. 495
PLACE UNDERWATER PERVIOUS TO El. 495
STEP 5
490
Started - Oct. 11, 1962
Completed - Nov. 6, 1962
El. 495
CONSOLIDATE BY VIBROFLOTATION
STEP 6
Started - Oct. 15, 1962
Completed - Jan. 2, 1963
El. 495
39,000 C.Y.
EXCAVATE & BACKFILL SLURRY TRENCH
STEP 7
9,000 C.Y.
Started - Oct. 18, 1962
Completed - Oct. 23, 1962
El. 495
13,000 C.Y.
COMPLETE FILTERS
COMPLETE SLURRY TRENCH
STEP 8
El. 583
43,000 C.Y.
Started - Oct. 19, 1962
Completed - Mar. 15, 1963
861,000 C.Y.
190,000 C.Y.
7,000 C.Y.
COMPLETE EMBANKMENT
STEP 9

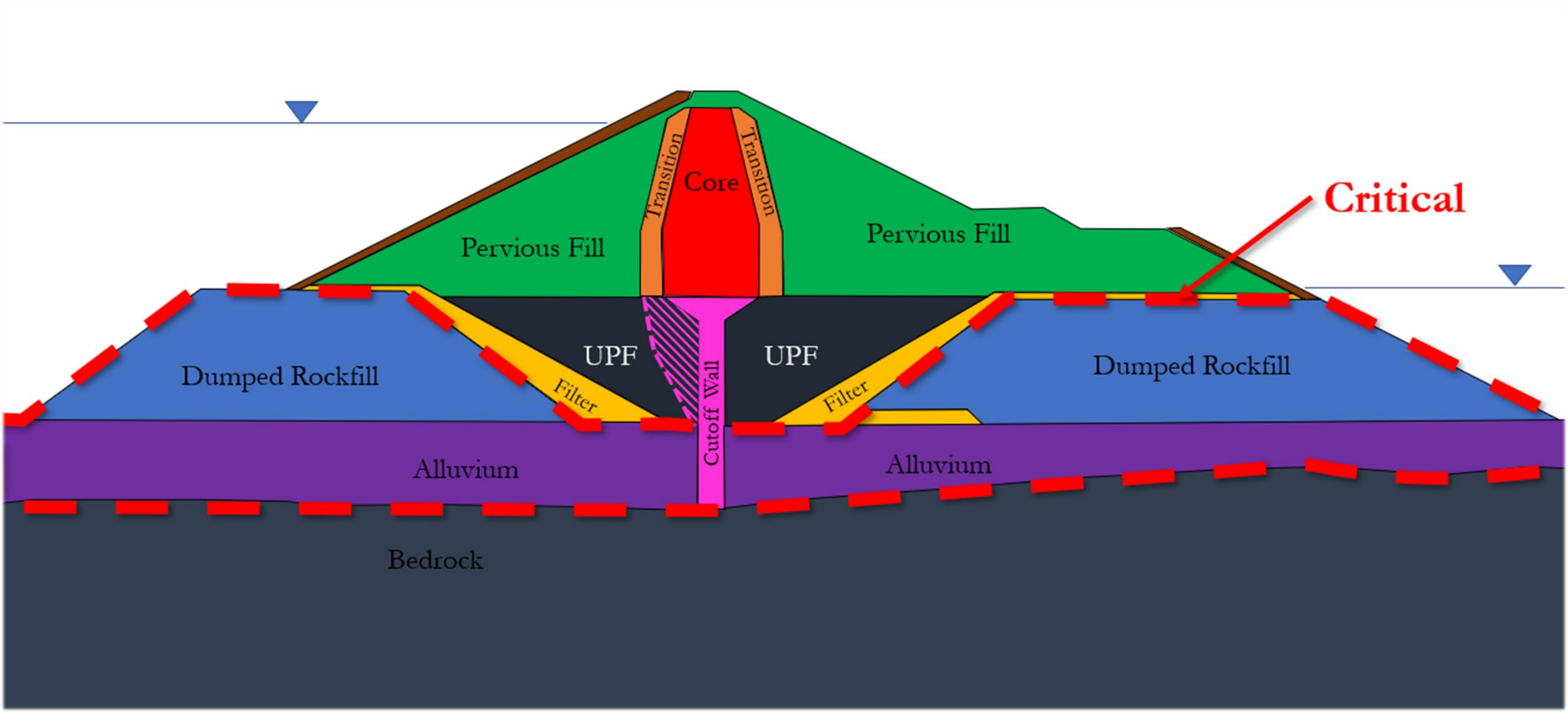



# RIVER EMBANKMENT SECTION

SCALE: 1"=50'

# RCS Seismic Stability

- 2012: Probabilistic seismic hazard analysis (PSHA)
- 2013 and 2014: Preliminary seismic stability analyses
  - Large earthquakes could result in liquefaction and strength loss in foundation materials, large crest displacements, overtopping, and failure (uncontrolled release of the reservoir)


Transition
Core
Transition
Critical
Pervious Fill
Pervious Fill
UPF
UPF
Dumped Rockfill
Dumped Rockfill
Filter
Filter
Cutoff Wall
Alluvium
Alluvium
Bedrock

# RCS Seismic Stability

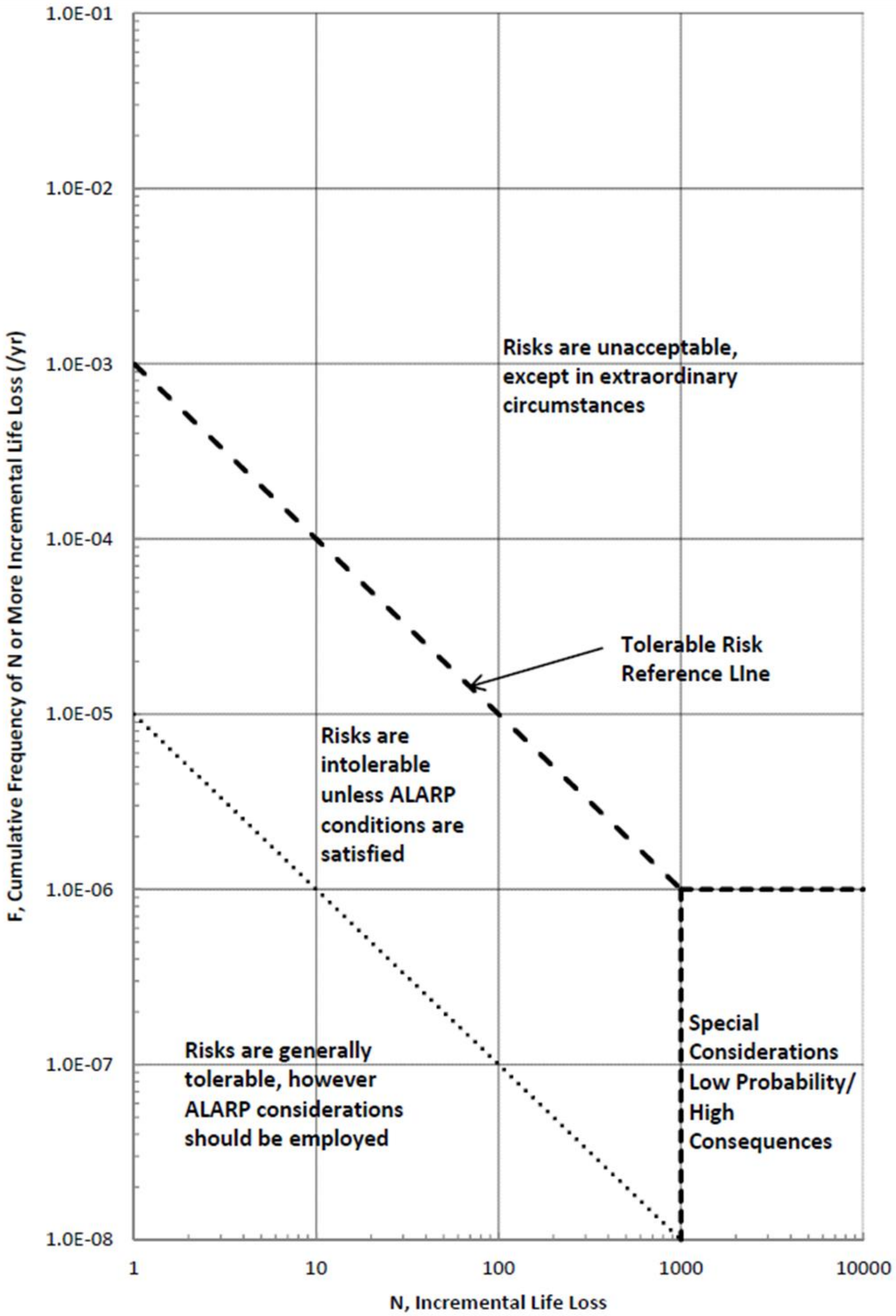
- 2015: Federal Energy Regulatory Commission (FERC) direction to convene Board of Consultants (BoC) to assess seismic stability of embankments
- Given complexity and uncertainty in analyzing embankment seismic stability and any mitigation, switched to risk-informed decision-making (RIDM) approach

# RIDM Approach

Wanapum Left Embankment Seismic Risk Assessment

# RIDM Approach

- Estimate the likelihood of life loss resulting from an earthquake-induced dam failure
- If the risk is unacceptable, select and develop mitigation specifically targeted and designed for risk-reduction



1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
F, Cumulative Frequency of N or More Incremental Life Loss (/yr)
1
10
100
1000
10000
N, Incremental Life Loss
Risks are unacceptable, except in extraordinary circumstances
Tolerable Risk Reference LIne
Risks are intolerable unless ALARP conditions are satisfied
Risks are generally tolerable, however ALARP considerations should be employed
Special Considerations Low Probability/ High Consequences

# RIDM Approach

- PSHA
  - Magnitude and frequency of earthquake loading, completed (updated) 2019
- Seismic Fragility Analysis
  - Likelihood of failure from hazard, completed March 2025
- Seismic Quantitative Risk Analysis (QRA)
  - Combines loss of life resulting from failure, failure likelihood, and hazard likelihood to obtain seismic risk; completed April 2025
- Dam Safety Case
  - Proposed approach for responding to risk, anticipated completion August 2025

# Fragility Analysis

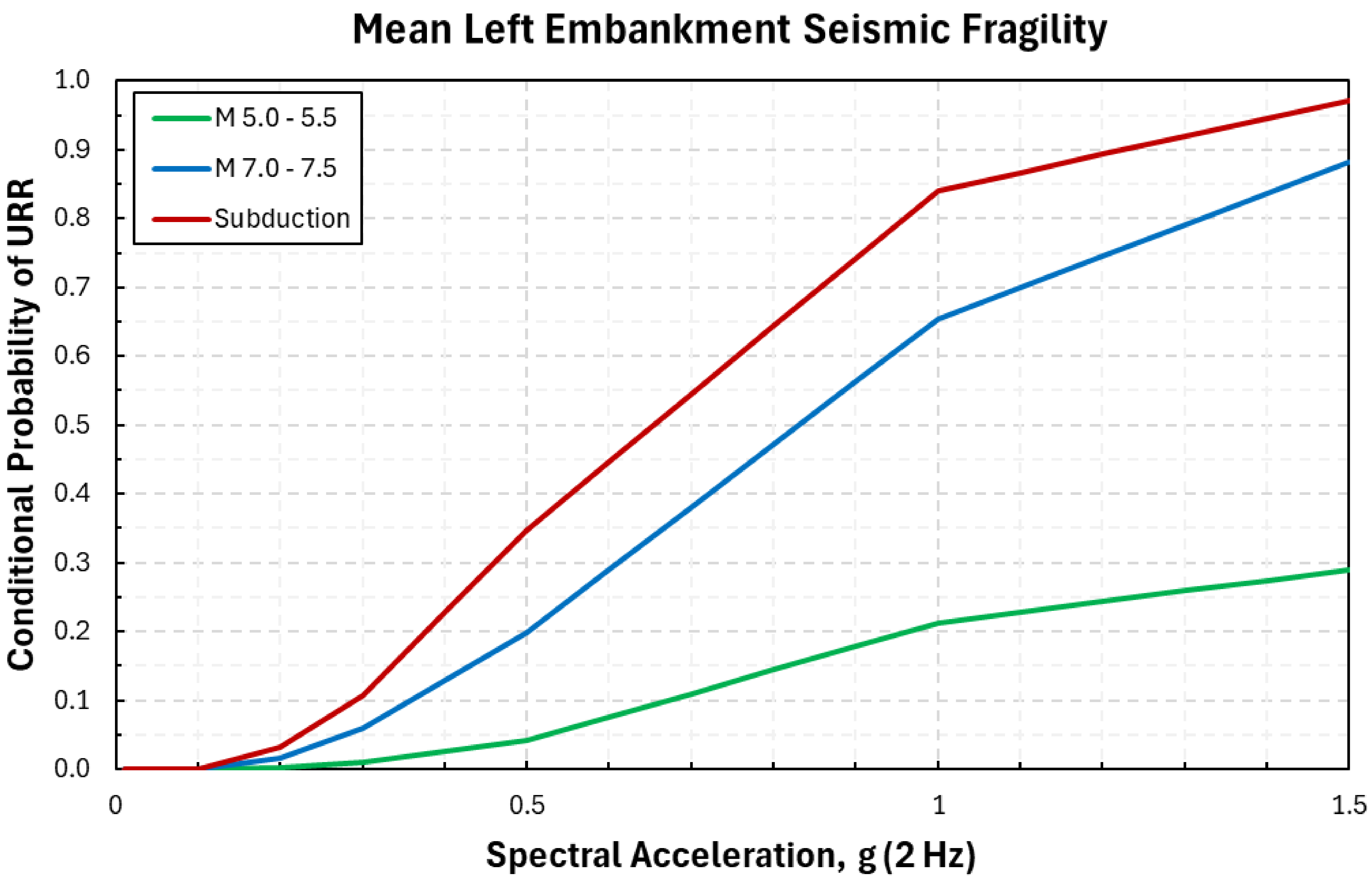
Wanapum Left Embankment Seismic Risk Assessment

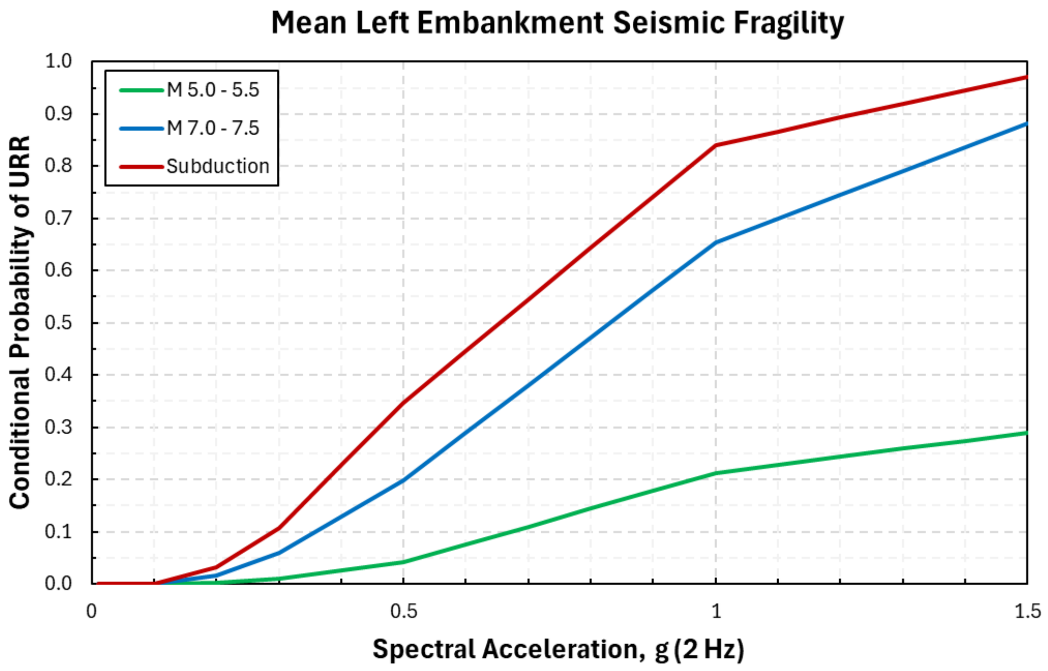
# Process

- Senior Seismic Hazard Analysis Committee (SSHAC)
  - Technical Integration (TI) Team – Performs Analysis
  - Participatory Peer Review Panel (PPRP) – Reviews Analysis
  - FERC – Provides Regulatory Oversight
- BoC members became part of the TI Team and PPRP

# Process

- Field Investigations
  - Drilling (BPT, sonic, SPT) and geophysical (shear wave velocity)
- Research
  - BPT/iBPT interpretation
  - Transverse cracking
- 2D Numerical Modeling
  - Nonlinear Dynamic Analysis (NDA) using FLAC
  - Approximately 26,000 production runs (maybe twice that total)
- Logic Tree
  - Conceptualize different potential inputs to model
  - Tens of millions of potential unique pathways

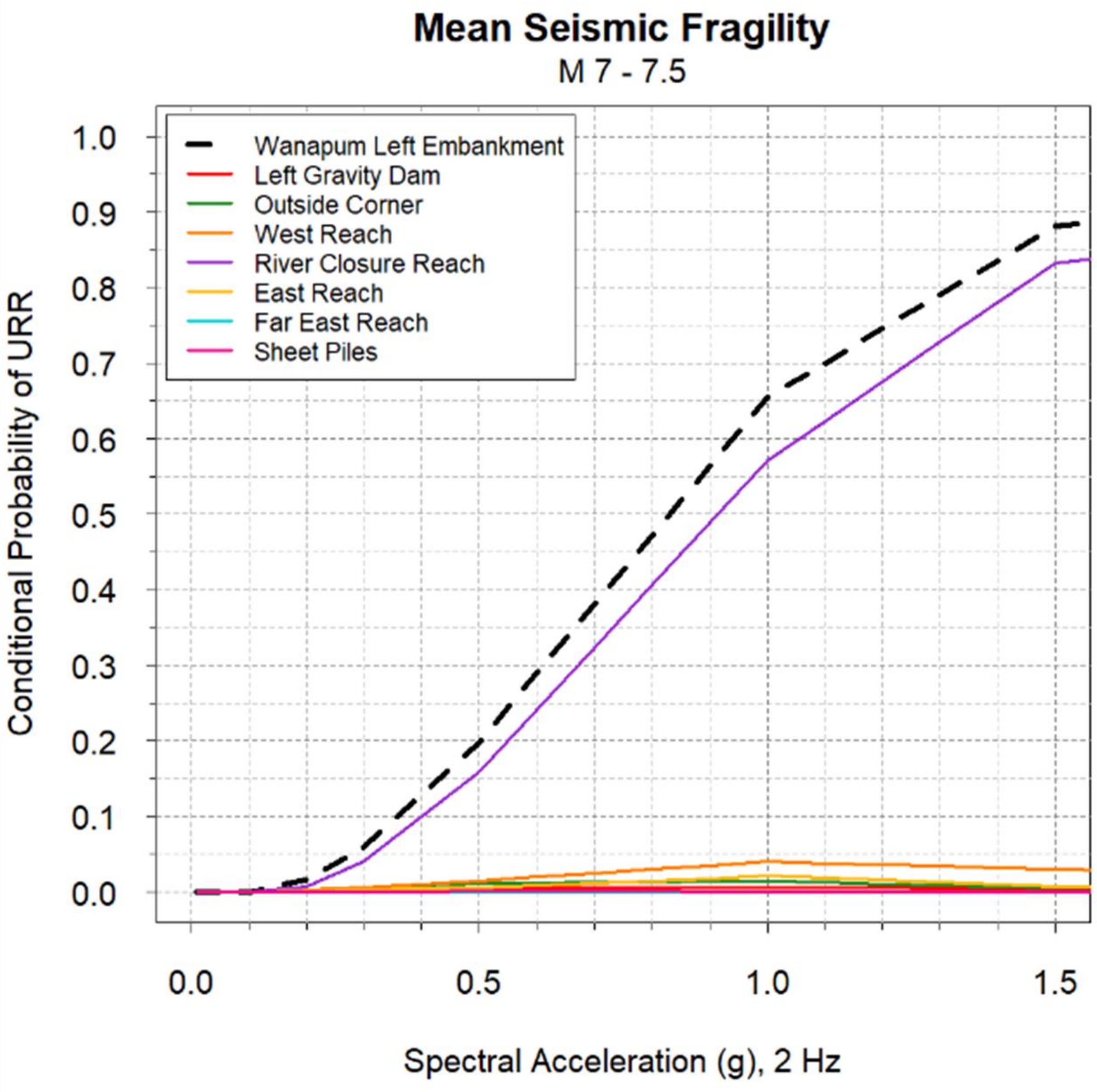

Mean Left Embankment Seismic Fragility
Conditional Probability of URR
Spectral Acceleration, g (2 Hz)
M 5.0 - 5.5
M 7.0 - 7.5
Subduction
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
0.5
1
1.5



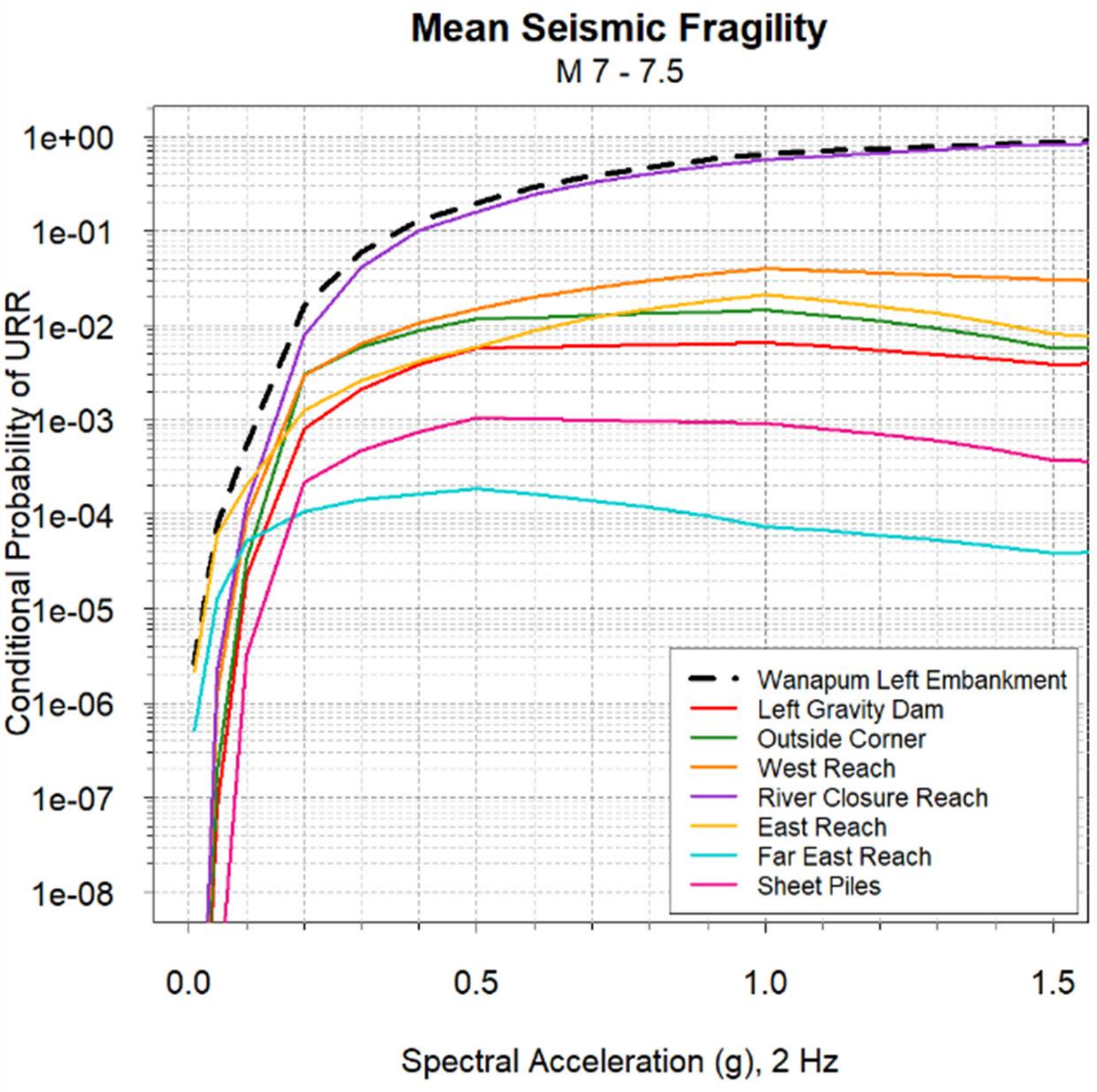

| Average Return Period (years) | Peak Ground Acceleration, PGA (g) | |
|---|---|---|
| | Crustal Earthquakes | Subduction Zone Earthquakes |
| 500 | ~ 0.084 | ~ 0.029 |
| 1,000 | ~ 0.13 | ~ 0.049 |
| 5,000 | ~ 0.32 | ~ 0.14 |
| 10,000 | ~ 0.47 | ~ 0.17 |
| 50,000 | ~ 0.96 | ~ 0.32 |
| 100,000 | ~ 1.3 | ~ 0.39 |

# Findings – RCS Dominates

- The reach that contributes the most to the total left embankment fragility is the River Closure Section (RCS).
- The contribution of other sections of the embankment to the total embankment fragility is much less (a factor of 3 to orders of magnitude), except at low ground motion levels (spectral accelerations less than 0.20g), where the overall fragility is low.



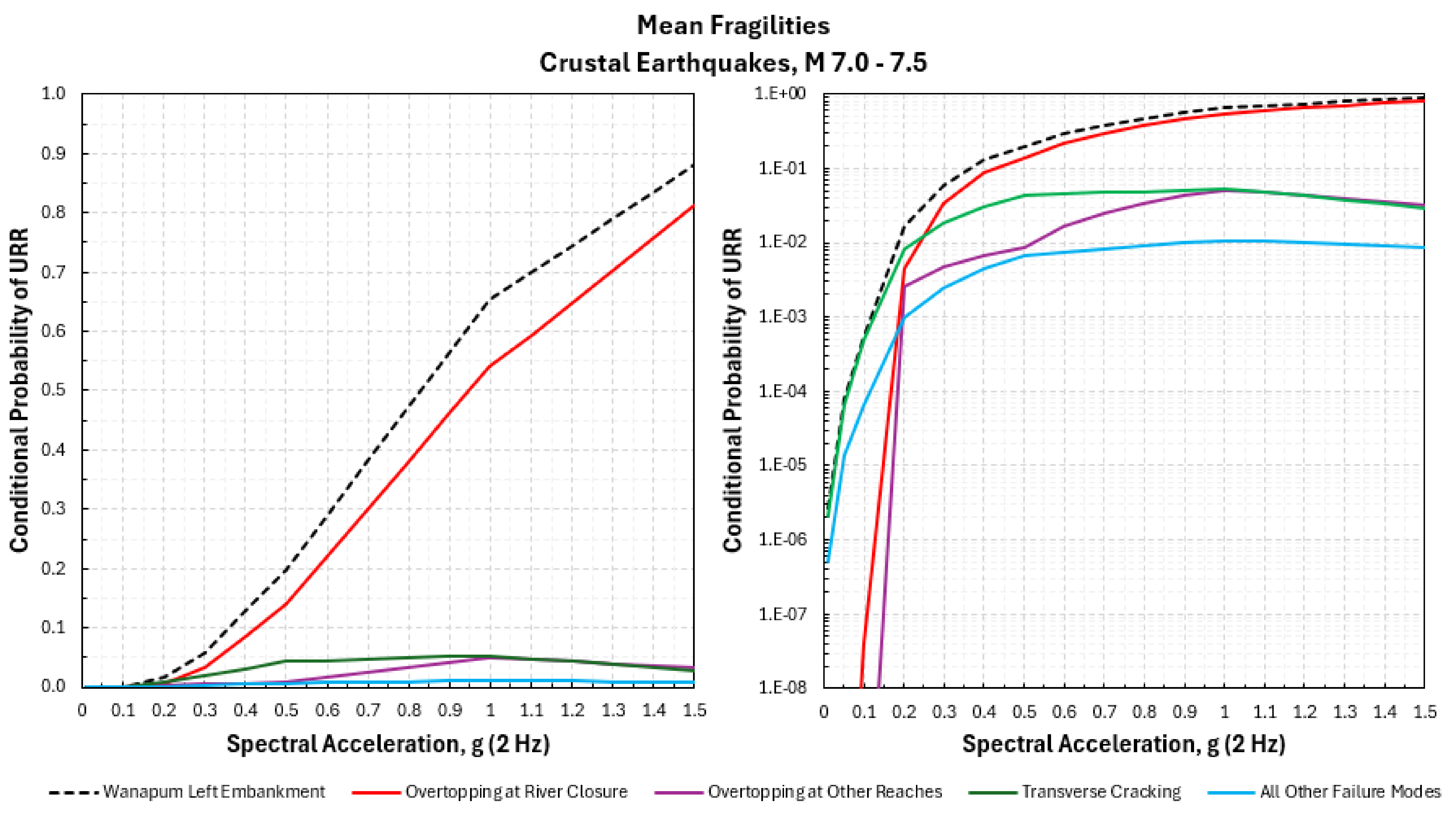
Mean Seismic Fragility
M 7 - 7.5
Wanapum Left Embankment
Left Gravity Dam
Outside Corner
West Reach
River Closure Reach
East Reach
Far East Reach
Sheet Piles
Conditional Probability of URR
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.0
0.5
1.0
1.5
Spectral Acceleration (g), 2 Hz

Mean Seismic Fragility
M 7 - 7.5
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
1e-07
1e-08
Conditional Probability of URR
Wanapum Left Embankment
Left Gravity Dam
Outside Corner
West Reach
River Closure Reach
East Reach
Far East Reach
Sheet Piles
0.0
0.5
1.0
1.5
Spectral Acceleration (g), 2 Hz

# Findings – Overtopping Dominates

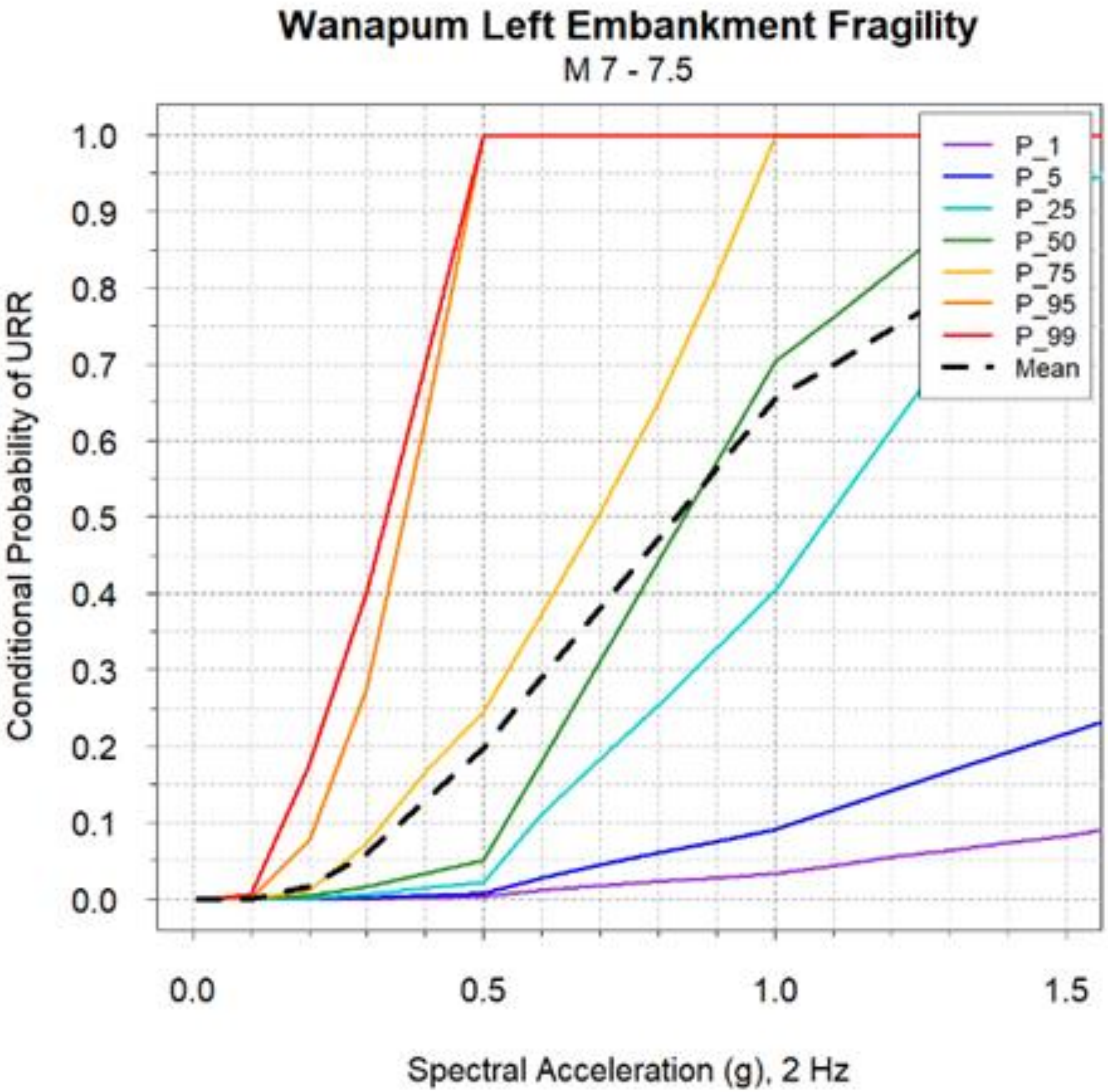
- Within the RCS, the potential for large displacements leading directly to embankment overtopping is the dominant failure mode. This is true for both crustal and subduction earthquakes. For this failure mode, under certain characterizations, the embankment can exhibit brittle behavior in which the potential for failure rises rapidly over a relatively narrow range of ground motions.



Mean Fragilities
Crustal Earthquakes, M 7.0 - 7.5
Conditional Probability of URR
Spectral Acceleration, g (2 Hz)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
Wanapum Left Embankment
Overtopping at River Closure
Overtopping at Other Reaches
Transverse Cracking
All Other Failure Modes

# Findings – Large Uncertainty

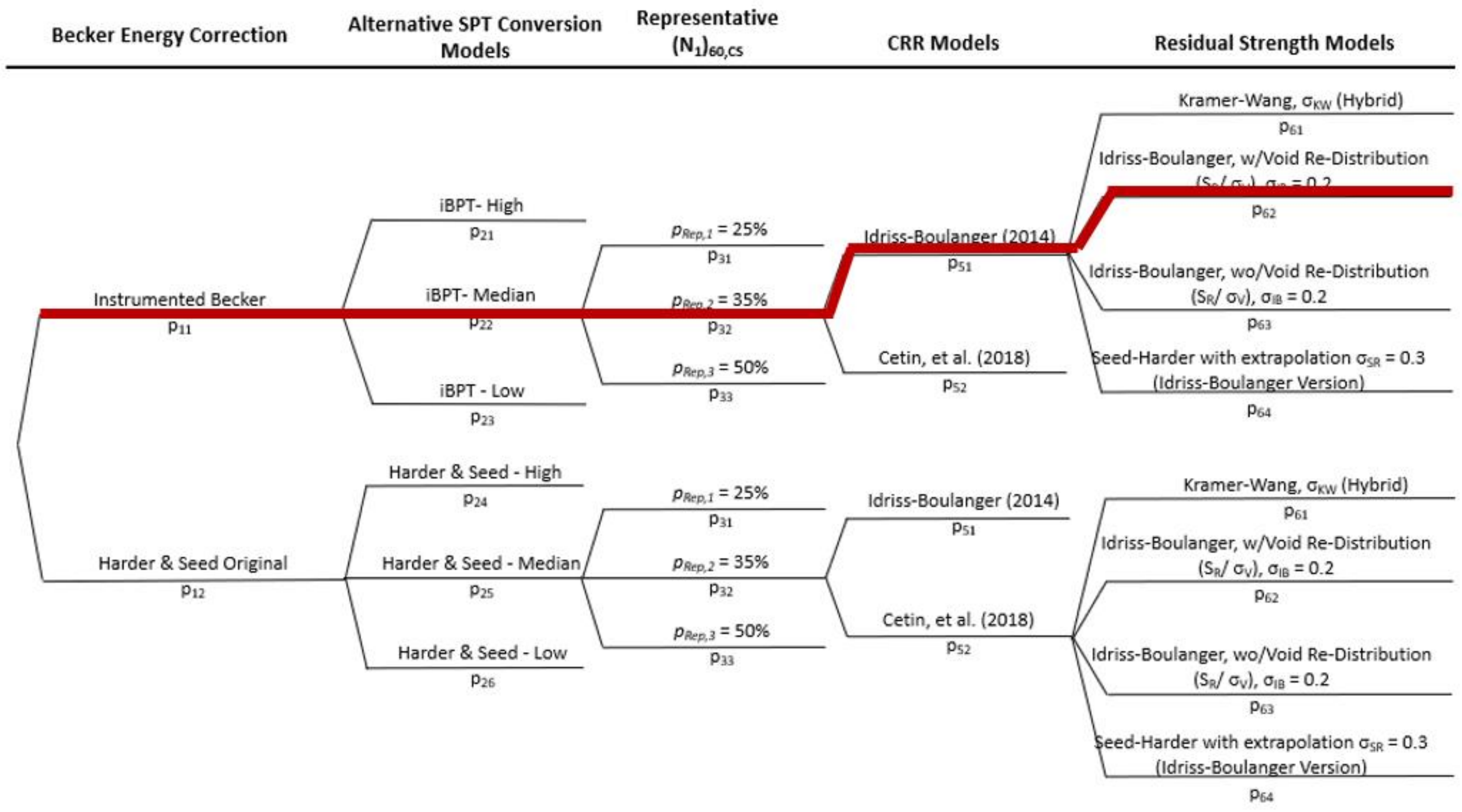
- There is considerable uncertainty in the estimate of the total left embankment seismic fragility for all magnitude earthquakes.
- While the uncertainty in the seismic fragility is large, sensitivity calculations indicate the estimate of the mean fragility is stable (not sensitive to large changes in key parameters).



Wanapum Left Embankment Fragility
M 7 - 7.5
P_1
P_5
P_25
P_50
P_75
P_95
P_99
Mean
Conditional Probability of URR
Spectral Acceleration (g), 2 Hz
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.0
0.5
1.0
1.5

# Findings – Many Credible Characterizations

- The large uncertainty is due to a number of factors. Foremost among these is the wide range in credible characterizations of the embankment soil properties which reflects the industry's current state-of-knowledge — principally, the estimates of the soil's strength, cyclic resistance, and residual strength after liquefaction occurs.



Becker Energy Correction
Alternative SPT Conversion Models
Representative $(N_1)_{60,cs}$
CRR Models
Residual Strength Models
Instrumented Becker
$p_{11}$
iBPT- High
$p_{21}$
iBPT- Median
$p_{22}$
iBPT - Low
$p_{23}$
$p_{Rep,1}$ = 25%
$p_{31}$
$p_{Rep,2}$ = 35%
$p_{32}$
$p_{Rep,3}$ = 50%
$p_{33}$
Idriss-Boulanger (2014)
$p_{51}$
Cetin, et al. (2018)
$p_{52}$
Kramer-Wang, $\sigma_{KW}$ (Hybrid)
$p_{61}$
Idriss-Boulanger, w/Void Re-Distribution
$p_{62}$
Idriss-Boulanger, wo/Void Re-Distribution
$(S_R/\sigma_V)$, $\sigma_{IB}$ = 0.2
$p_{63}$
Seed-Harder with extrapolation $\sigma_{SR}$ = 0.3
(Idriss-Boulanger Version)
$p_{64}$
Harder & Seed Original
$p_{12}$
Harder & Seed - High
$p_{24}$
Harder & Seed - Median
$p_{25}$
Harder & Seed - Low
$p_{26}$
$p_{Rep,1}$ = 25%
$p_{31}$
$p_{Rep,2}$ = 35%
$p_{32}$
$p_{Rep,3}$ = 50%
$p_{33}$
Idriss-Boulanger (2014)
$p_{51}$
Cetin, et al. (2018)
$p_{52}$
Kramer-Wang, $\sigma_{KW}$ (Hybrid)
$p_{61}$
Idriss-Boulanger, w/Void Re-Distribution
$(S_R/\sigma_V)$, $\sigma_{IB}$ = 0.2
$p_{62}$
Idriss-Boulanger, wo/Void Re-Distribution
$(S_R/\sigma_V)$, $\sigma_{IB}$ = 0.2
$p_{63}$
Seed-Harder with extrapolation $\sigma_{SR}$ = 0.3
(Idriss-Boulanger Version)
$p_{64}$

# Risk Analysis

Wanapum Left Embankment Seismic Risk Assessment

# Questions?

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