Federal Energy Regulatory Commission

Identifying, Describing, and Classifying Potential Failure Modes

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Risk Informed Decision Making
Level 1 Training

Adapted from Bureau of Reclamation Best Practices Presentation

Potential Failure Mode Analysis

- Potential Failure Mode Analysis (PFMA) process adopted by the FERC in 2002.
- All High and Significant Hazard Dams in FERC's inventory currently have PFMAs.
- PFMA reviews performed during each Part 12D inspection every 5 years.

Definition of a PFM

- A specific **chain of events** leading to a dam failure.
- The FERC defines a failure as an **uncontrolled release** of water. Therefore, a failure does not need to be a complete and catastrophic failure of the dam.
- The PFM should be **developed with no regard** of likelihood or possibility.

Review Key Concepts for a PFMA

- Collect all relevant **background** material.
- Lead engineer and facilitator, at a minimum, should **thoroughly review all** background material.
- All Team Members should **diligently** review background material sufficiently to become familiar with the project.
- Take a fresh look. Eliminate the mentality of "**we have looked at this a million times**." Think of the movie Groundhog Day – every day is a new day.

Review Key Concepts for a PFMA

- Perform **site examination** with an eye toward potential vulnerabilities.
- Involve project **operating personnel** in the potential failure modes discussions.
- **Think** beyond traditional analyses, as appropriate.
- To be done correctly, a full PFMA could take up to a week, depending upon the size of the project.
- A **PFMA review** every 5 years could take **two days or more**, depending on the size of the project.

Identifying a PFM

- Typically done in a **team setting** with a diverse group of qualified personnel for the dam.
- Facilitator (senior-level engineer) elicits possible potential failure modes based on the team's understanding of **vulnerabilities** of the dam.
- Facilitator (senior-level engineer) makes sure each potential failure mode is understood and **described thoroughly** from initiation to failure.
- Post large scale drawings/sections on the walls and **sketch** out the potential failure modes (as appropriate).
- One time in life where **negative thinking is encouraged!**
  - Think of every way the dam can fail.

Describing a PFM

- **Three key elements of a potential failure mode description are:**
  - **The Initiator** (e.g., reservoir load, deterioration/aging operation/systems malfunction, earthquake, flood, etc.)
  - **The Failure Mechanism/Progression** (Including location and/or path) (**Step-by-step progression**)
  - **The Resulting Impact on the Structure** (e.g., full or partial failure, rapidity of failure, breach characteristics)

Potential Failure Mode Analysis

- But PFMA's are old news? Right?
- They should be, but the FERC's internal SLPRA results and our internal PFMA reviews with RIDM in mind indicate that does not seem to be the case.
- Let's review the development of a PFM in detail…

Describing a PFM

- **Although you might be thinking… what's new?**
  - Need detailed **step by step** description of how the dam will fail from the moment it starts until the moment it fails.
  - Many current PFMs are **not detailed sufficiently** to fully portray the exact step by step progression that results in the failure of the dam.
  - We need a **better understanding** of the real objective of a PFM to develop a proper PFM.
  - **What's new is that these requirements for a PFM are not being consistently followed.**

Potential Failure Mode Considerations

Potential Failure Mode Considerations

- The list of **items** to consider for potential failure mode development is almost **never ending**, especially for some internal erosion PFMs for embankment dams.
- Develop the **entire** PFM (initiation to failure), even if it's the team's decision that it is physically impossible for the PFM to progress any further. You need a **complete** PFM!
- Use engineering judgment and common sense.
- Develop the PFM with the **thought process** that each part of the PFM will happen and the **dam will fail** or there will be an uncontrolled release of water.

Potential Failure Mode Considerations

- Each dam is **unique** in its precise PFMs, but the following loading conditions should be considered as a minimum.
  - Normal day-to-day (Static) loading (reservoir level)
    - Consider seasonal reservoir fluctuations
  - Seismic loading
  - Hydrologic loading
  - Systems/Operations
    - Automated systems
    - Operator error

Example 1

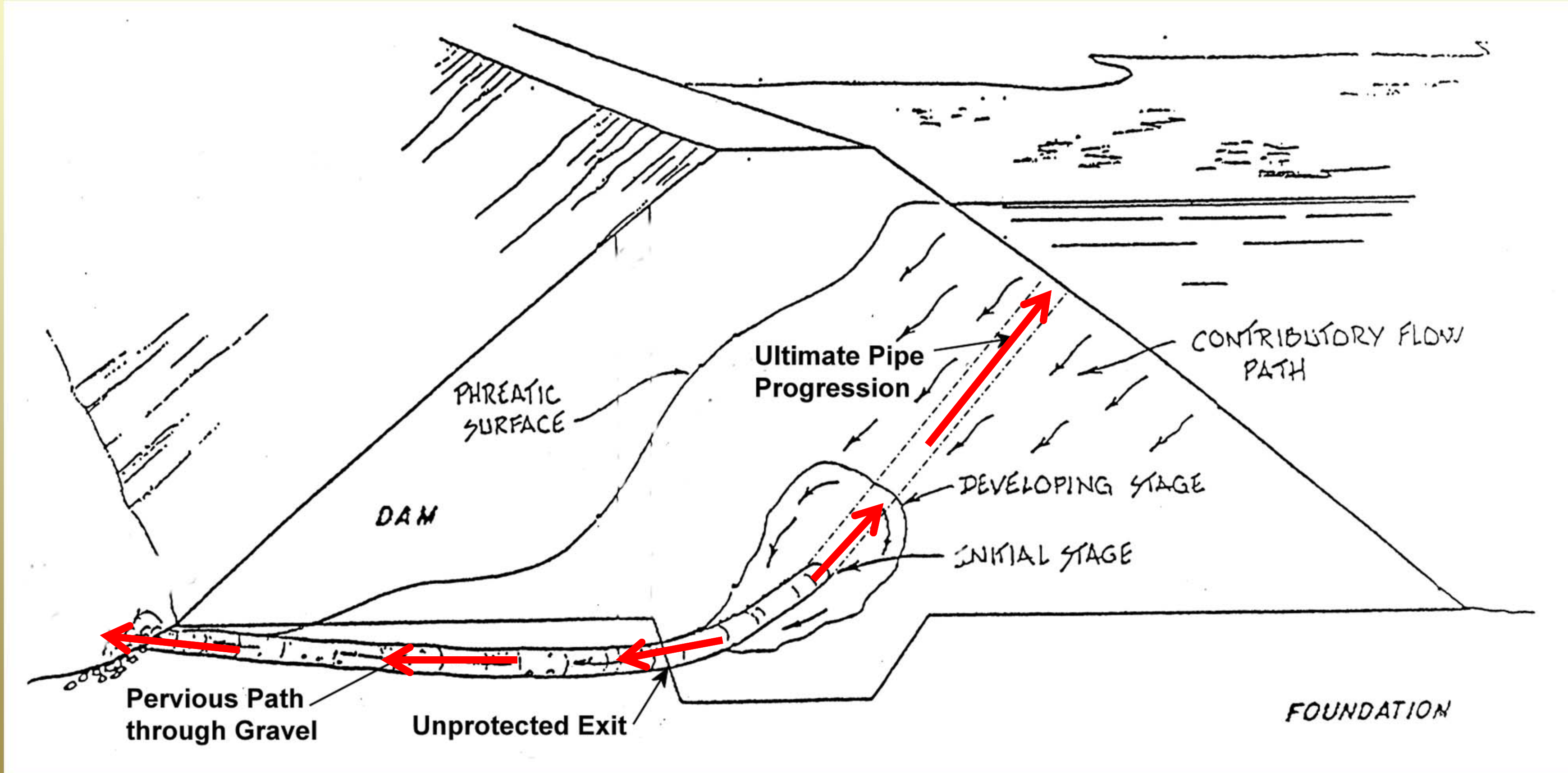
Piping

Potential Failure Mode Description

- **PFM Frequently Developed:**
  - Piping from the embankment into the foundation.
- **More Appropriate PFM:**
  - When the reservoir is above elevation 5634 feet, internal erosion of the core initiates into the open-work gravel foundation at the interface of the foundation with the cutoff trench near Station 2+35, as a result of poor foundation treatment. Core material erodes into and through the foundation and exits at the toe of the dam through an unfiltered exit. Backward erosion occurs until a "pipe" forms through the core and continues upstream until reaching the reservoir. Seepage velocities increase, enlarging the pipe until a portion of the upstream face of the embankment collapses into the pipe, which continues to enlarge until the crest of the dam collapses, resulting in an uncontrolled release of the reservoir.

Sketch of Potential Failure Mode

Attempt to write the PFM as if you do not have a sketch.



Example 2

Concrete Dam

Identifying and Describing

Surveying results indicate the dam has moved several inches since monitoring began.

What PFM is this?

Potential Failure Mode Description

- **PFM Frequently Developed:**
  - Sliding of the concrete dam on the foundation.
- **More Appropriate PFM:**
  - During normal maximum reservoir elevation and (1) a continuing increase in uplift pressure on the shale layer slide plane, or (2) a decrease in shearing resistance due to gradual creep on the slide plane, sliding of the buttresses initiates. Major differential movement between two buttresses takes place causing the deck slabs to become unseated from their simply supported condition on the corbels. Two bays quickly fail followed by the failure of adjacent buttresses due to lateral water load resulting in an uncontrolled release of the reservoir.
  - Or is this actually correct?

Potential Failure Mode Description

- This is actually **two** separate and distinct PFMs – Do not combine different loading conditions or failure mechanisms into one PFM.
- There should be **no** either/or statements in a PFM. Only definitive statements.

Potential Failure Mode Description

- PFM 1:
  - During normal maximum reservoir elevation, ***a continuing increase in uplift pressure on the shale layer slide plane*** initiates sliding of the buttresses. Major differential movement between two buttresses takes place causing the deck slabs to become unseated from their simply supported condition on the corbels. Two bays quickly fail followed by the failure of adjacent buttresses due to lateral water load resulting in an uncontrolled release of the reservoir.

- PFM 2:
  - During normal maximum reservoir elevation, ***a decrease in shearing resistance due to gradual creep on the slide plane*** initiates sliding of the buttresses. Major differential movement between two buttresses takes place causing the deck slabs to become unseated from their simply supported condition on the corbels. Two bays quickly fail followed by the failure of adjacent buttresses due to lateral water load resulting in an uncontrolled release of the reservoir.

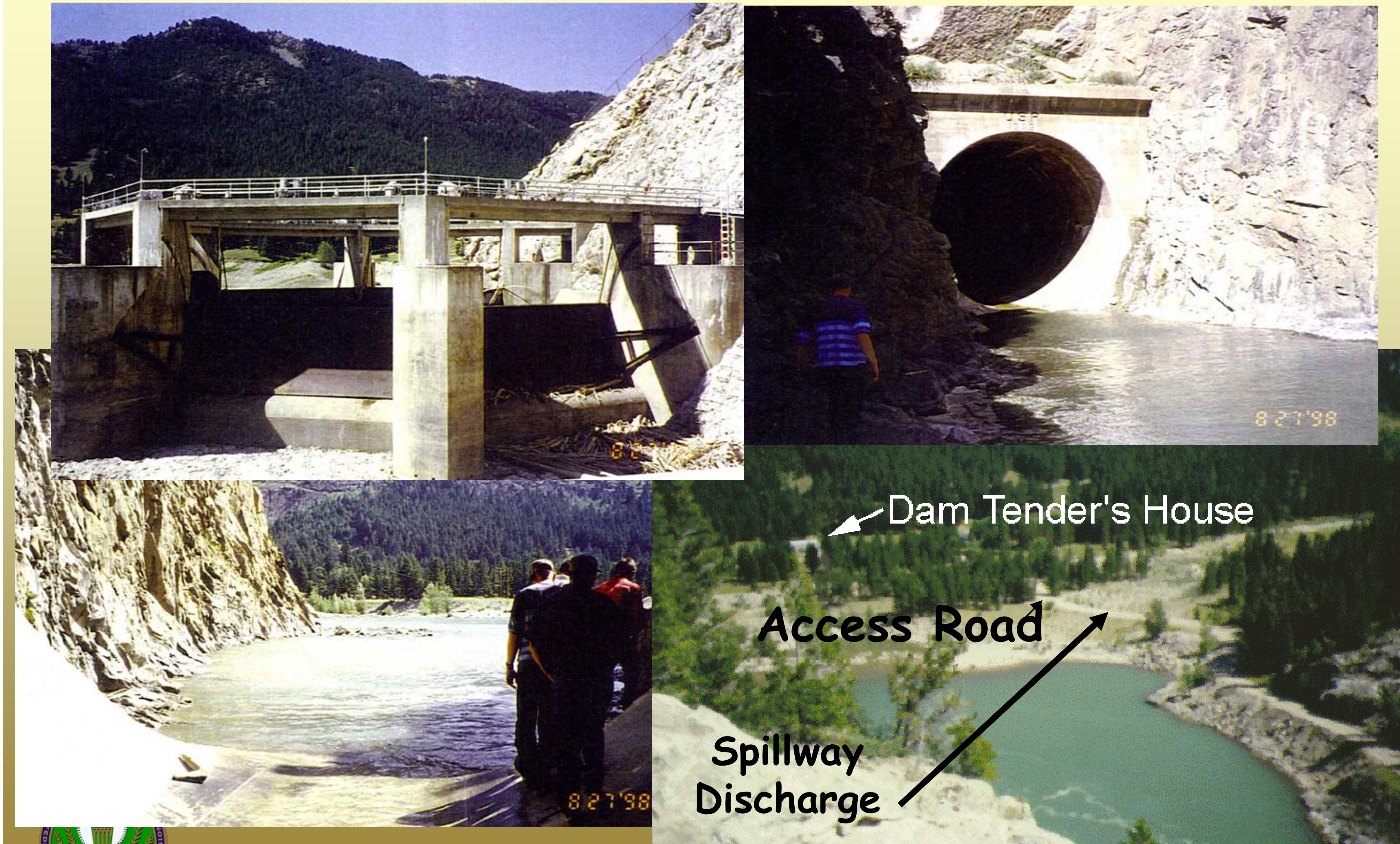
Example 3

Spillway Gates

Potential Failure Mode Description

- **PFM Frequently Developed:**
  - Dam overtopping due to gate operation failure.
- **More Appropriate PFM:**
  - A storm event requires the passage of 9,000 cfs through the spillway to prevent overtopping the dam. This flow is more than can be safely passed through the only remotely controlled gate, which has restricted opening procedures and a limit switch to prevent releasing flows that will wash out the only access road to the dam. As happened in 1994, the limit switch fails to work due to a loss in communications equipment. The gate opens fully, releasing flows that wipe out the access road. An operator is deployed to the site to manually open additional spillway gates, but cannot make it to the dam. The release capacity of the single automated gate is insufficient and the dam overtops, eroding the embankment and resulting in an uncontrolled release of the reservoir.

Photos of Potential Failure Mode



Decision Making Process for PFMs

- For each potential failure mode:
  - List adverse or "**more likely**" factors for the development of the PFM.
  - List favorable or "**less likely**" factors for the development of the PFM.
  - Discuss and document in **extreme detail** in the PFMA report so the reasoning can be understood by others reading the report years down the road; (ask, "**why did we say that**?," and write down the answer).
  - Highlight the **key factors** that affect the judgment.

- Going back to the piping PFM, let's look at "more likely" and "less likely" factors for the PFM.

Example Adverse "More Likely" Factors

- The gravel alluvium in contact with the embankment core on the downstream side of the cutoff trench is similar to the transition zones which do not meet modern "no erosion" filter criteria relative to the core base soil.

- The gravel alluvium may be internally unstable, leading to erosion of the finer fraction through the coarser fraction and even worse filter compatibility with the core.

- The reservoir has never filled to the top of joint use; it has only been within 9 feet of this level. Most failures occur at high reservoir levels; the reservoir would fill here for a 50 to 100-year snow pack (based on reservoir exceedance probability curves from historical operation).

Example Adverse "More Likely" Factors

- The core can sustain a roof or pipe; the material was well compacted (to 100 percent of laboratory maximum), and contains some plasticity (average Plasticity Index ~ 11).
- There is likely a significant seepage gradient from the core into the downstream gravel foundation, as evidenced by the hydraulic piezometers installed during original construction (and since abandoned).
- It is likely that all flow through the foundation cannot be observed due to the thickness and pervious nature (transmissivity) of the alluvium.
- The embankment is constructed of silty material with a low PI and the alluvium is mostly cohesionless sand, so a rapid erosion breach would likely occur down to bedrock.

Example Favorable or "Less Likely" Factors

- Very little seepage is seen downstream; the weir at the downstream toe, which records about 10 gal/min at high reservoir when there is no preceding precipitation, indicates the core is relatively impermeable. These flow rates may be too small to initiate erosion.

- The core material is well compacted (to 100 percent of laboratory maximum) and has some plasticity (average Plasticity Index ~ 11), both of which reduce its susceptibility to erosion.

- No benches were left in the excavation profile that could cause cracking and the abutments were excavated to smooth slopes less than 2H:1V.

- If erosion of the core initiates, the gravel alluvium may plug off before complete breach occurs (see criteria for "some erosion" or "excessive erosion", Foster and Fell, 2001).

Example Unknowns

- Document unknowns discussed during the review regarding the PFM
  - Although the seepage volumes are small, it is not clear that all of the seepage can be readily observed.
  - The actual filtering characteristics of the transition zone is unknown. Additional research or sample collection and analyses are needed.
  - **Unknown unknowns**. How much do you know about what you don't know? Document the discussion about this and how it influenced your decision about the PFM.

Screening for Risk Estimates

- Once the PFM is fully developed and all the more likely, less likely, and unknown factors are developed, the next step is to **screen** the PFM to determine if it should move forward to develop a quantitative risk estimate.

- This would likely include screening out PFMs that the Team determined to be so remote that the PFM is non-credible. At this point there is typically **no need to estimate** the risk.

Screening for Risk Estimates

- General failure mode risk development or disposition statements:
  - Failure is in progress or **imminent** ("forget" risk analysis and take interim action).
  - Failure mode is **credible** (carry forward for risk estimates).
  - **Insufficient information** to determine credibility (carry forward for risk estimates, perform sensitivity analyses on key parameters and determine if more analyses or investigations are required).
  - Failure mode is **not credible** (do not carry forward for risk estimates)

Credible Statement Example

Credible Example and Rationale

- This potential failure mode is **credible** and will be carried forward for analysis of risk.
- Rationale: The gravel transition zone (and likely the gravel alluvium) clearly does not meet modern "no erosion" filter criteria and a seepage gradient exists from the core into the downstream foundation alluvium. Although the seepage volumes are small, evidence suggests that not all of the seepage can be readily observed.

Non-Credible Example

Non-Credible Example

- A large storm event results in inflows of 100,000 cfs that require the operation of spillway gates to pass the flows. Severe winter weather freezes the spillway gates making them inoperable. The reservoir rises until overtopping the embankment dam. The downstream face of the dam begins to erode and progresses upstream through the embankment eventually breaching the dam resulting in an uncontrolled release of the reservoir.

- The screening for this might look something like the following:

Non-Credible Rationale

- This potential failure mode is considered to be **non-credible** and will not be included in the analysis of risk or monitoring program.
- **Rationale**: Examination of historical weather data indicates that cold freezing temperatures at the lower elevations near the dam have never occurred at the same time warmer conditions and rain storms have occurred at the higher upper basin elevations to create this volume of inflow. These conditions are considered to be remote for the meteorological regime at the site. Therefore, the chances of one or more spillway gates being frozen shut at the same time there is a large rain storm in the upper basin are considered to be so remote as to be non-credible.

Insufficient Information Example

Insufficient Information Example

- An earthquake with a PHA of 0.32 liquefies a sand layer exposed in the cutoff trench during construction. The liquefaction of the layer results in sufficient deformation of the embankment that the reservoir begins to flow over the embankment. The flow continues to erode the embankment, resulting in an uncontrolled release of the reservoir.

- The screening for this might look something like the following:

Insufficient Information Rationale

- There is **insufficient information** to determine the credibility of this potential failure mode. It will be carried forward for analysis of risk and sensitivity study. Heightened awareness in this area will be included in the post-earthquake monitoring

- Limited information (cutoff trench map) suggests there is possibly a layer of fine sand beneath the shells of the dam. However, there has been no exploratory drilling or testing to determine how far the layer extends upstream or downstream of the cutoff trench or how dense the layer might be. Therefore, this potential failure mode will be carried forward to a risk analysis with different assumptions made regarding the continuity and density of the layer to examine the sensitivity of the risks and the potential value of additional information.

Potential Failure Mode Analysis

- Three critical components to PFMA **report**
  - Documentation
  - Documentation
  - Documentation
- If the report is not clear and precise, there is no proof that any discussions took place and no clear understanding why the PFMA team made the decisions they did. This could result in reworking the PFM in the future.

Consequences of Failure

- Consequences should be addressed after fully developing the PFM, but keep in mind:
  - Different failures have different impacts downstream, both possible life loss and economic impacts
    - Time to failure (full release of reservoir)
    - Seasonal volume of reservoir impacts downstream differently
- Be aware that a potential failure mode with low consequences may have a high likelihood of occurrence.

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