Agenda

- TVA Dam Safety Risk-Informed Decision Making Program
- Tellico Project Semi Quantitative Risk Assessment (SQRA)
  - Project Background
  - Risk status prior to SQRA
  - Risk Driving Failure Modes
  - Results
  - SQRA Team Recommendations
- Lessons Learned
1. Purpose and Scope of the Risk Program

TVA Dam Safety Risk-Informed Decision Making Program
TVA Risk Management Program

• In March 2016, TVA adopted risk informed decision making as a tool for ensuring and improving the safety of TVA’s dams.

• Since 2016, TVA has completed eleven Semi-Quantitative Risk Assessments (SQRAs) and two limited scope Quantitative Risk Assessments (QRAs).

• The order of risk assessments is primarily dependent upon which dams are thought to have higher risks, based on PFMAs and Screening Level Risk Assessment (SRA) completed between 2009 and 2012.

• Most risk assessments to date have been performed for dams that have one or more issues (Tellico is an example).
Risk Management Program Context

• TVA’s Dam Safety Program is governed by procedures which are designed to comply with the Federal Guidelines for Dam Safety and FERC guidelines.

• TVA’s Dam Safety Program is self regulated and includes an internal governance and oversight group.
Advantages of Risk Informed Decision Making (RIDM)

• Understand each dam
  - Analyze and assess risks associated with TVA dams to inform the decision making process. Risks include loss of life, environmental, reputational, and economic.
  - Includes assessment of non-standards based failure modes (erosion through karst features, operational errors).

• Ensure appropriate level of action and investment
  - Create a structure to assess the risk of dam assets, formulate plans for risk reduction actions, establish guidelines for risk tolerance and evaluate the cost effectiveness of incremental risk reductions.

• Invest at the right time in the right asset
  - Prioritize dam safety actions.
Tolerable Risk Guidelines

- TVA follows risk guidelines that are patterned after the approach of other federal agencies.
### TVA Dam Safety Risk-Informed Analysis Continuum

<table>
<thead>
<tr>
<th>Routine</th>
<th>Non-Routine</th>
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<tbody>
<tr>
<td><strong>SRA</strong></td>
<td><strong>SQRA</strong></td>
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<tr>
<td>Screening Level Risk Assessment</td>
<td>Semi-quantitative Risk Assessment</td>
</tr>
<tr>
<td><strong>Purpose</strong></td>
<td><strong>Purpose</strong></td>
</tr>
<tr>
<td>- Aids in initial portfolio prioritization</td>
<td>- Aids in portfolio prioritization</td>
</tr>
<tr>
<td>- Identify potential project vulnerabilities</td>
<td>- Identify project vulnerabilities</td>
</tr>
<tr>
<td>- Identify and prioritize any data collection, analyses, needs (O&amp;M and DSAP).</td>
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</tr>
<tr>
<td><strong>Uncertainty:</strong> Very High</td>
<td><strong>Uncertainty:</strong> High</td>
</tr>
<tr>
<td><strong>Cost/Duration:</strong> $30k/2 mos</td>
<td><strong>Cost/Duration:</strong> $250k/6 mos</td>
</tr>
<tr>
<td><strong>IES/Mod Study</strong></td>
<td><strong>IES</strong></td>
</tr>
<tr>
<td><strong>Purpose</strong></td>
<td><strong>Purpose</strong></td>
</tr>
<tr>
<td>- Update critical project info and review (e.g. loading)</td>
<td>- Update critical project info and review</td>
</tr>
<tr>
<td>- Address life safety, economic, and environmental consequences</td>
<td>- QRA on risk-driving FMs</td>
</tr>
<tr>
<td>- Compare and select risk management plan</td>
<td>- Risk-informed recommendations</td>
</tr>
<tr>
<td><strong>Uncertainty:</strong> Low</td>
<td><strong>Uncertainty:</strong> Med</td>
</tr>
<tr>
<td><strong>Cost/Duration:</strong> $1M/2 yrs</td>
<td><strong>Cost/Duration:</strong> $1M/2 yrs</td>
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TVA Portfolio Risk Management Framework

- Issues are typically identified by a routine dam safety activity (blue)

- Issues then enter a non-routine risk assessment process (red)

Abbreviations:
- DS – Dam Safety
- DSAR – Dam Safety Action Rating
- OMR – Operations, Maintenance & Repair
- PFMA – Potential Failure Modes Analysis
- SRA – Screening-level Risk Assessment
SQRA Purpose and Scope

Purpose
• Aids in portfolio prioritization
• Identify project vulnerabilities
• Identify and prioritize any data collection, analyses, needs (O&M and DSAP)

Scope
• Review all background info
• PFMA with SQRA
• Risk-informed recommendations
Advantages of SQRAs

• Balance between SRA and QRA.
• Completed with information available at time of workshop.
TVA SQRA Process

• Risk Assessments start with facilitated Potential Failure Modes brainstorming.
• Consider potential failure mode for each major project feature.
• Failure modes that are deemed to be risk-driving are fully developed and failure likelihood and life loss consequences are assigned.
• The process is to determine the “Risk Driving Failure Modes.”

• For TVA, the focus to date has been on failure modes that could lead to life loss.

• Hydrologic loading is considered for flood events with annual chance of exceedance as small as 1 in 1,000,000.
• Seismic loading is considered for ground motions with annual chance of exceedance as small as 1 in 100,000.
Consequences

• Consequence assessments focus on downstream life safety impacts.
• Direct economic damages are computed, but do not explicitly influence the risk assessment outcome at this time.
SQRA Outcome

- Each risk-driving PFM placed in “box” that represents one order of magnitude.
2. Baseline Risk Assessment

Tellico Project SQRA
TVA Watershed Map

Power & Non-Power Dams

- Tennessee River System and Watershed
- Dam
- Metropolitan Area
- Fossil Plant
- Nuclear Plant
Team Members

- Performed mostly by internal staff
- Consistency review was performed by the USACE
- Team Members:

  2 Facilitators
  3 Structural Engineers
  4 Geotechnical Engineers
  1 Geologist/Seismologist
  1 Hydrologist
  1 Instrumentation Engineer
  3 Dam Safety Inspectors (Civil, Electrical, and Mechanical)
  1 Water Resources Engineer (TVA River Forecast Center)
  2 Former TVA employees who were involved in the design and the construction of Tellico Dam
Vicinity Map
Project Description

Location of Project: Tennessee River near Lenoir City, Tennessee.
Purpose of Project: Power generation and flood control
Brief Physical Description: embankment (2760 ft.), gated spillway (190 ft.), non-overflow sections (300 ft.). In addition, there are 2 saddle dams: one is 350 feet and the other is 470 feet long. One emergency spillway, 2000 feet long.
Project Features

- Right Rim Extension
- Main Embankment
- Concrete Dam
- Emergency Spillway
- Saddle Dams 2 and 3
- Saddle Dam #2
- Saddle Dam #3
- Main Embankment
- Right Rim Extension
- Emergency Spillway
- Concrete Dam
- 3 Radial Gates
Project Features

Concrete Dam
Length: approx. 540 feet; Maximum Height: 129 feet

Embankment: Compacted impervious-rolled earth fill
Length: 2760 feet; Maximum Height: 105 feet; Crest Elevation: El. 830

PT Anchors: 92 anchors; depth: 65-97 feet

PT Anchors: 92 anchors; depth: 65-97 feet

PT Anchors

EL. 834.9

Grout Curtain
Upstream Berm, El. 795

Cutoff Trench
Roller Compacted Fill
Trench in Rock

Overburden

Headwater, El. 813

Base Line

Outlet Drain
Downstream Berm

Crest of Dam
El. 830

Cutoff Trench
Grout Curtain

ROCK, EL. 725+/

RIPRAP

INTERIOR CHIMNEY DRAIN

GROUT CURTAIN
UPSTREAM BERM, EL 795
Project Features

- Emergency spillway: RCC structure
- Maximum Height: 13.5 ft.
- Crest Elevation: EL. 817

- Saddle Dam #2
- Compacted impervious-rolled earthfill Embankment
- Length: 470 ft.; Height: 23 ft.

- Saddle Dam #3
- Compacted impervious-rolled earthfill Embankment
- Length: 350 ft.; Height: 32 ft.
Risk status prior to SQRA

- PFMA (December 2010)
- Screening Risk Assessment (May 2012)
  - Suggested “DSAC 4”
- FY13 - FY15 Stability Analysis and Field Modifications in support of TVA Nuclear Program
- Initial DSAR Assigned (September 2015)
  - Performance during earthquakes (Concrete, Embankment, and Foundation)
  - Piping through the foundation
  - Potential cracking at the Concrete-Rock-Interface (CRI) during normal operating condition
  - No SQRA. Baselined based on SRA.
  - DSAR 3 assigned
Hydrologic Loading - Flood Hazard Curve

<table>
<thead>
<tr>
<th>Key Point</th>
<th>Elevation</th>
<th>Exceedances</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAXIMUM HW</td>
<td>832.9</td>
<td></td>
</tr>
<tr>
<td>Top of closed gates</td>
<td>815</td>
<td>Yes</td>
</tr>
<tr>
<td>Top of planned surcharge</td>
<td>817</td>
<td>Yes</td>
</tr>
<tr>
<td>Unregulated spillway flow begins</td>
<td>817</td>
<td>Yes</td>
</tr>
<tr>
<td>Top of fully open gates</td>
<td>829</td>
<td>Yes</td>
</tr>
<tr>
<td>Operating deck overtopped</td>
<td>830</td>
<td>Yes</td>
</tr>
<tr>
<td>Top of embankment</td>
<td>834.9</td>
<td>No</td>
</tr>
</tbody>
</table>
Downstream Consequences

PMF Failure and Sunny Day Inundation at Lenoir City

- Life Loss Estimates included in SQRA are based on Initial Risk Screenings, done in 2011/2012.
- Evaluated Life Loss for PMF Failure and Sunny Day Failures in Inundation Zone included in 12-hour travel time.

PMF Failure and Sunny Day Inundation at Loudon
Potential Failure Modes – Brainstorming

Thirty one potential failure modes were identified in which 6 were considered to be risk driver modes:

- **PFM 2**: Failure of the spillway section along the CRI during an earthquake.
- **PFM 4A**: Failure of the spillway section along a lift joint during an earthquake.
- **PFM 6A**: Piping from main embankment into foundation rock cavities.
- **PFM 9**: Post-EQ transverse crack leads to concentrated leak erosion. (Combined with PFM 12)
- **PFM 12**: Earthquake causes liquefaction of foundation soils which produces large deformations of the foundation soils and cracking/displacements in the main embankment soils. Transverse cracks in the embankment are enlarged by concentrated leak erosion and eventually seepage associated with the cracks erodes the embankment to produce large scale loss of embankment material and dam failure.
- **PFM 27**: Liquefaction under dam (Main Embankment). (Combined with PFM 12)
PFM 2: Failure of the spillway section along the CRI during an earthquake

- Failure Likelihood: Low to Moderate (1:30,000 to 1:300,000)
  - Conservative seismic analysis methodology used
  - It is very unlikely that the spillway monoliths would catastrophically fail along the CRI during the 1:3,000 earthquake

- Confidence: Low
  - Conservatisms within the methodology likely overestimate the severity of damage to the structure

- Consequences: Low to Moderate

- Confidence: Low
  - Breach parameterization for inundation maps that the population at risk (PAR) is based on is unknown and the PAR has not been updated since 2010

Schematic of potential Earthquake Cracking
PFM 4A: Failure of the spillway section along a lift joint during an EQ

- Failure Likelihood: Low (1:100,000 to 1:1,000,000)
  - Historically, dams that have experienced earthquakes >0.3g have performed well with minimal cracking and damage with no failures noted

- Confidence: Low
  - There is currently a lack of structural analysis for this potential failure plane

- Consequences: Low to Moderate

- Confidence: Low
  - Breach parameterization for inundation maps that the population at risk (PAR) is based on is unknown and the PAR has not been updated since 2010

Schematic of potential Earthquake Cracking
PFM 6A: Piping from Main Embankment into Foundation Rock Cavities

General schematic showing initial progression of piping and erosion of embankment fill into foundation rock defects.

- Failure Likelihood: Low (1:100,000 to 1:1,000,000)
  - A very large quantity of material will need to be removed from the foundation and embankment before a stope can make contact with the reservoir
  - No sinkholes have occurred in the embankment and piezometers show no trends that may be associated with increasing seepage or piping

- Confidence: Moderate
  - Foundation defects are known to exist. However, many factors may affect the probability of these features contributing to seepage and piping failure

- Consequences: Low

- Confidence: Low
  - Breach parameterization for inundation maps that the population at risk (PAR) is based on is unknown and the PAR has not been updated since 2010
PFM 12: Post-earthquake instability leads to transverse cracking and concentrated leak erosion

- **Failure Likelihood**: Moderate (1:10,000 to 1:100,000)
  - Soil erosion susceptibility and the potential for an earthquake to trigger this failure mode is plausible
- **Confidence**: Low
  - Uncertainty exists on analyses to date (no deformation analysis) and a lack of performance data to support this failure mode
- **Consequences**: Low
- **Confidence**: Low - Moderate
  - Breach parameterization for inundation maps that the population at risk (PAR) is based on is unknown and the PAR has not been updated since 2010
Incremental Life Safety Risk Matrix

**Risk-Driver PFMs**

- **PFM 2**: Failure of the spillway section along the CRI during an earthquake
  Confidence (f) Low (lol) Low

- **PFM 4A**: Failure of the spillway section along a lift joint during an earthquake
  Confidence (f) Low (lol) Low

- **PFM 6A**: Piping from Main Embankment into Foundation Rock Cavities
  Confidence (f) Mod (lol) Low

- **PFM 12**: Post-earthquake instability leads to transverse cracking and concentrated leak erosion
  Confidence (f) Low (lol) Low-Mod
Non-Breach Life Safety Risk Matrix

Downstream Non-Damaging Discharge: 80,000 cfs

Spillway Flow:
Top of flood control pool ACE = 1/40
Maximum discharge: 1,000,000 cfs

Inflow Design Flood (IDF):
Uses current methodology/HMR
Required Freeboard: 2 feet
Available Freeboard: 2 feet

Downstream Structures:
Kingston Dike
SQRA Team Recommended DSAR

DSAR 3 (no change)

DSAR 3 Definition – Moderate Incremental Risk – For confirmed and unconfirmed dam safety issues, the combination of life, economic, or environmental consequences with likelihood of failure is moderate.

- Failure Likelihood for all risk-driver PFMs was categorized as low to moderate.
- Recent formal inspection conducted in March 2017 did not reveal any concerns/issues that would warrant a change in the project risk level.
- Estimated Potential Life loss:
  - 113 for Sunny Day Failure
  - 6 for PMF Failure.
Tellico Dam Total Risk

2012 Total Risk

2017 Total Risk
SQRA Team Recommendations

- **Fort Loudoun and Tellico Dams could be evaluated together as a combined system for future risk assessments:**
  - The two dams are operated as one system because the two reservoirs are located adjacent to one another and linked by a canal
  - The two dams have the same hydrologic and seismic hazards and consequences
- Perform more refined seismic analysis (3D FE time history) of the concrete structures to address PFMs 2 and 4A
- Perform seismic deformation (including PE stability sensitivity analysis) of the embankment to address PFM 12
- Perform internal erosion analysis and geophysical testing to address PFM 6A
- **These analyses should not be performed prior to the completion of the Downstream Consequence Assessment for Fort Loudoun and Tellico in FY18** (to include consideration of impact on Kingston Dike), and the regional seismic hazard study which is currently planned for FY18/FY19
SQRA Team Recommendations (cont.)

- A more comprehensive review and evaluation of the Tellico Dam instrumentation should be performed.
  - The comprehensive evaluation may indicate where additional instruments are needed or where existing instruments are not useful.
  - This recommendation is oriented toward PFM 6A but also provides for better understanding of the uplift data applicable to PFM 2.
3. Risk Reduction Assessment

To Be Determined
4. Limitations, Decisions, Risk Communication and Lessons Learned
Limitations of the Approach

• Time constrained.
  – Both low and high risk dams take time to complete the process.
  – Workshops typically completed in one week.
• Vulnerability to extensive questioning and doubt when reviewed by technical experts not familiar with, or not in favor of, the SQRA process.
• Expert opinion based.
• There can always be more study.
Risk Assessment Outcomes

- TVA team much more familiar with facilities.
- Allows interaction across workgroups at TVA.
- Understanding of dam vulnerabilities.
- Ensure appropriate level of action and investment.
- Invest at the right time in the right asset.
Risk Assessment Impacts on Decision-Making

• Result of Risk Assessments are the assignment of a Dam Safety Action Rating (DSAR).
  – which is similar to USACE DSAC rating.

• DSAR is considered among multiple factors (life loss, economic, TVA Power Operations) when prioritizing:
  – Additional studies,
  – O&M projects, and
  – Capital projects.
Value Added by Risk Assessments

- Studies and projects are focused on the risk-driving failure modes.
- Aids decision making by providing a framework that can be applied across the TVA inventory:
  - Reduces influence of opinions and perceptions.
  - Risk is a common language between TVA Business Units.
  - Consistent process lends to credibility.
- SQRA Results provide indication of total risk being driven by:
  - Probability of Failure, or
  - Consequences.
Risk Communication

- Risk Assessments provide Dam Safety Professionals with the findings in a format that can be discussed with non-technical individuals.
- TVA currently does not communicate the risk process to the public. However, the process informs TVA if external communications are warranted.
- Typically, SQRAs do not generate external risk communications.
- TVA did use Risk to inform communications for issues at Pickwick and Boone.
Risk Assessment Lessons Learned

• Preparation prior to the SQRA workshop is key.
• Lacking consequences for several different failure scenarios.
• Methodology for consequences evolving at TVA.
  – information for Tellico was overly conservative.
• Understanding of consequences by team members.
• Subject Matter Experts (SMEs) must know when to be strong/stubborn.
• How do we perform “Risk Calibration” and demonstrate that we have a repeatable process?
Confidence and Uncertainty

- Expert opinion is always subjective.
- Confidence in results is sometimes increased by performing special studies or investigations in advance of the risk workshop.
- For Tellico Dam, a recent site investigation and stability analysis were used to inform the risk assessment.
- Confidence in the annual probability of failure (APF) is elicited as being either low, moderate or high.
- Uncertainty is implicitly assumed to fall within an order of magnitude for APF and life loss (LL).