Current State-of-Practice in Dam Risk Assessment

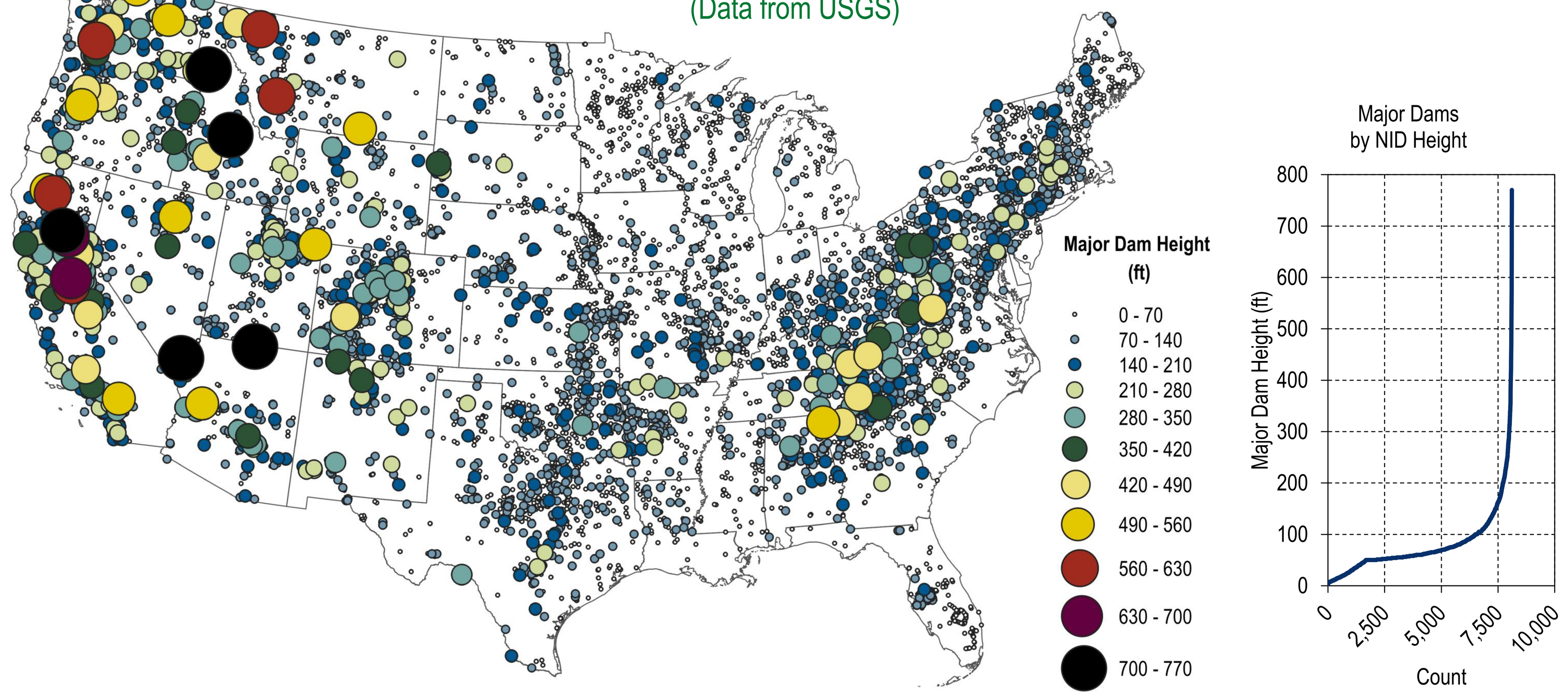
Scott DeNeale[1] (denealest@ornl.gov), Greg Baecher[2], Kevin Stewart[1]

[1]Environmental Sciences Division, Oak Ridge National Laboratory, [2]Center for Disaster Resilience, University of Maryland

Background

Dams provide significant benefits to the nation. Major cities could not function without the fresh water supply stored in dammed reservoirs, and many electrical systems rely on dependable hydroelectric power supply. Mainstream dams on rivers across the US protect inland valleys against the ravages of floods while providing navigable waters for transportation and irrigation for agriculture. However, dams can also be dangerous. If a dam loses containment, downstream property damage can be catastrophic with potential loss of life. In short, while dams provide many essential services, dam failure flooding can present significant risks.

Fig. 1. Major dam distribution in contiguous US by NID height (Data from USGS)



Study Objective

With the potential threat that dam failure flooding can pose to nuclear power plants, this project supports the US Nuclear Regulatory Commission (NRC) in surveying the current state-of-practice in dam risk assessment to support risk-informed operating and new reactor licensing and oversight. The information being assembled is intended to aid the NRC in developing guidance on the use of probabilistic flood hazard assessment (PFHA) methods and support the provision of risk information to NRC's licensing framework in the context of flooding hazards due to dam failure.

Fig. 2. Dam incidents in CONUS by type based on NPDP data. (Data from National Performance of Dams Program).

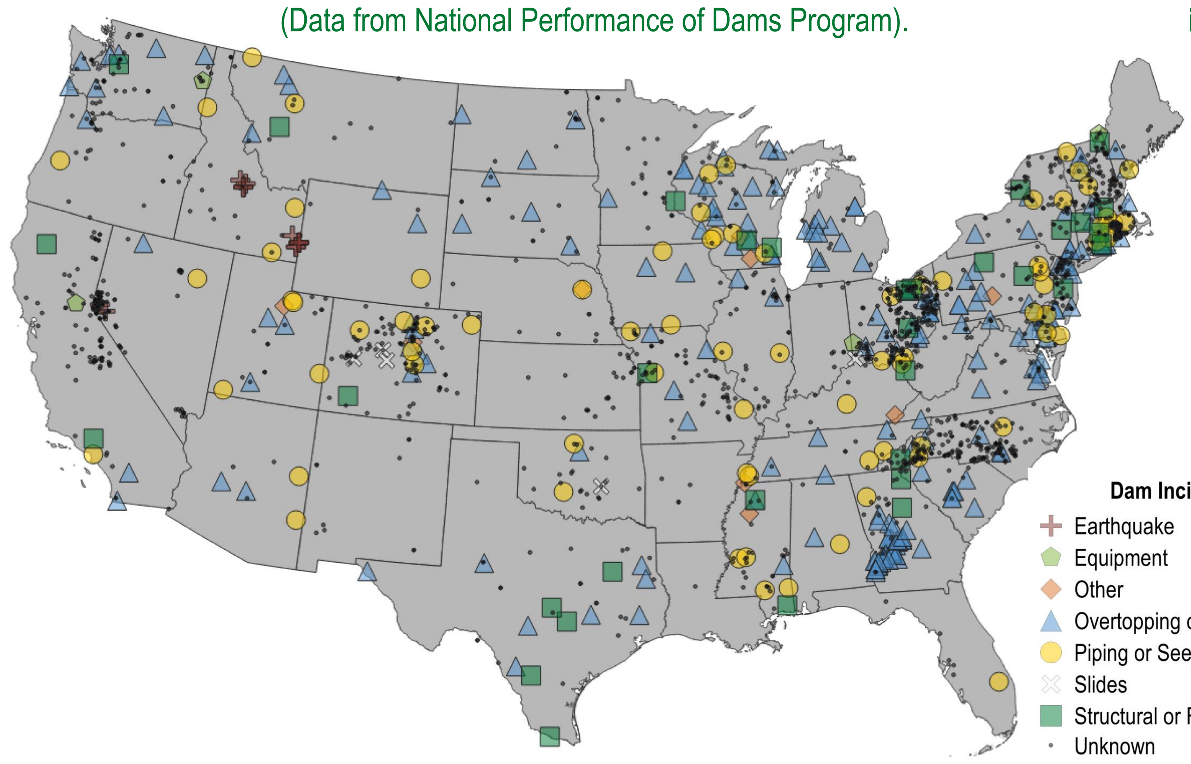
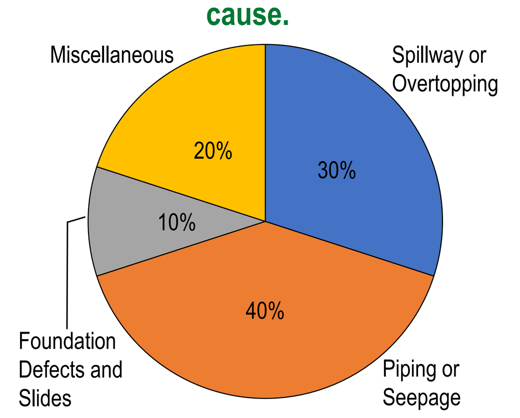


Fig. 3. Approximate fraction of international dam failures by proximate cause.



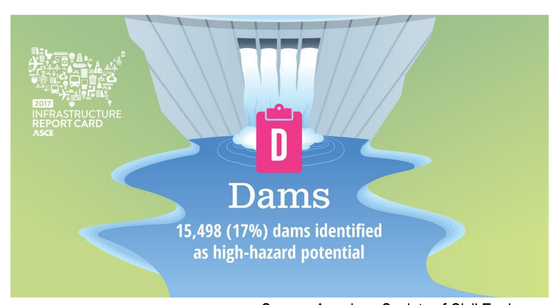
Current Paradigm in the US

Risk-informed decision making (RIDM): enables structured, engineered approaches to identifying, classifying, and quantifying potential dam failures and provides a mechanism for dam owners, designers, operators, and regulators to communicate dam risk and mitigate concerns

Probabilistic risk analysis (PRA): practiced by the Corps, Reclamation, and many private sector dam owners, yet its implementation may be challenging due to gaps in knowledge, uncertainty associated with the physics of dam failure, and difficulty in communicating results with stakeholders

2017 ASCE Infrastructure Report Card gives US dams a 'D' grade

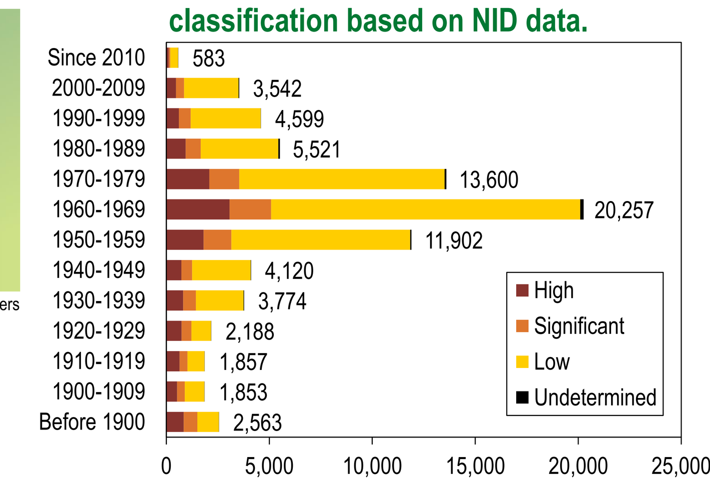
The report indicates that with an average dam age of 56 years, increasing population and development trends, and a lack of investment, the number of high-hazard-potential dams and deficient high-hazard-potential dams continues to climb.



Source: American Society of Civil Engineers

"*Many dams are not expected to safely withstand current predictions regarding large floods and earthquakes…many of these dams were initially constructed using less-stringent design criteria for low-hazard potential dams due to the lack of development.*"

Fig. 4. US dams by completion date and hazard classification based on NID data.



Dam Safety Risk Assessment Framework

Risk combines the probability and severity of an adverse event. Existing literature describes a "risk triplet," consisting of three questions used to define risk. These are (1) what can happen? (2) how likely is it that it will happen? and (3) if it does happen, what are the consequences?

Fig. 5. Common vertical and horizontal loads on a concrete gravity dam and foundation

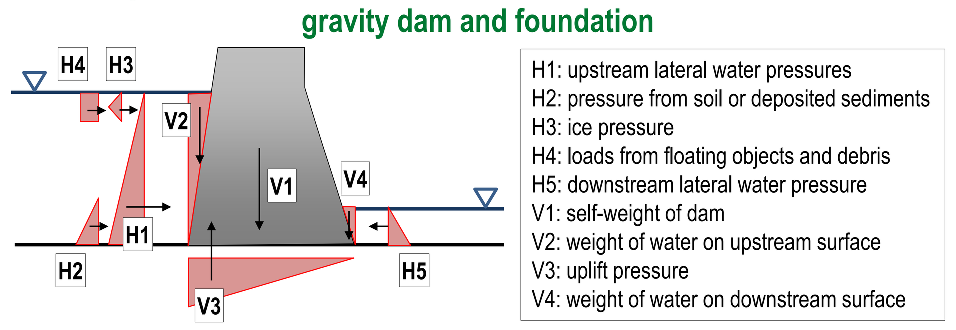


Fig. 6. Risk analysis modeling framework

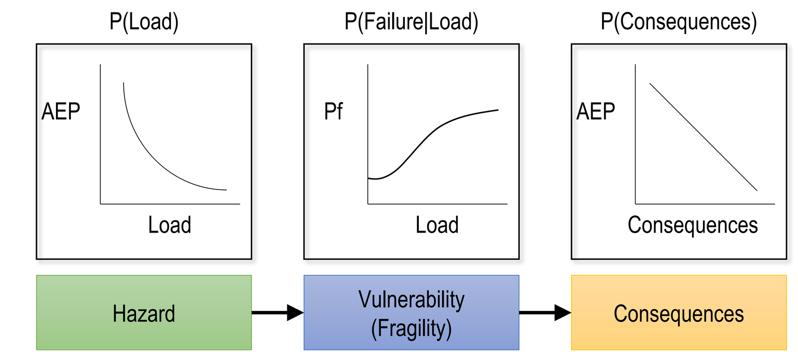
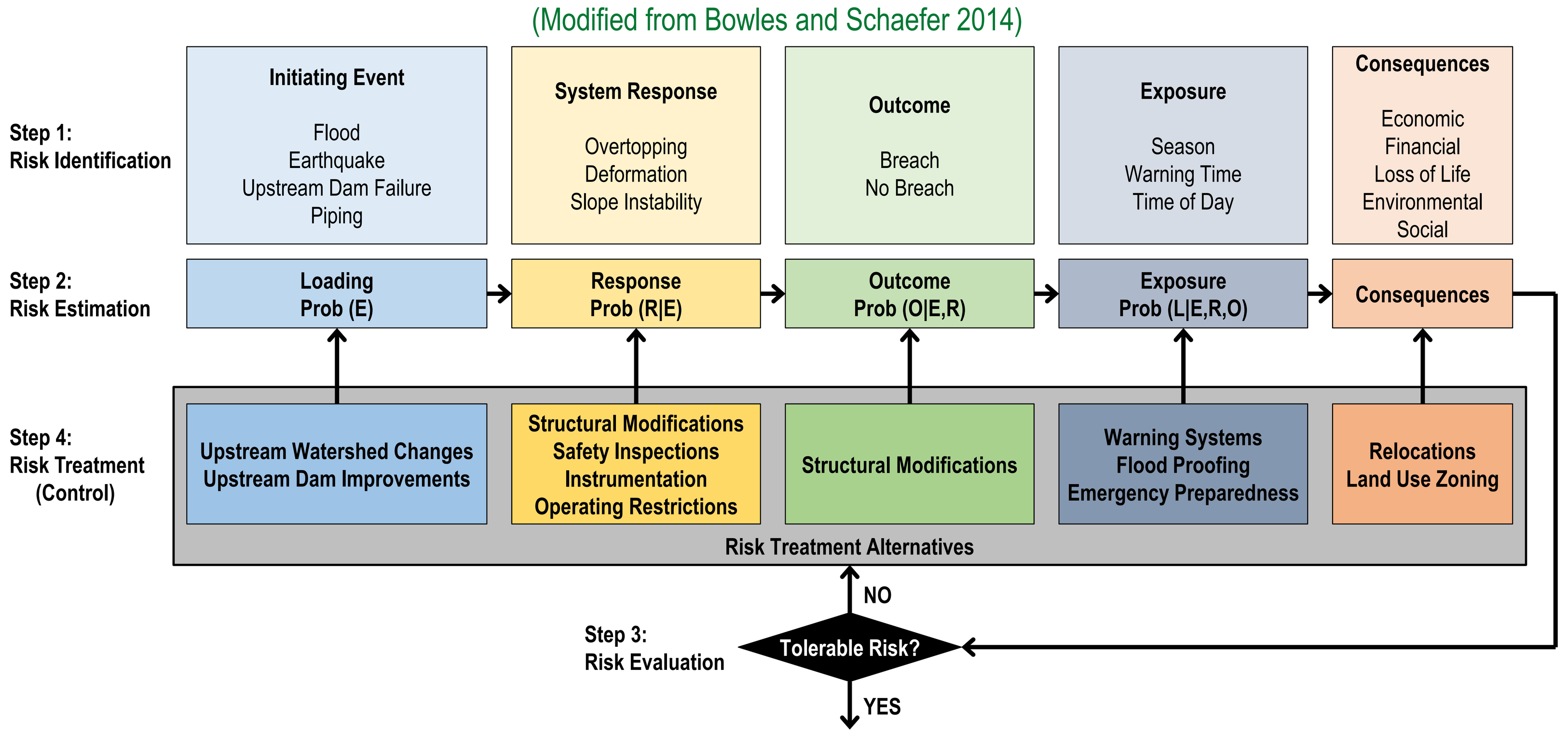


Fig. 7. Framework for dam safety risk assessment. (Modified from Bowles and Schaefer 2014)



Example Dam Risk Assessment Tools

Event tree analysis: an inductive analysis process that utilizes an event tree graphical construct that shows the logical sequence of the occurrence of events in, or states of, a system following an initiating event.*

Fault tree analysis: a systems engineering method for representing the logical combinations of various system states and possible causes which can contribute to a specified event (called the top event).*

Fragility curve: a function that defines the probability of failure as a function of an applied load level.*

Dam-break analysis: an analysis that provides an estimation of downstream flooding effects resulting from dam failure. The analysis includes a dam-break analysis and the routing of the dam-break hydrograph through the downstream channel and areas that would be inundated.*

*ICOLD (2005) definitions

Fig. 8. Example of a fault tree applied to the problem of dam failure. (Modified from Parr and Cullen 1988)

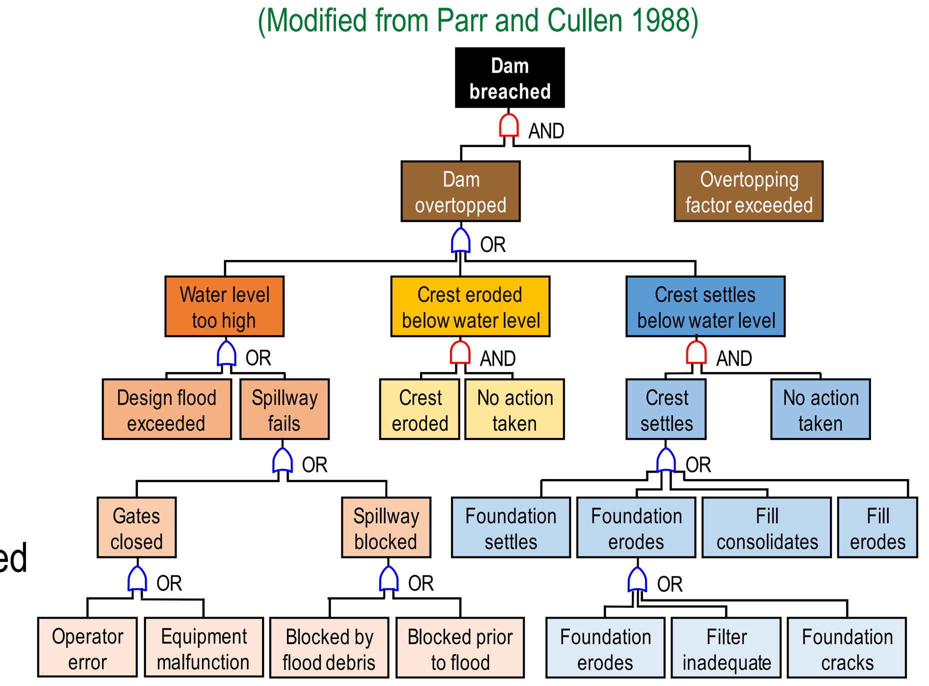


Fig. 9. Example fragility curve with multiple damage states. (Modified from Carturan et al. 2013)

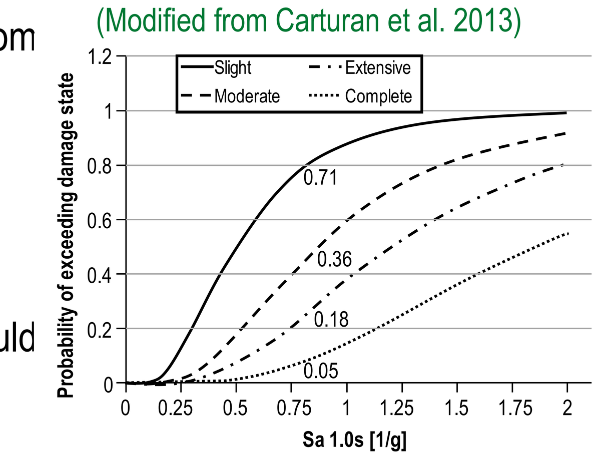
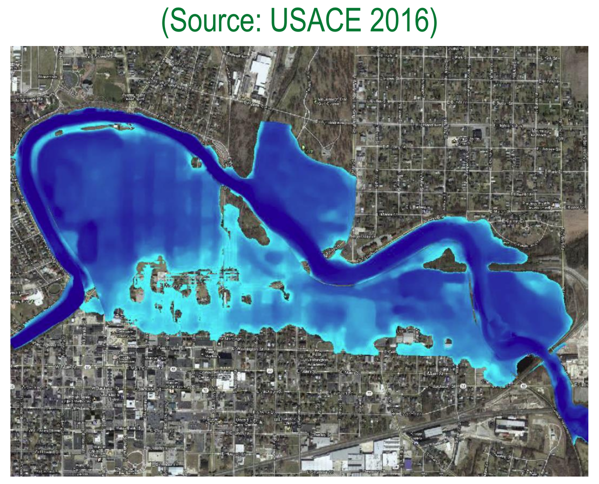


Fig. 10. Example HEC-RAS flood inundation map showing water depth. (Source: USACE 2016)



Summary

As dams continue to age beyond their design lives, they will be exposed to continued risk of large floods, earthquakes, and other hazards, and the threat of dam failure disasters may grow in the future. Climate change may exasperate this exposure, while shifting technological paradigms, cyber security threats, and operational demands may impact risk. Yet federal and state dam safety frameworks have provided a valuable safety net for preventing major calamities, and risk prioritization tools have been leveraged with success.

The literature survey *(to be published as an ORNL Report in 2019)* highlights the history and importance of dam safety in the US, describes the primary federal and state organizations engaged in dam safety, describes the primary physical and operational considerations in dam engineering, summarizes the principal features of dam safety risk assessment and modeling, summarizes the critical aspects of operational risk, documents the relevant software tools for dam risk analysis, catalogues historical dam failures, and provides insights from recent dam incidents and failures. The information assembled provides a critical review of key aspects of dam risk assessment, including (among others):

- Probabilistic engineering analysis methods for assessing dam stability and integrity;
- Reliability of key components such as gates, gate hoists, valves, etc.;
- Systems analysis approaches;
- Reliability of operational and emergency procedures; and
- Methods for estimating breach initiation and progression and propagation of uncertainties.

Johnstown flood from South Fork Dam failure (1889; overtopping)

Remaining monolith following St. Francis Dam failure (1928, internal erosion w/ overturning)

Eroded Baldwin Hills Dam (1963, internal erosion along fault plane)

Breach flow through Teton Dam (1976, piping during initial reservoir filling)

Malfunctioning Folsom Dam gate (1995, trunnion pin failure)

Debris blockage at Kerckhoff Dam spillway (1997, debris accumulation)

Evacuated Taum Sauk Reservoir (2005, sensor dislodgement during operation)

Spillway blockage at Marseilles Lock (2013, barge accumulation)

Damaged Oroville Dam spillway (2017, spillway defects)

Sponsor

U.S. Nuclear Regulatory Commission (NRC)
Office of Nuclear Regulatory Research

Research Leads:
Scott DeNeale, Oak Ridge National Lab
Greg Baecher, University of Maryland
Kevin Stewart, Oak Ridge National Lab

NRC Leads:
Meredith Carr
Joseph Kanney

4th Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop

Rockville, MD | April 30 – May 2, 2019

Hosted by the US Nuclear Regulatory Commission

References

Bowles, D. S. and M. Schaefer. (2014). "Probabilistic Flood Hazard Assessment, Dam Performance PRA and Nuclear Plant Risk." *Proceedings of the 9th Nuclear Plants Current Issues Symposium*, Charlotte, North Carolina, July 9, 2014.

Carturan, F., C. Pellegrino, R. Rossi, M. Gastaldi, and C. Modena. (2013). "An integrated procedure for management of bridge networks in seismic areas." *Bulletin of Earthquake Engineering*, 11(2), 543–559, Dordrecht, The Netherlands.

ICOLD (International Commission on Large Dams). (2005). *Risk Assessment in Dam Safety Management. A Reconnaissance of Benefits, Methods and Current Applications. Bulletin 130*, International Commission on Large Dams, Paris.

Parr, N. M. and N. Cullen. (1998) "Risk management and reservoir maintenance." *Journal of the Institution of Water and Environmental Management*, 2, 587–593.

USACE (US Army Corps of Engineers). (2016). *HEC-RAS River Analysis System 2D Modeling User's Manual*. CPD-68A, US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, Davis, CA.