QuestStructures

Quantitative Risk Assessment for Design and Evaluation of Concrete Dams

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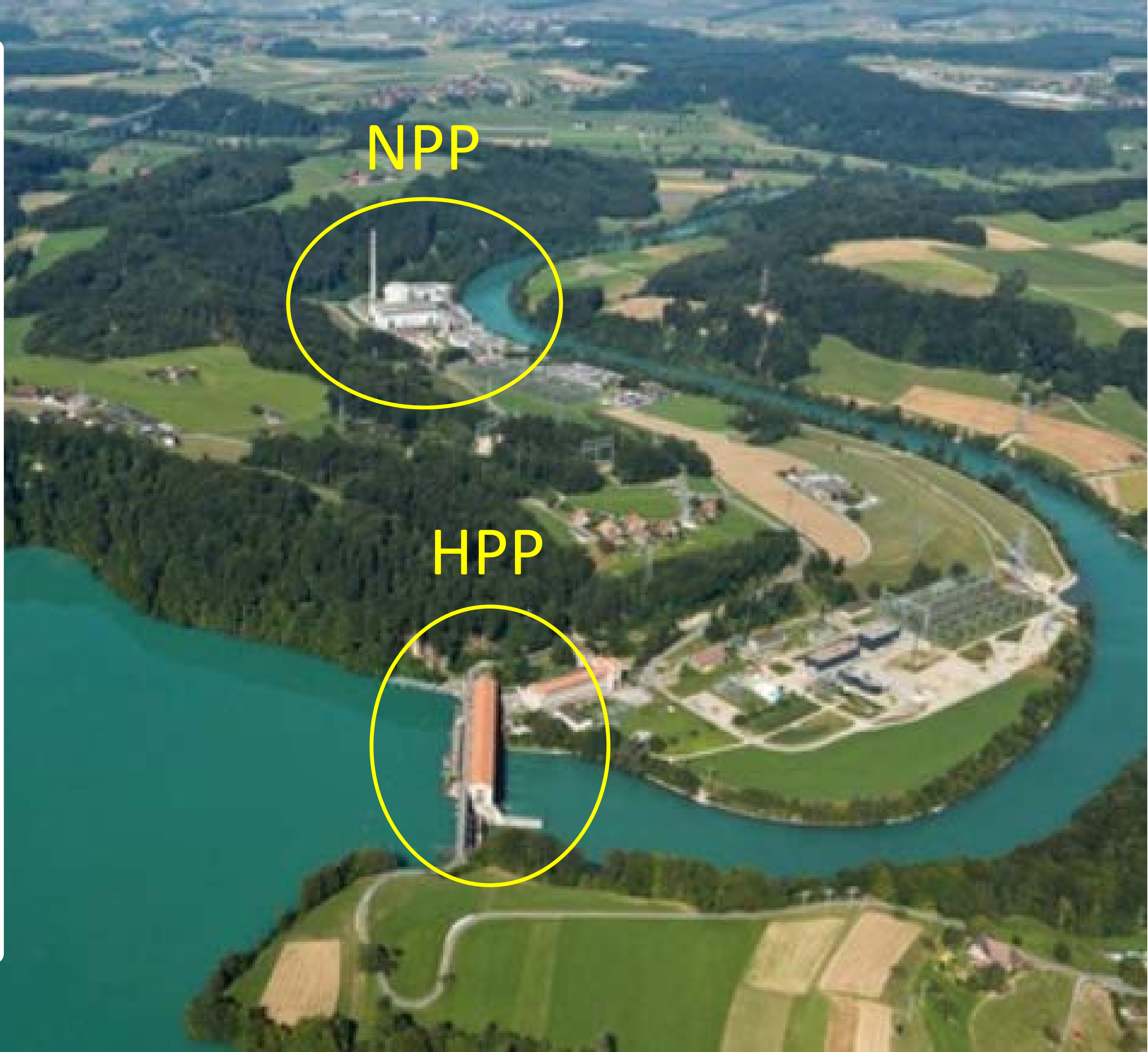
Seismic Risk Assessment of Dams

- Identify and estimate probability of loads (PSHA)
- Identify and estimate probability of failure, given the loads
- Identify consequences (loss of life, economic, or environmental)
- Integrate the three

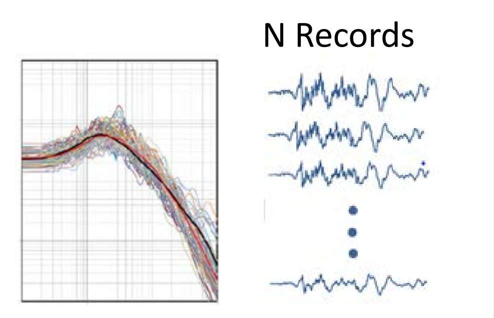
Mühleberg NPP and HPP

- An initial SPRA of NPP in 2006 with PEGASOS seismic input indicated dam is one of the dominant contributors to seismic risk
- This prompted estimation of seismic fragility of the existing dam for a thorough SPRA
- Later, the 2011 Fukushima event prompted additional studies including strengthening of the dam using risk-based design



Seismic Fragility Methodology

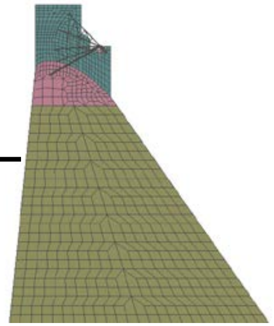
Nonlinear Analyses with Latin Hypercube Simulation (LHS)



Seismic Input

- Define failure modes
- Select simulation method
- Select number of simulations, N

Define Failure & Approach



Structure

- Select Variables significant to seismic response
- Define PDF for each variable
- Assign N equal-probability values to each variable

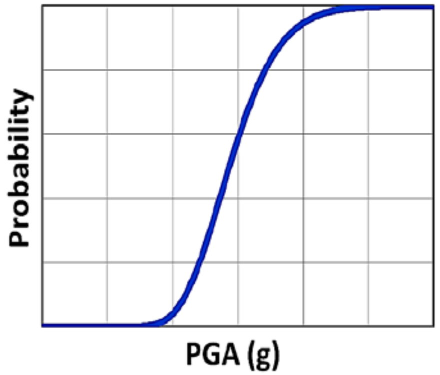
Variables & Uncertainty

- Select one value randomly for each variable
- Select one TH randomly
- Repeat random selection to define N trials

Define Trials

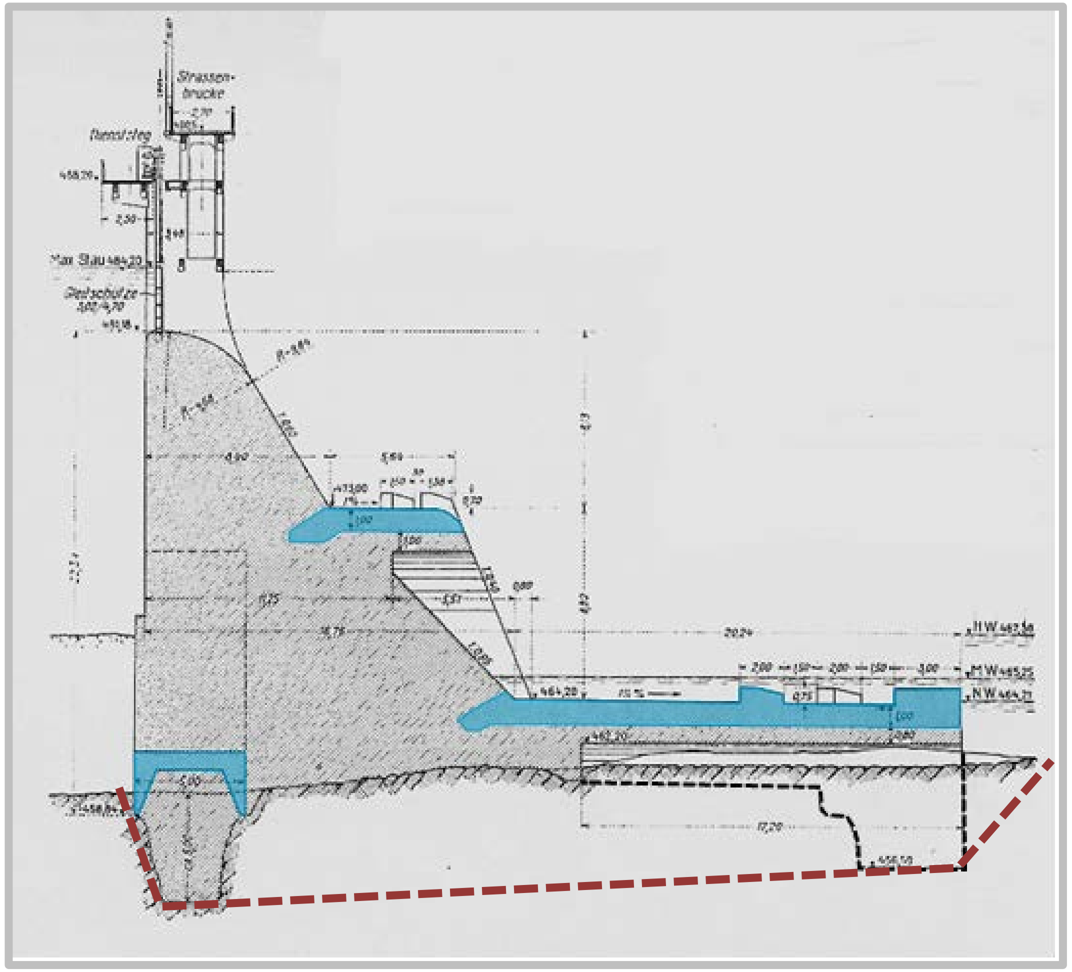
- Analyze N trials at 5 or more GMLs
- Determine PF at each GML
- Least square fit the results to obtain fragility and uncertainty

NL Analyses / PF

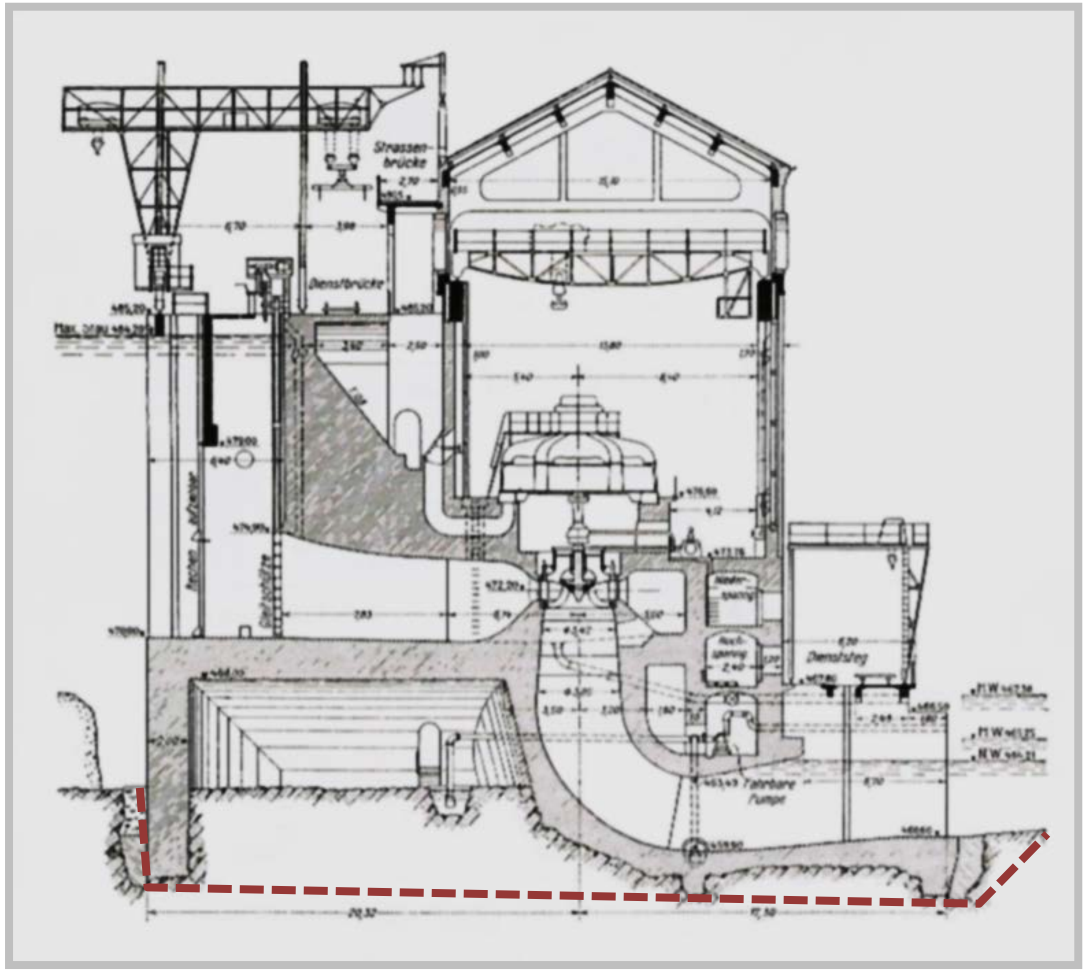


Dam Sections and Potential Failure Mode

Weir Section

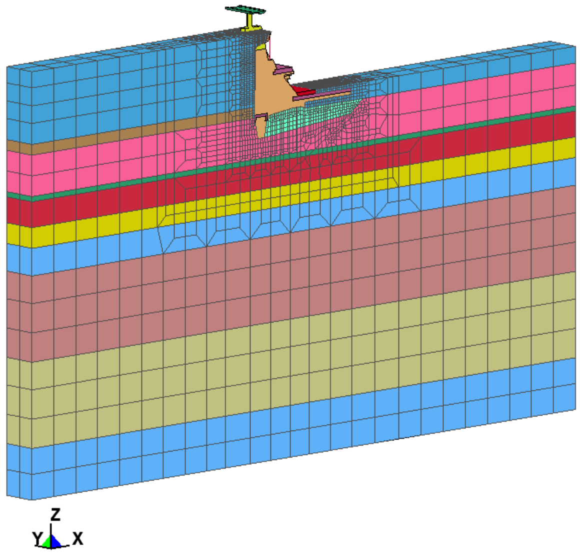


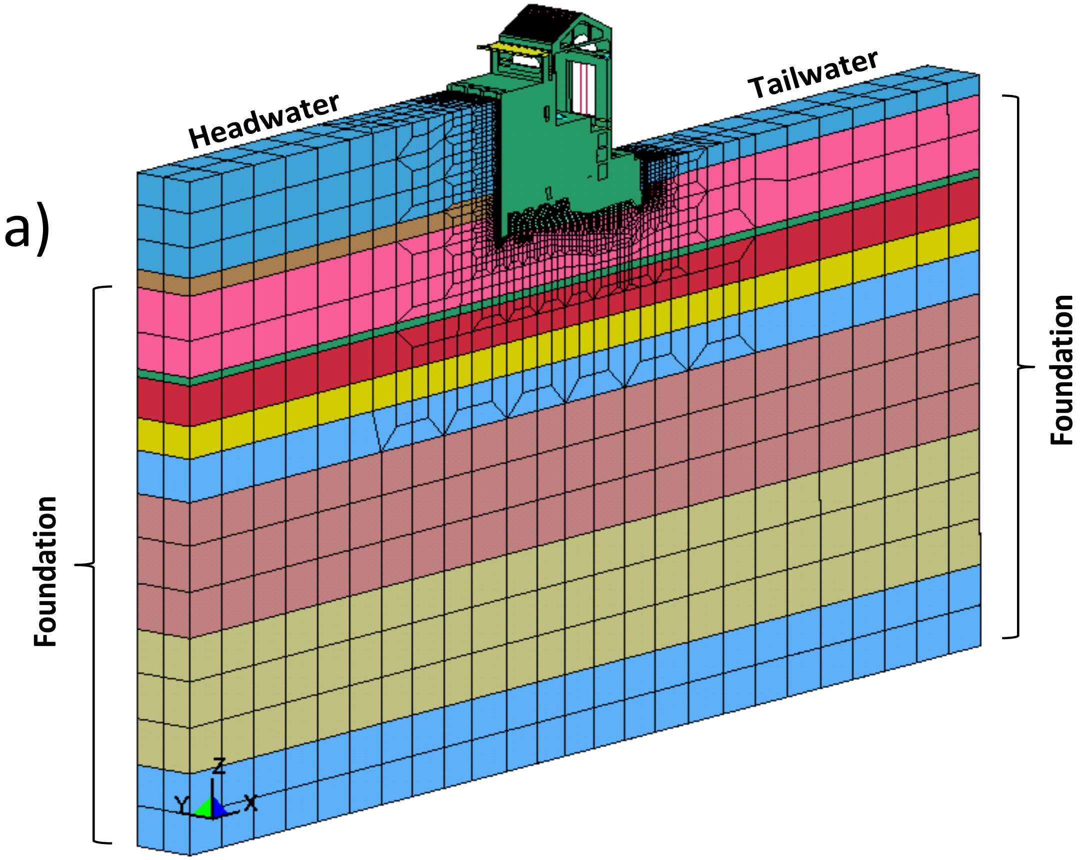
Turbine Building Section



Nonlinear Models of Existing Dam

- Compressible water
- Foundation mass and damping
- Transmitting B.C's
- Traction seismic input at bottom and sides
- Nonlinear slip surface (tie-break w/failure criteria)
- Nonlinear Turbine Building columns



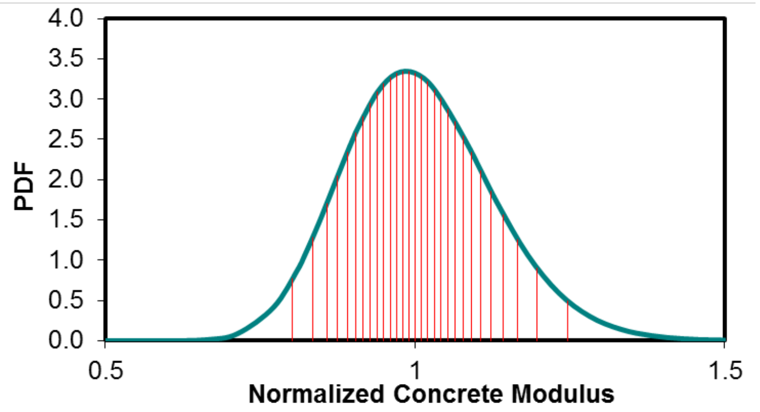


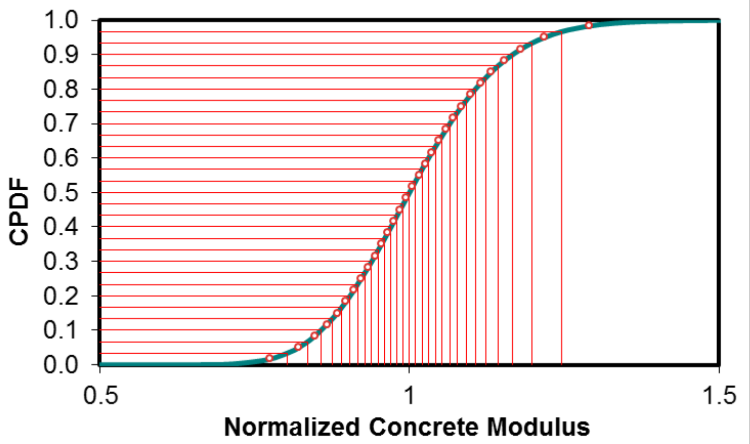
Input Variables – LHS Sampling

- EQ ground motion – 30 THs
  - 30 THs to randomly select from
  - DF_H=0.18, DF_V=0.25 for variability about geomean
- Concrete modulus (35,460 MPa, β =0.30)
- Concrete damping (5% , β =0.35)
- Rock modulus (3,000-8,200 MPa, β =0.25)
- Base sliding cohesion (480 kPa, β =0.25)
- Base sliding friction (23°, β =0.15)
- Rock wedge cohesion (650 kPa, β =0.20)
- Rock wedge friction (17°, β =0.25)

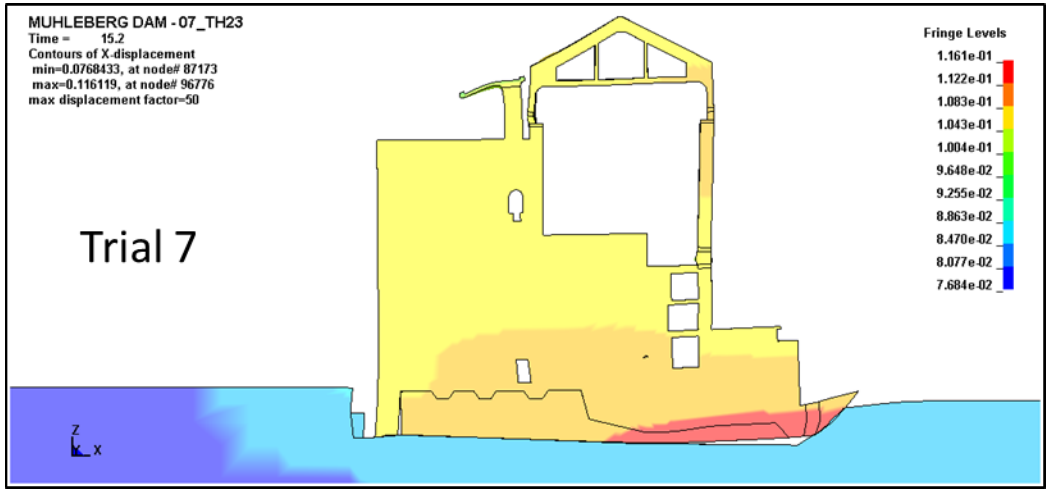
Composite runs: 30 trials at 8 GMLs for 240 runs
Randomness runs: 30 trials at 5 GMLs for 150 runs

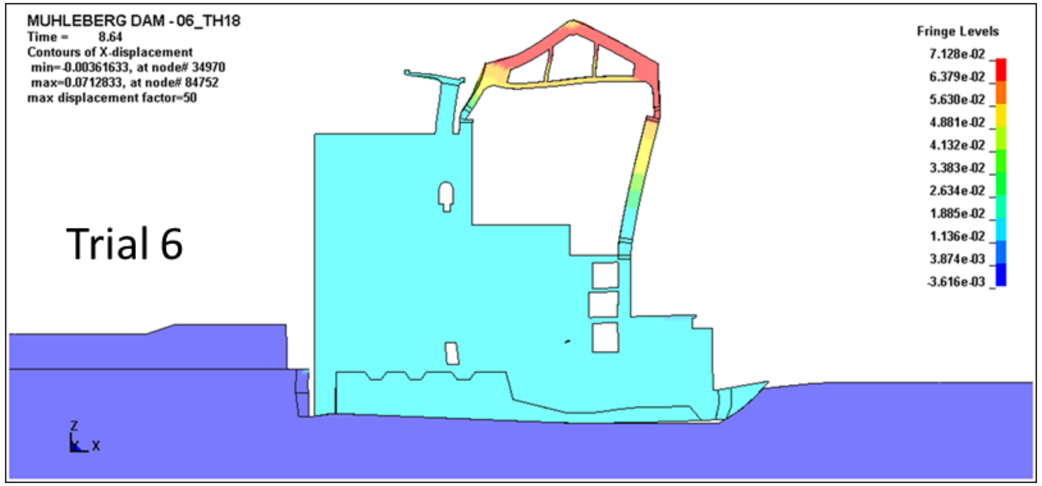
LOGNORMAL

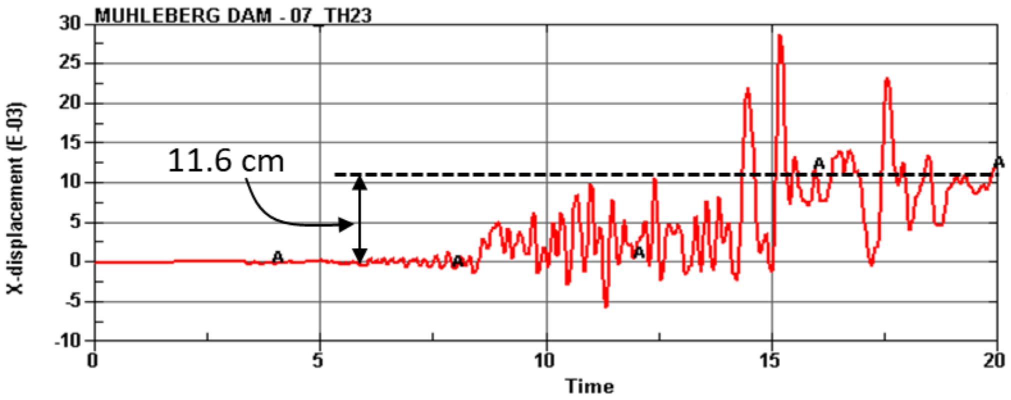


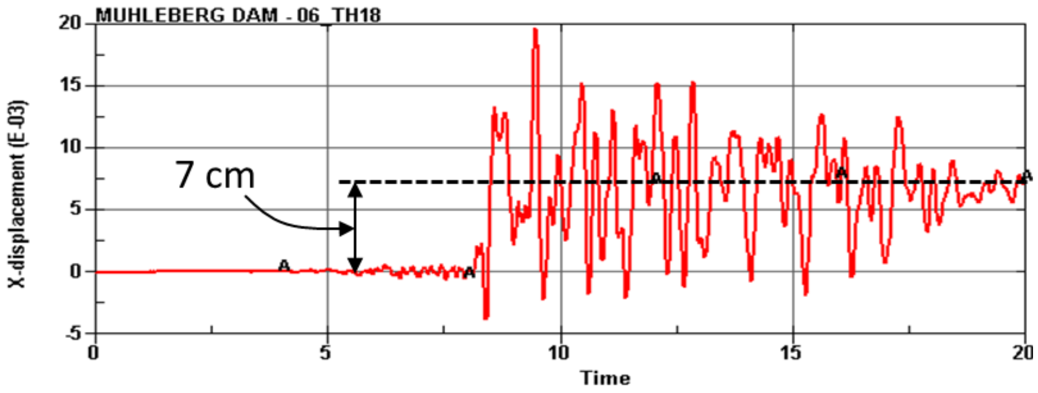


Sliding Failure at 0.85g



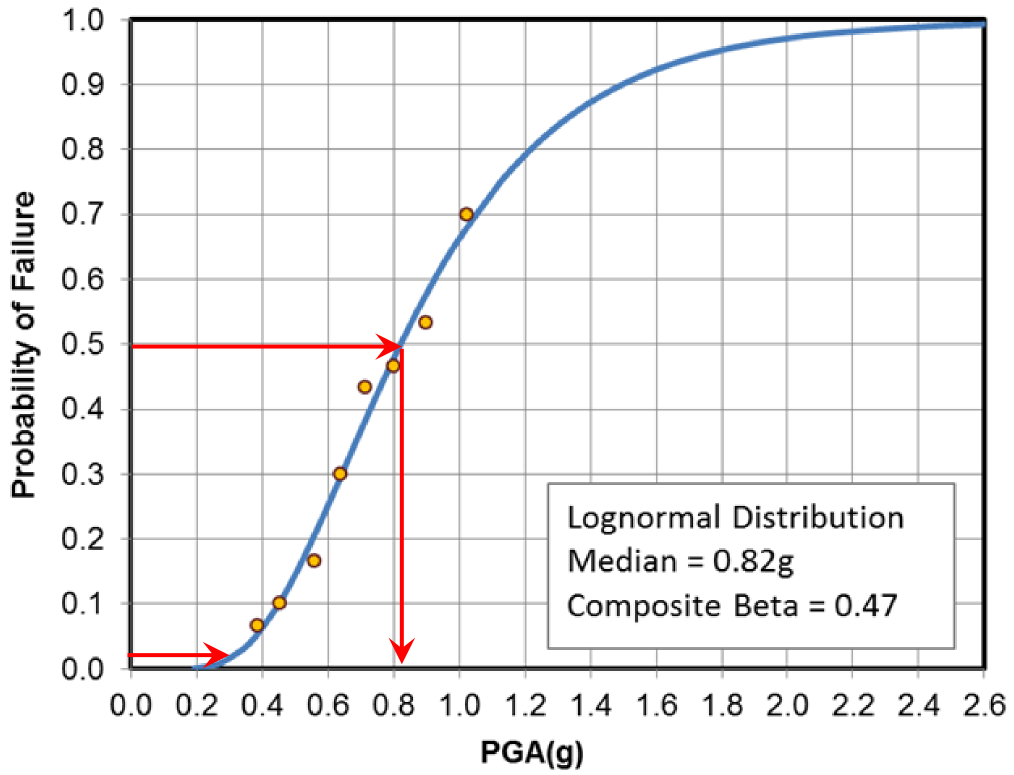






Seismic Fragility of Existing Dam

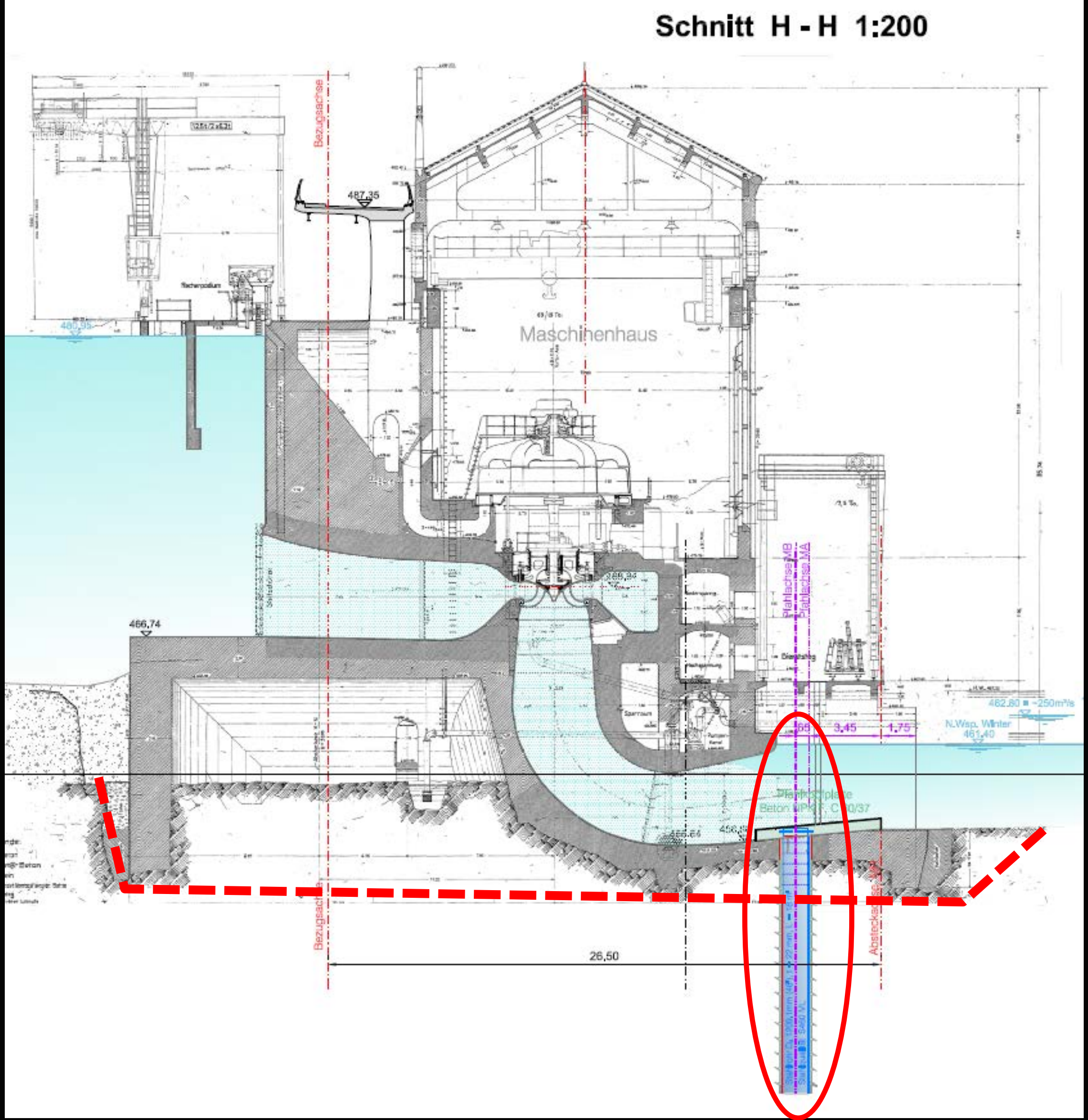
- **Composite Fragility** – 240 nonlinear runs on HPC Cloud Services
- **Randomness Fragility** – 150 nonlinear runs on HPC Cloud Services

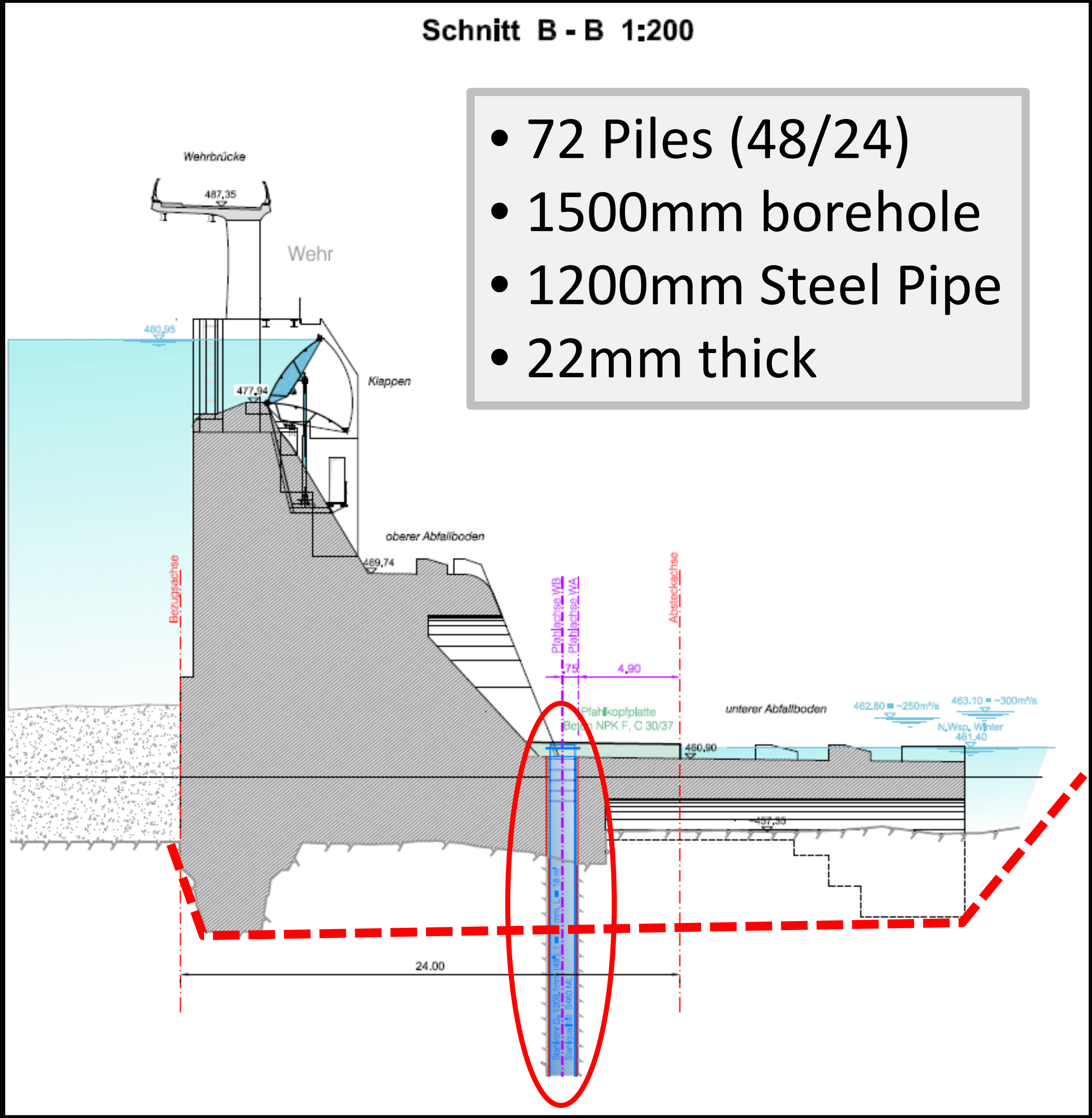


A_m = 0.82g	Median capacity in terms of PGA
β_c = 0.47	Log standard deviation of composite variability
β_r = 0.13	Log standard deviation of randomness
β_u = 0.45	Log standard deviation of uncertainty
HCLPF = 0.3g	High confidence of low probability of failure

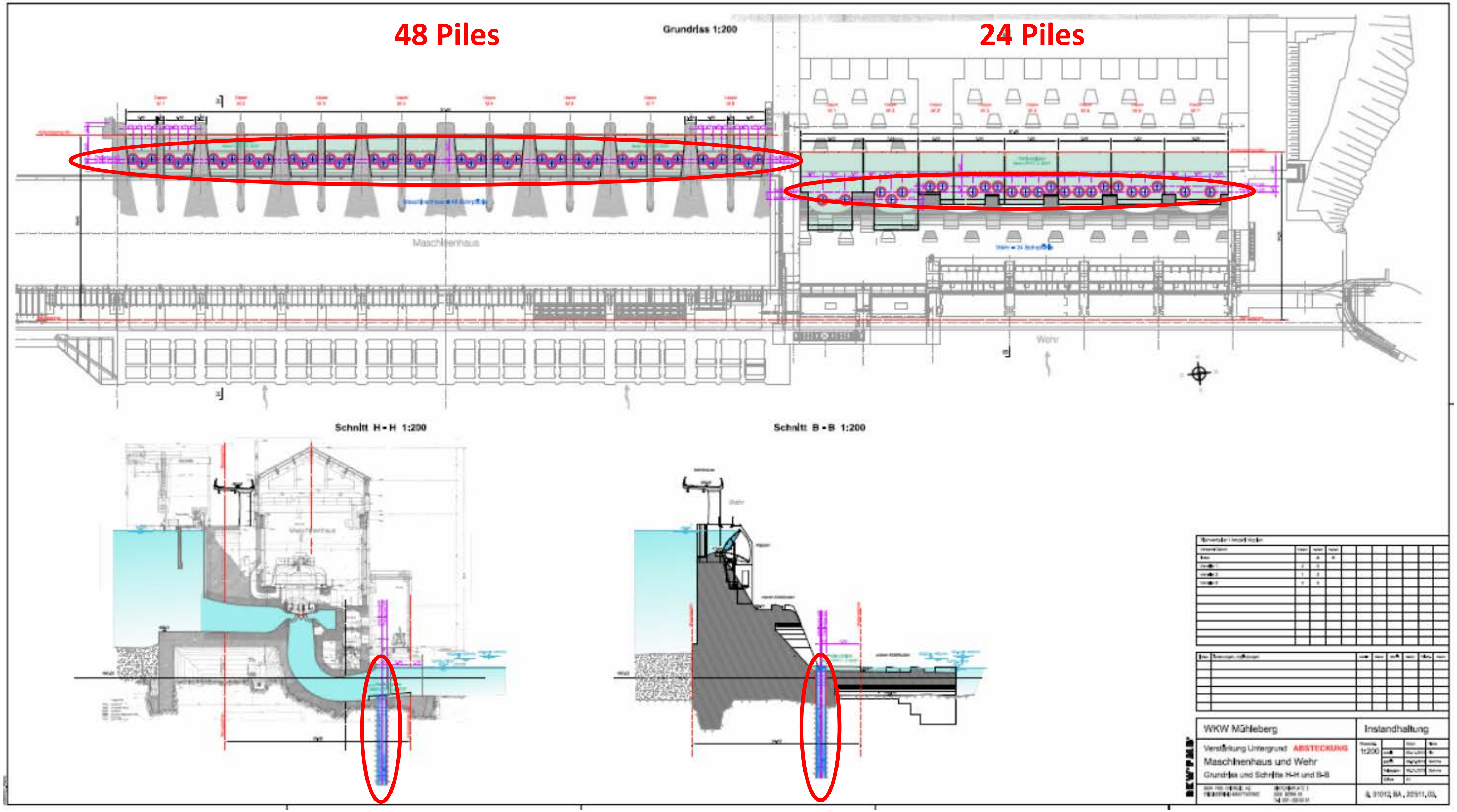
$$\beta_u = \sqrt{\beta_c^2 - \beta_r^2}$$

Strengthened Dam



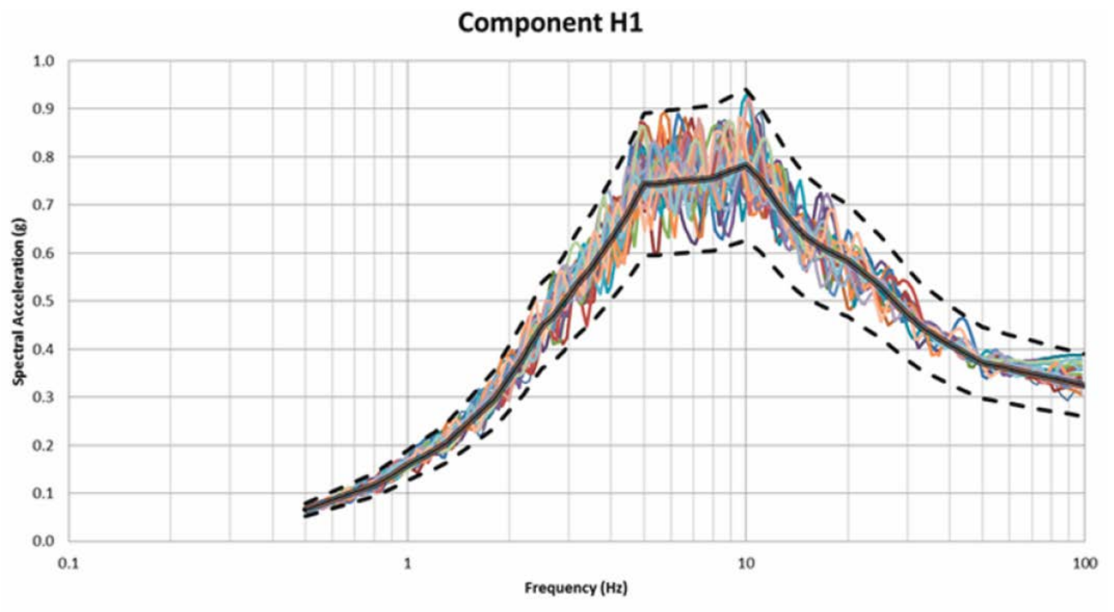


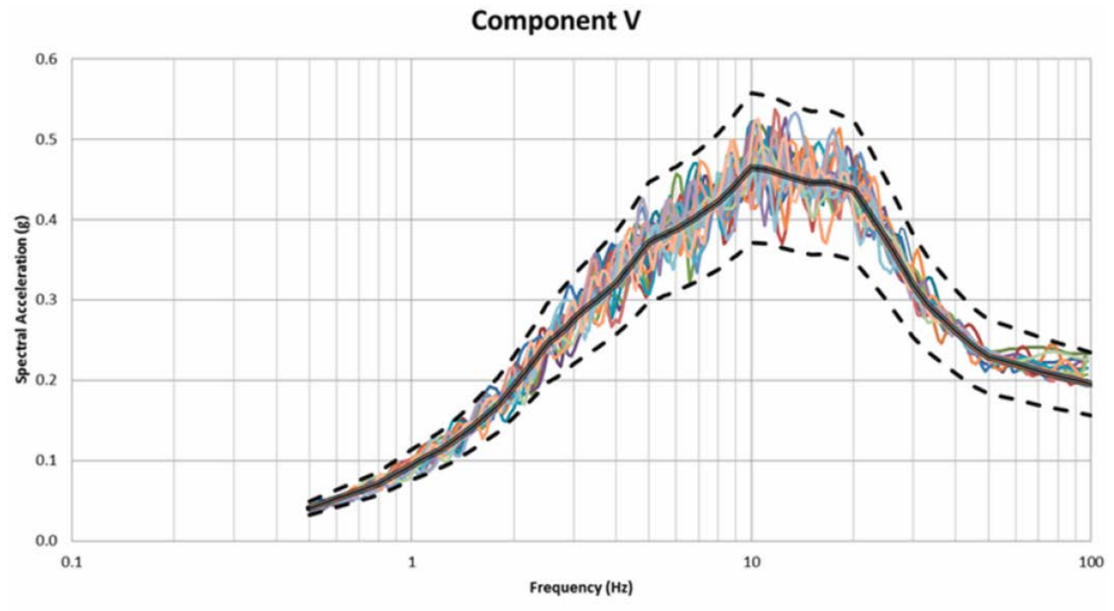
- 72 Piles (48/24)
- 1500mm borehole
- 1200mm Steel Pipe
- 22mm thick


48 Piles
24 Piles
Grundriss 1:200
Maschinenhaus
Wehr
Schnitt H-H 1:200
Schnitt B-B 1:200
WKW Mühleberg
Instandhaltung
Verstärkung Untergrund ABSTECKUNG
Maschinenhaus und Wehr
Grundriss und Schnitte H-H und B-B
1:200

Final Ground Motion

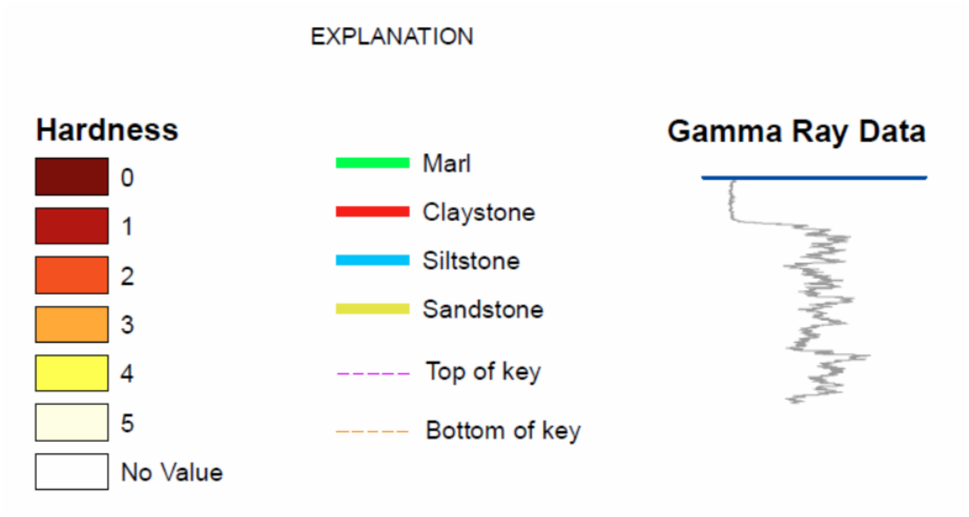
- UHS corrected for kappa
- Acceleration records selected from M_w5-7 at 25 km
- Acceleration records modified following NUREG/CR-6728 Guidelines
- Components checked for statistical independency
- Scaled by “directional factors” to account for variability about geomean (DF_H= 0.18, DF_V= 0.25)

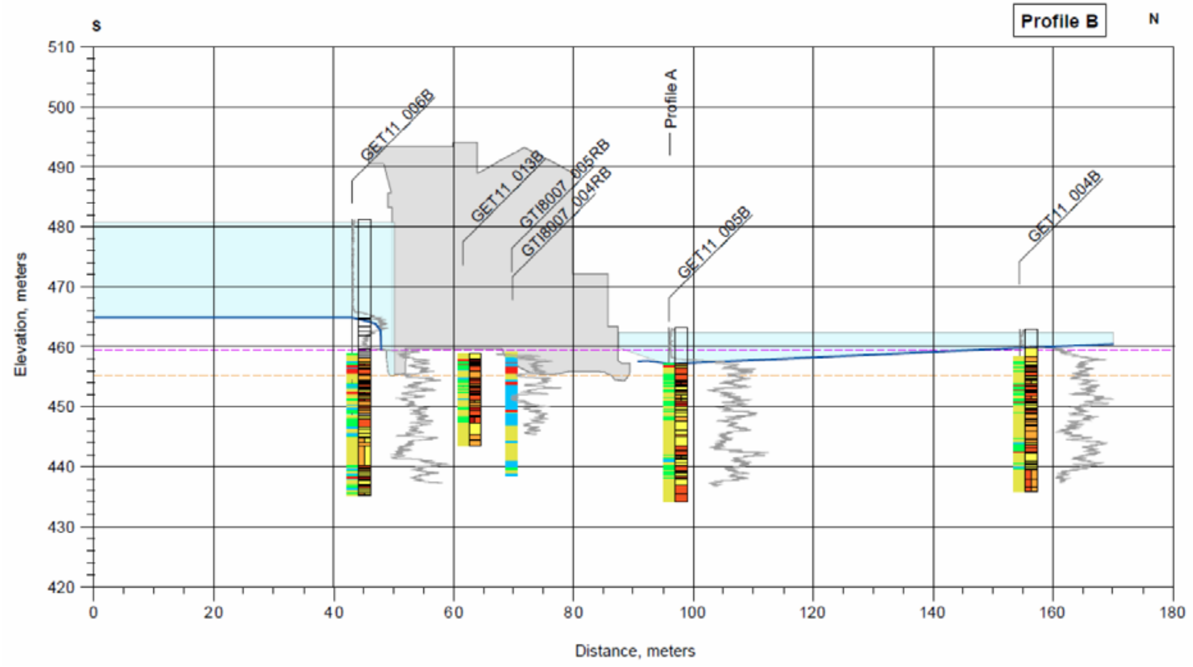


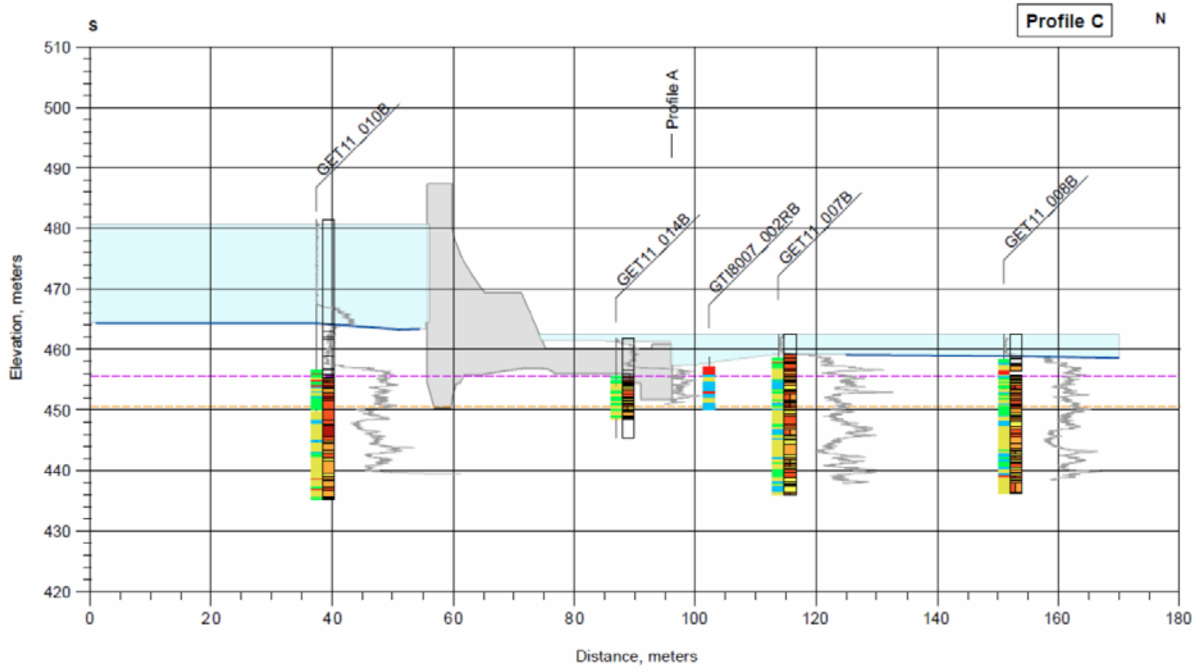


Foundation Rock

- Sections Showing foundation rock types beneath dam
- Shear strength parameters and their variabilities measured
- Slip surface confirmed



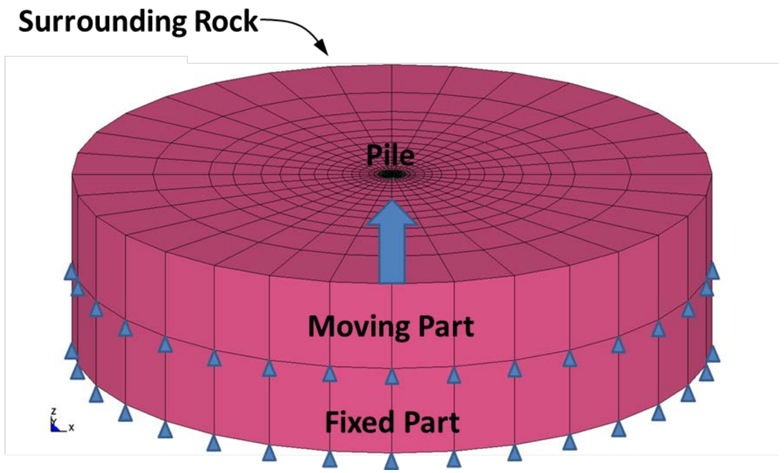


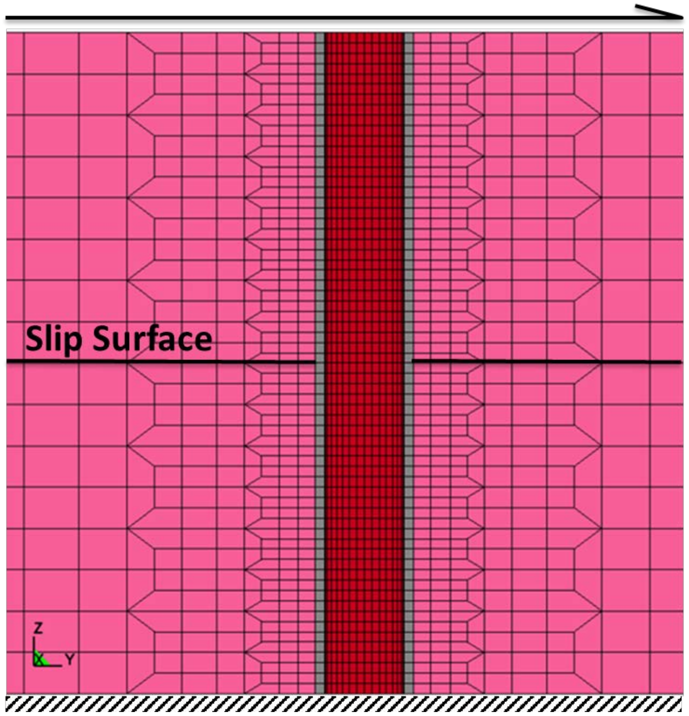


Concrete-filled Steel Pipe Pile

Pushover analysis to obtain Shear Capacity

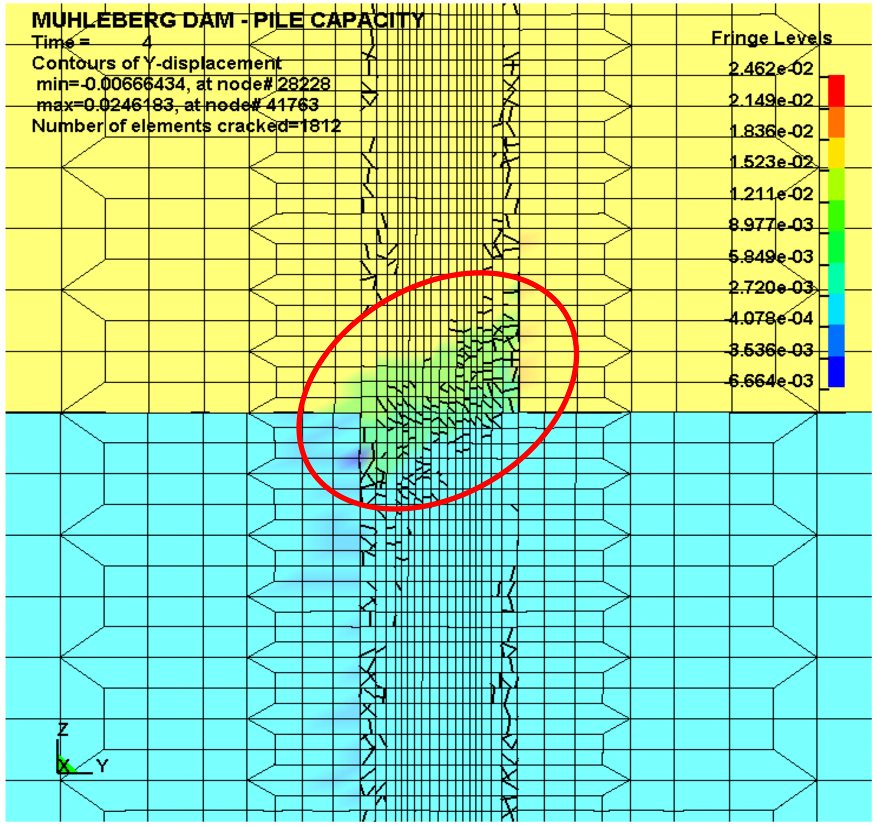
- Rock: Moving and fixed parts
- Pile: 1200-mm-diameter steel pipe
- Steel pipe: Plastic kinematic shell elements
- Concrete: Winfrith nonlinear concrete
- Contacts: Between pipe, concrete, and rock
- Parameters controlling shear capacity
  - Concrete compressive strength, f'_c
  - Concrete tensile strength, f'_t
  - Steel yield strength, f_y
  - Steel rupture strength, ε_u



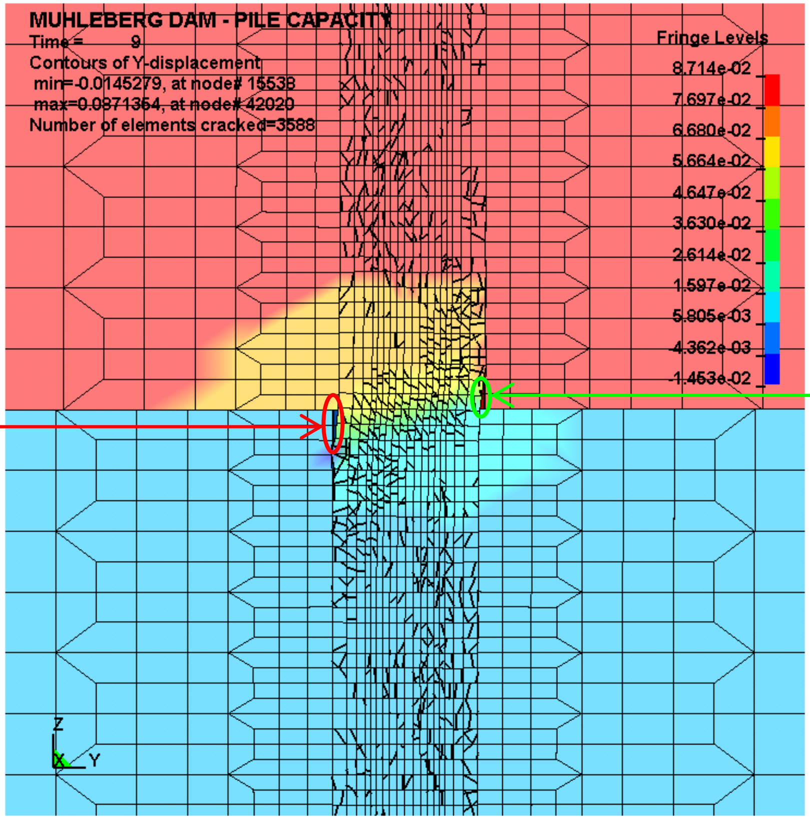


Pile Response Before and at Failure

Before Failure at 2.5 cm



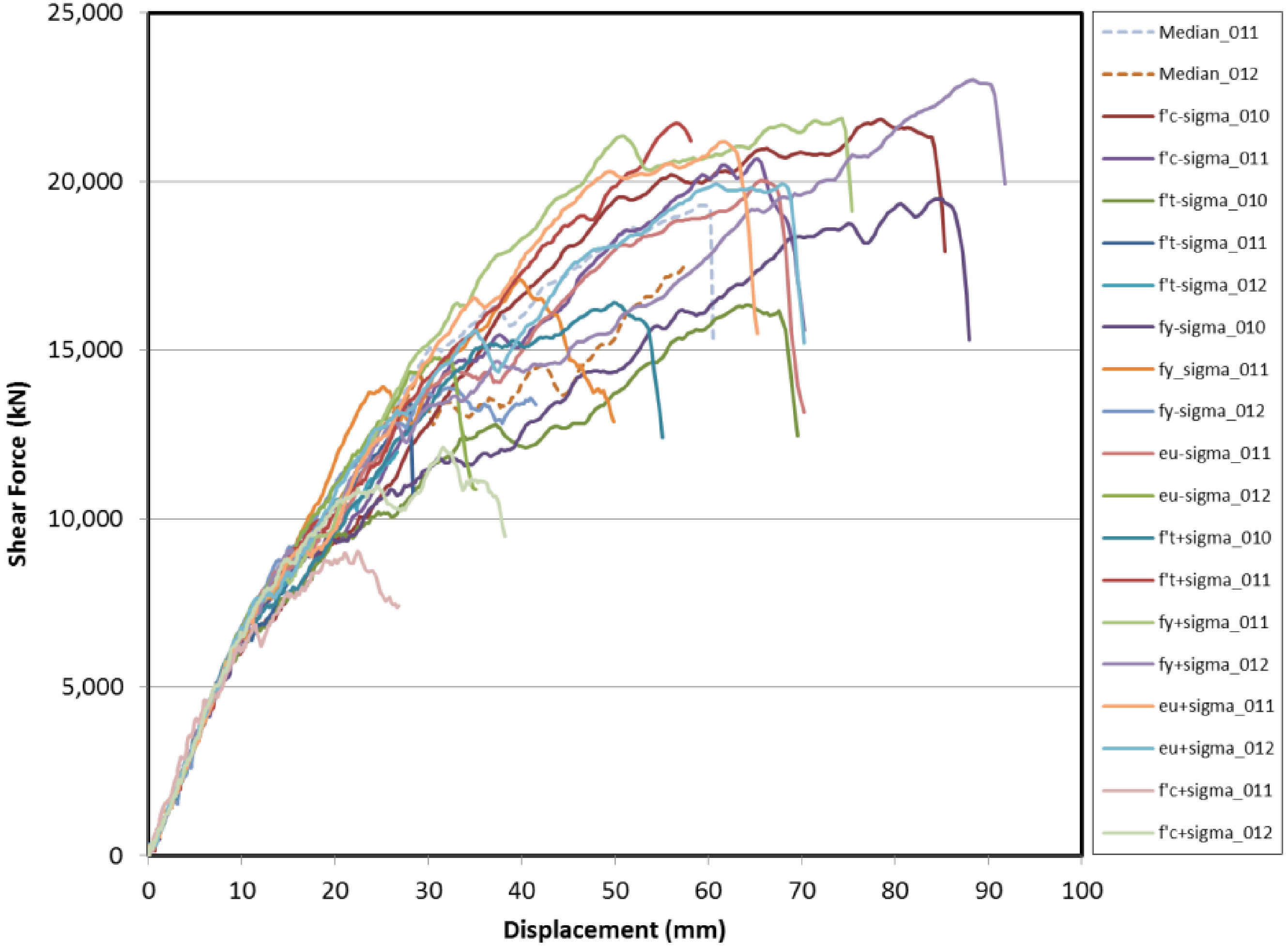
At Failure at 8.7 cm



Gap developed in back of pile

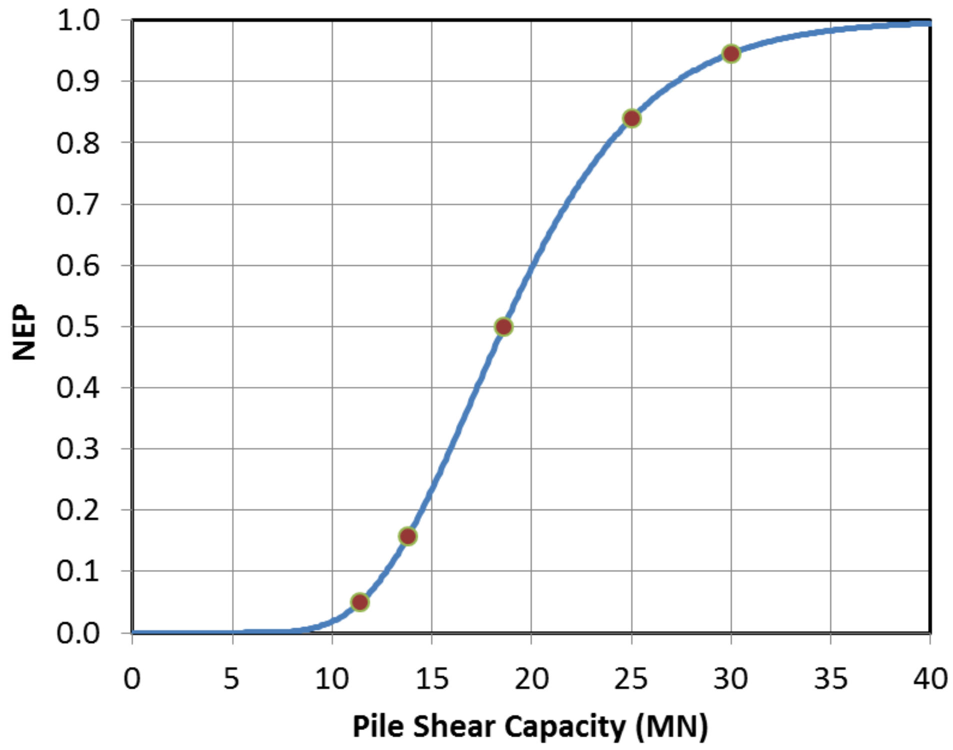
Gap developed in front of pile

Pile Shear Capacity Results



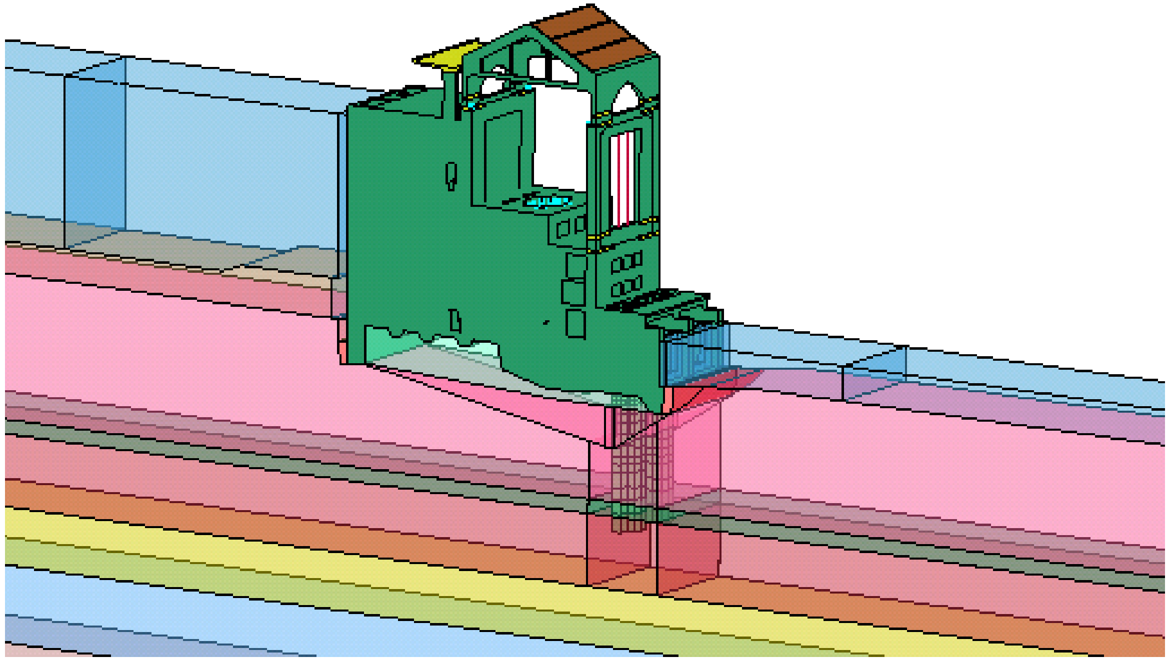
Median Pile Capacity = 18.6 MN

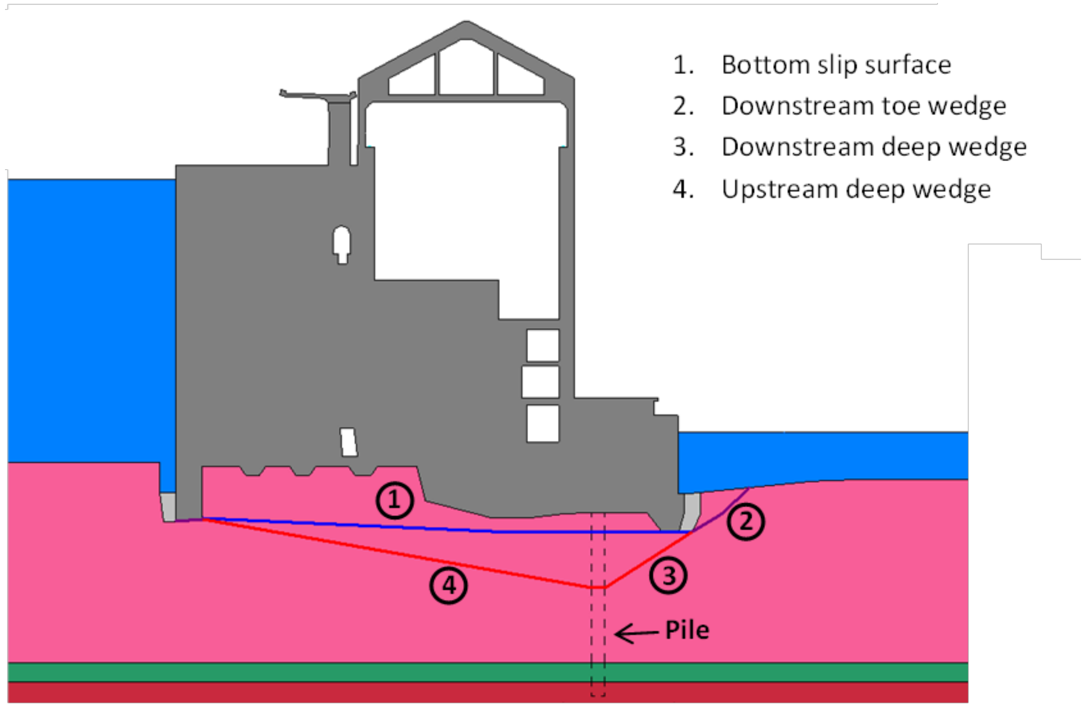
Logarithmic Standard Deviation, β = 0.298



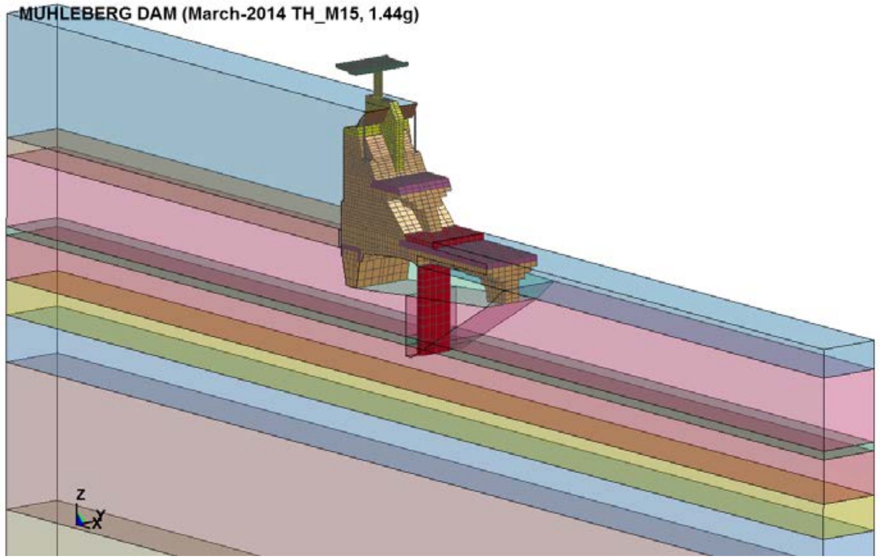
Model of Strengthened Dam with Piles

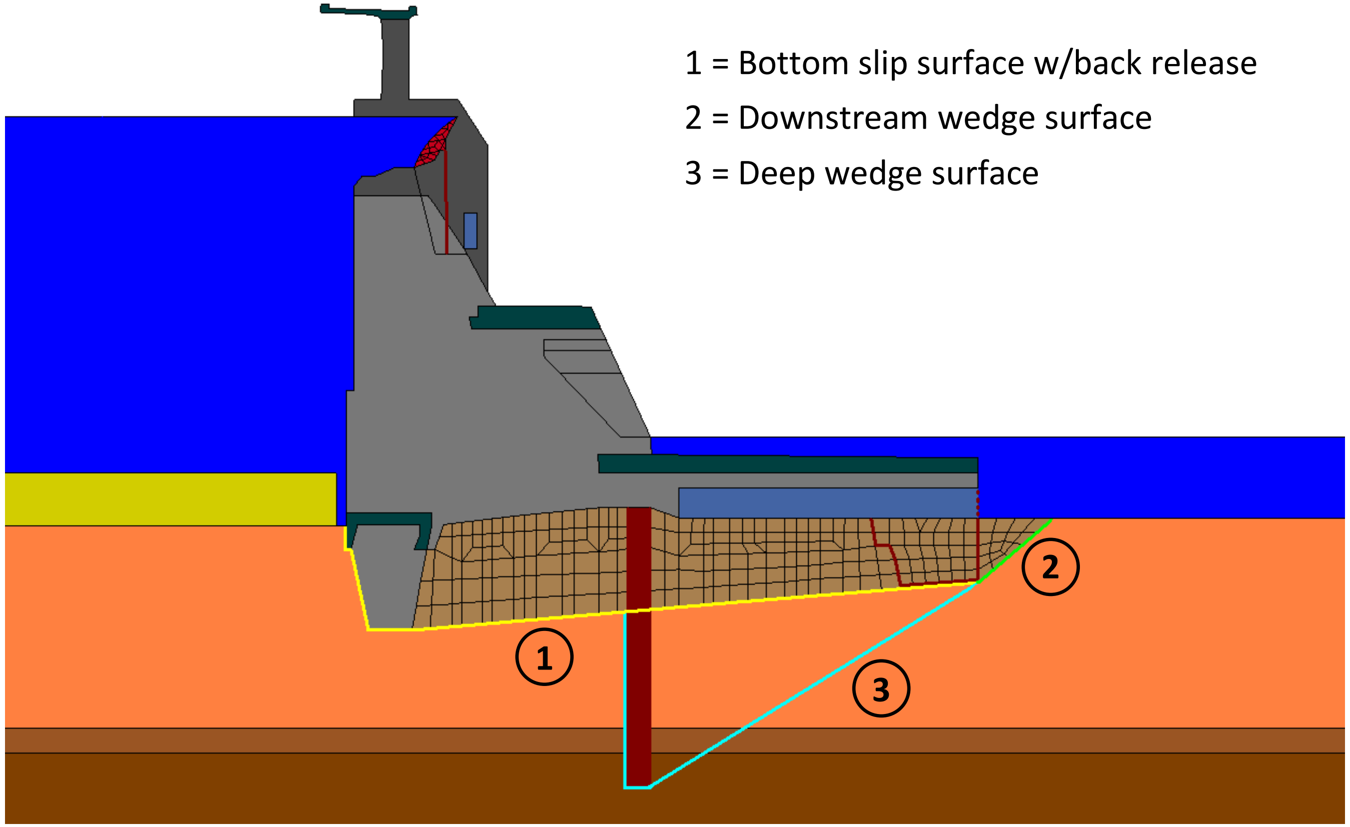
- Compressible water with radiation damping
- Foundation with mass, damping, transmitting boundaries, and traction input
- Multiple failure surfaces
- Piles included





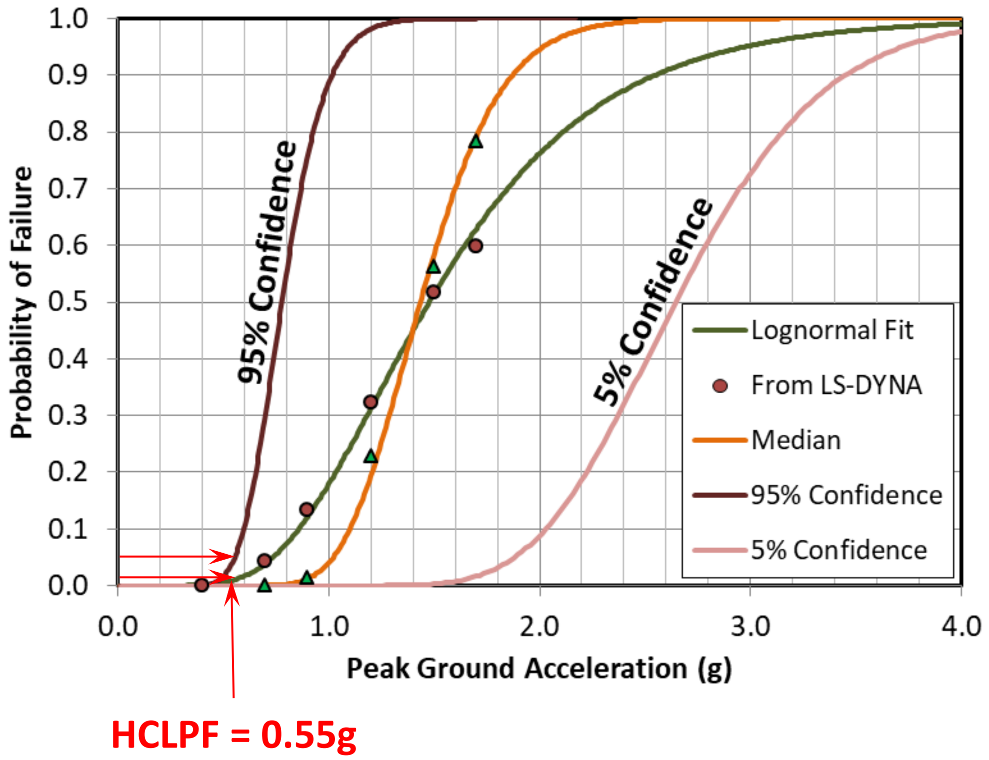
Model of Strengthened Weir with Piles





Seismic Fragility of Strengthened Dam

- **Composite Fragility –** 180 nonlinear runs on HPC Cloud Services
- **Randomness Fragility –** 150 nonlinear runs on HPC Cloud Services



A_m = 1.48g	**Median capacity in terms of PGA**
β_c = 0.42	Log standard deviation of composite variability
β_r = 0.21	Log standard deviation of randomness
β_u = 0.37	Log standard deviation of uncertainty
HCLPF = 0.55g	High Confidence of Low Probability of Failure

$$\beta_u = \sqrt{\beta_c^2 - \beta_r^2}$$

Installation of Concrete-filled Pipe Piles

Piles installed at Weir toe

Pile cap steel reinforcement

Closing Remarks

- Probabilistic modeling using nonlinear analysis with LHS offers an efficient method to estimate probability of failure and address uncertainty for risk-based design
- Subjective estimation of probability used in practice verbal descriptors may work for portfolio risk assessment but not for evaluation and risk-based design of a specific dam