ENGINEERING GUIDELINES FOR THE EVALUATION OF HYDROPOWER PROJECTS

CHAPTER 18 – LEVEL 2 RISK ANALYSIS

DRAFT FOR PUBLIC COMMENT

FEDERAL ENERGY REGULATORY COMMISSION
888 First Street NE
Washington, DC 20426

Revision Log		
No.	**Date**	**Description**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ACE	annual chance exceedance
AEP	annual exceedance probability
APF	annual probability of failure
BOR	U.S. Department of the Interior, Bureau of Reclamation
D2SI	Division of Dam Safety and Inspections (FERC)
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
PAR	population at risk
PFM	potential failure mode
PFMA	potential failure mode analysis
RIDM	risk-informed decision making
SQRA	semi-quantitative risk analysis
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

DEFINITIONS

18-1 INTRODUCTION

18-1.1 Purpose

This guideline describes the procedures used to conduct a Level 2 risk analysis in the Federal Energy Regulatory Commission (FERC) Part 12D dam safety program. As presented in Risk-Informed Decision Making (RIDM) Risk Guidelines (FERC, 2016), the primary purposes of a Level 2 risk analysis are:

- Evaluate the project potential failure modes and associated risks;
- Identify the need for additional studies and determine the priority for those studies;
- Identify and prioritize any data collection and analyses;
- Identify operations and maintenance, monitoring, emergency action plan, training and other recurrent needs;
- Provide a better understanding of potential failure modes and a basis for future dam safety inspections and activities; and
- Provide support to inform dam safety decisions for taking action (or not) to better define risks through higher level studies, or reduce risks.

The risk analysis process described in this document is similar to the semi-quantitative risk analysis method documented in Chapter A-4, Semi-Quantitative Risk Analysis of the Best Practices in Dam and Levee Risk Analysis (BOR/USACE, 2018). However, there are some minor, but subtle and important differences between each process, including some differences in the failure likelihood descriptors.

18-1.2 Need

Level 2 risk analyses have developed as a result of:

1. The need to provide further distinction of the former potential failure mode analysis (PFMA) categories, including an improved process of evaluating the likelihood/frequency of dam failure, frequency of loading, and estimated consequences for each potential failure mode.
2. The need to maintain the current state-of-the-practice in dam safety. Many other federal agencies and international organizations are now using risk analyses in their dam safety programs. In the United States, this includes the Bureau of Reclamation (BOR), U.S. Army Corps of Engineers (USACE), and the Tennessee Valley Authority. The risk methodologies and the state-of-the-practice has evolved to the point where risk analysis and assessment methods have become key tools and information in identifying, evaluating, and managing risk in dam safety.

3. The opportunity and ability to leverage an already significant investment in time and effort to review documents and project information needed to perform a PFMA and other Part 12D responsibilities, including inspection and evaluation of the project. The Federal Guidelines for Dam Safety require that all dams undergo an inspection and review that documents the condition of a dam at a point in time (FEMA, 1979). As implemented by FERC, this is the Part 12D inspection and review. Significant effort is required to prepare for these inspections and reviews. This effort includes reviewing project information, studies, analyses, performance and monitoring information, and other key project data. Through the course of these efforts, much project knowledge is amassed and evaluated. The incremental addition of a risk analysis to this process enhances the value of the effort at a relatively low cost. Typically, only limited additional engineering analyses and studies are needed to perform a risk analysis since the risk analysis generally relies on existing information.

In addition, in evaluating, reviewing, and prioritizing dam safety concerns, the FERC has found it extremely beneficial to also have a sense of the risks associated with each potential failure mode for each project. This information, combined with the information obtained through other dam safety submittals (inspection reports, dam safety surveillance and monitoring plans and reports, emergency action plans, owner's dam safety plans, and others), provides an overall basis to provide consistent and transparent dam safety decisions.

Finally, the dam owner and operator are in the legal position of being responsible for the safety of their dam, its operation, and the consequences of a failure should one ever occur. All dam owners must fully understand and appreciate their legal, regulatory, moral, and social obligations of owning a dam. Without a deliberate effort to identify and understand the risks that a dam imposes on its surroundings, in both the magnitude and frequency of the hazards and magnitude of potential consequences, including impacts to life, health, and property, an owner cannot fulfill these obligations.

18-1.3 Approach

The traditional ongoing dam safety inspection, monitoring, and maintenance activities are of critical importance, but focusing them in a risk-informed manner should result in better management of dam safety programs and activities. While PFMA is the process for identifying potential failure modes, semi-quantitative risk analysis (SQRA) is a process to evaluate their significance from a risk perspective. A Level 2 risk analysis uses an SQRA approach and is a risk categorization system that assigns likelihood and consequence categories to potential failure modes based on existing data and available consequence estimates. A Level 2 risk analysis utilizes a risk matrix approach to assess individual potential failure modes as well as the total risk for a project. The SQRA method provides a relevant risk categorization system that is a useful and quick means to prioritize dam safety activities, especially to determine if higher level studies would be beneficial for specific potential failure modes (BOR/USACE, 2018).

For efficiency, a Level 2 risk analysis is typically performed in conjunction with a potential failure modes analysis (PFMA) as part of a Part 12D Comprehensive Assessment (CA). The risk analysis portion of a CA is built upon the PFMA and is based on existing data and limited development of seismic and hydrologic loading and estimated consequences.

Level 2 risk analyses will normally be conducted for all dams in FERC's Part 12D program as part of a CA (typically on a 10-year cycle), but more frequently as justified to accommodate unusual performance issues or other issues that need to be evaluated further to review or revise priorities. See Chapter 16 of the Engineering Guidelines for more information regarding the Part 12D program and Comprehensive Assessments.

The outcomes of a Level 2 risk analyses include a complete, yet concise and focused, report that captures key information and "builds the case" for the path forward. Other outcomes include a better understanding of the project and the primary risk-drivers, better prioritization of studies, and more focused inspections and surveillance and monitoring. A Level 2 risk analysis focuses on all credible potential failure modes (as defined in Engineering Guidelines Chapter 17) in order to determine which PFMs are considered significant at the dam.

Additional information on RIDM and how Level 2 risk analyses fit into the overall risk management framework in FERC's dam safety program is included in Risk-Informed Decision Making Risk Guidelines (FERC, 2016), available at:

http://www.ferc.gov/industries/hydropower/safety/guidelines/ridm.asp

18-1.4 Limitations

For all the benefits provided by a Level 2 risk analysis, typically the results will not be suitable for determining if the existing dam safety risks are tolerable. Higher level risk analyses (typically Level 3 and Level 4 risk analyses) will be required to demonstrate risk tolerability. More information on Level 3 and 4 risk analyses is provided in Chapter 2 of the FERC Risk-Informed Decision Making Risk Guidelines (FERC, 2016).

This document describes the process and procedures for performing a Level 2 risk analysis. This document does not present information on risk analysis methodology. Risk analysis methodology references are included in Best Practices for Dam and Levee Safety Risk Analysis (BOR/USACE, 2018).

18-2 BACKGROUND

There are generally three primary elements when considering dam safety risk:

1. Frequency/Probability of loading
2. Likelihood of dam failure (response)
3. Adverse consequences

One component of risk is the probability of failure. The probability of failure is a function of both the frequency/probability of the loading condition that could lead to failure and the likelihood of failure given the loading condition. Failure has historically been defined as an uncontrolled, potentially life-threatening release of the reservoir due to breach. However, as discussed in Chapter 17 of the FERC Engineering Guidelines, failure can also include partial or operational failures that may not lead to an uncontrolled release of the reservoir, but can still result in major consequences (economic losses, operational restraints, etc.) to the dam owner, the public, other stakeholders, or the environment.

The other component of risk is the magnitude of consequences should failure occur. Failure consequences can take many forms, including loss of human life, destruction of downstream property, loss of service (project benefits, which may include power generation, recreation, etc.), environmental damage, and socio-economic impacts. For semi-quantitative evaluations, the focus is typically on the potential for life loss, with the idea that the broader socio-economic, environmental, and property damages would be generally commensurate. However, certain projects may require an explicit treatment of economic consequences which may include costs associated with disruption to water supply, flood damage to property, loss or disruption of services of regional or national significance, and others.

18-3 LEVEL 2 RISK MEASURES

Chapter 2 of the RIDM Risk Guidelines (FERC, 2016) provides a summary of typical risk measures. The primary risk measures included in a Level 2 risk analysis are:

1. Societal incremental life safety risk
2. Non-breach life safety risk
3. Annual probability of failure

These risk measures are typically estimated using a semi-quantitative approach although quantitative methods can also be used.

For those projects where economic consequences and other consequences (environmental, cultural, etc.) may be significant or large (relative to a dam owner's ability to fund or pay for damages as a result of a failure or incident), at a minimum, a qualitative assessment of those consequences must be provided.

Although not formally estimated, individual incremental life safety risk estimates can be conservatively assumed to be equivalent to the annual probability of failure estimates.

18-4 OVERVIEW OF LEVEL 2 RISK ESTIMATING PROCESS

The basic steps for a Level 2 risk analysis are described below. The foundation of the Level 2 risk analysis are the results from the PFMA. This includes the review of the available project information. The review of the project information for the performance of the Level 2 risk analysis is generally completed with the project review conducted for the PFMA, as described in Chapter 17 of the FERC Engineering Guidelines. The review of information includes:

- basic statistics and key features of the dam (e.g., type of dam, height of dam, reservoir volume, etc.);
- available design reports/design memos, construction photographs, and engineering studies/ reports, site investigations, etc.;
- historical operating condition loadings (reservoir levels and freeboard);
- performance monitoring information from visual observations and instrumentation; and
- other information included in the Supporting Technical Information Document (STID) and other applicable sources.

The following information and studies are performed prior to the risk analysis and the results are reviewed and used during the risk analysis session:

- Develop/Review/Update Loading Estimates. Loading estimates should be developed for:
    - Hydrologic loading (probabilistic hydrologic hazard curves). Of particular note are the frequencies of: the flood of record, the flood at the peak spillway capacity, the flood at the dam crest, and the projected frequency of the probable maximum flood (PMF). Development of the hydrologic loading curves is discussed in Section 6.2 of this chapter.
    - Seismic loading (probabilistic seismic hazard curves). Of particular note are the ground motions associated with the approximate return period of the maximum credible earthquake (MCE) and the ground motions used in any previously performed seismic analyses along with their approximate return period. Development of the seismic loading curves is discussed in Section 6.3 of this chapter.
- Develop/Review/Update Consequence Estimates. Consequence estimates, generally loss of human life, for the most critical PFM scenarios and locations are needed. Interpolation/extrapolation of this information can be used to develop similar estimates for other PFMs and for other PFM locations. A qualitative assessment of economic risk and other significant risks should also be included.

Development of consequence estimates are discussed in Section 9.0 of this chapter.

The following steps are performed as part of the Level 2 risk analysis session:

1. Perform a PFMA. The PFMA can be performed as a separate session prior to the Level 2 risk analysis or can be performed integral with the Level 2 risk analysis. The PFMA should be performed in accordance with guidance provided in Chapter 17 of the FERC Engineering Guidelines.
2. Perform Additional Screening of PFMs. Additional screening of credible PFMs is performed to evaluate which PFMs are significant and should be carried forward into the Level 2 risk analysis and which PFMs are minor and do not have to be carried forward into the risk analysis. Additional screening guidance is provided in Section 7.0 of this chapter.
3. Develop Failure Likelihood and Consequence Estimates. Review, revise, and expand the factors from the PFMA that make the potential failure mode more likely and less likely to occur, including analysis results where applicable, and identify the key factors. Develop new factors, as needed. Determine the failure likelihood. A similar process is used to determine a consequence for each potential failure mode. Additional guidance is provided in Sections 8.0 and 9.0 of this chapter.
4. Develop Confidence Estimates. Develop estimates of confidence for the failure likelihood and consequence estimates for each potential failure mode. Additional guidance is provided in Section 10 of this chapter.
5. Develop Potential Interim Risk Reduction Measures and Management Actions. Measures should include potential changes to type and frequency of dam safety inspections, improvements to the surveillance and monitoring, improvements to the emergency action plan (EAP), the need for follow up studies, and others. Additional guidance is provided in Section 10 of this chapter and in Chapter 17 of the FERC Engineering Guidelines.
6. Portray Risk Estimates. The risk measures summarized in Section 3.0 of this chapter are determined for each PFM and are plotted on established risk matrices. Additional guidance is provided in Section 11.0 of this chapter.

Finally, the results of the Level 2 risk analyses are documented in a report. The report documents the PFMs considered in the risk analysis; the failure likelihood, consequence estimates, and the rationale for their assignment; the confidence in the rating along with the rationale for its assignment and what additional information could be gathered to improve the confidence rating, if applicable; identified risk reduction measures and management actions; and the portrayal of the risk estimates. Additional risk analysis report documentation guidance is provided in Section 12.0 of this chapter.

An overall flow of the Level 2 risk analysis process is shown on Figure 1.

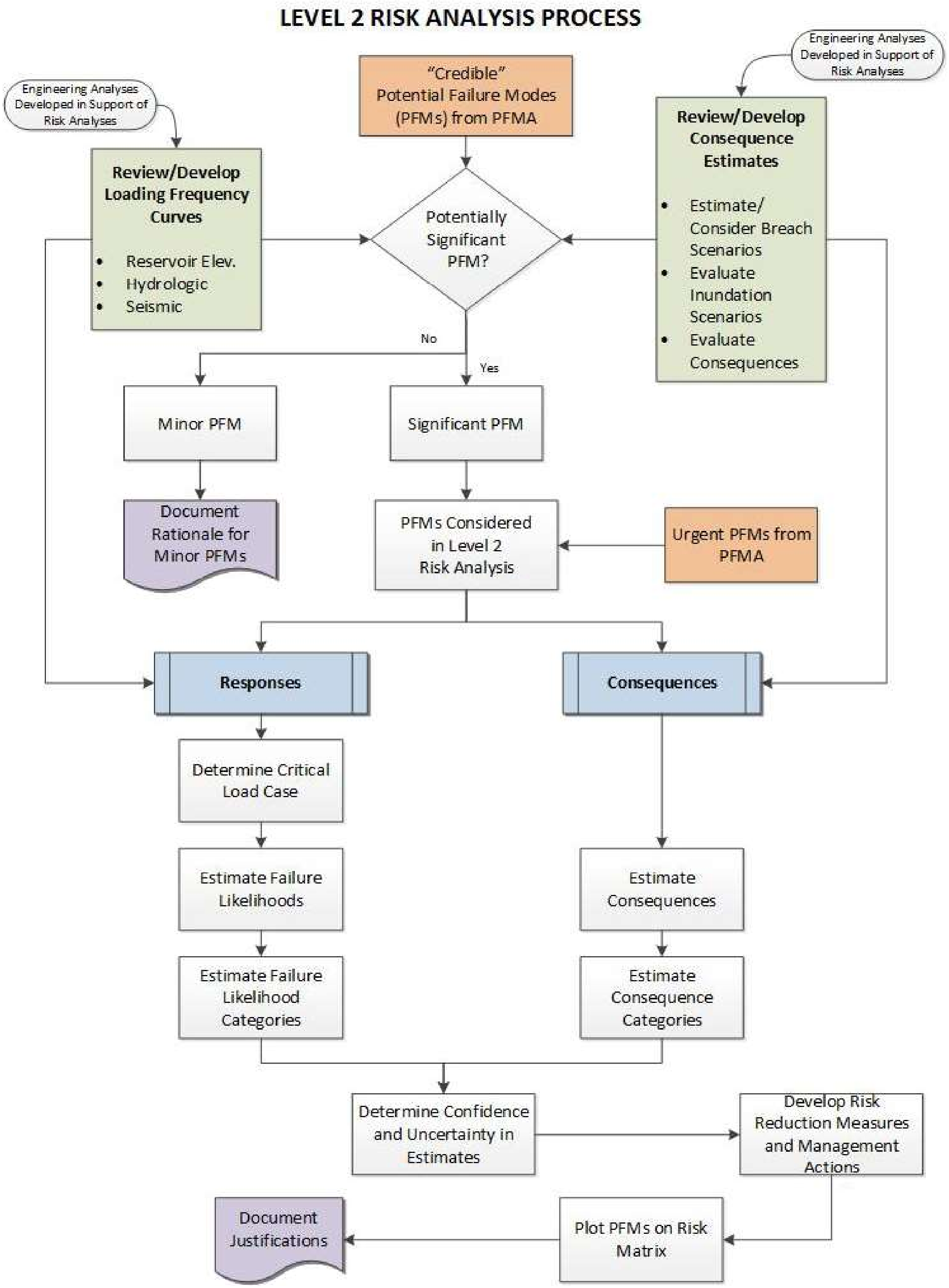


Figure 1: Level 2 Risk Analysis Process

18-5 LEVEL 2 RISK ANALYSIS TEAM

18-5.1 General

Ideally the Level 2 risk analysis session will be conducted concurrently or immediately following the PFMA session. This approach has the advantage that it efficiently uses the individuals already gathered for the PFMA session: similar or identical personnel are typically used for both the PFMA and risk analysis sessions, and project information is fresh and easily recalled because there has been no break or interruption in time between the different sessions.

Similar to the PFMA, advance planning is imperative to ensuring a successful Level 2 risk analysis. And like the PFMA, some questions should be addressed prior to conducting the risk analysis session, including:

1. What technical disciplines should be represented on the risk team?
2. How many people are expected to attend the risk session?
3. How many days is the session expected to last?
4. What size of meeting room will be needed for the session?
5. Are there special considerations that should be accommodated in the session?

The Licensee should discuss these and other questions with the FERC dam safety engineer during the initial planning phase of the Level 2 risk analysis. Once the key members of the risk team have been identified and selected, these questions should be revisited and plans adjusted accordingly.

18-5.2 Team Composition

The composition of the Level 2 risk analysis team is expected to be similar or nearly identical to that of the PFMA team with perhaps some exceptions. Like the PFMA team, the risk team generally comprises:

- Team Leader
- Facilitator(s)
- Core Team
    - Technical representatives from the owner’s staff
    - Subject matter experts
    - Independent Consultant(s)
- Note-takers
- FERC Dam Safety Professionals

- O&M Staff
- Supplemental Resources

The roles of each are similar to the roles and responsibilities described in FERC Engineering Guidelines Chapter 17, Potential Failure Mode Analysis.

In most cases it is likely that the facilitator(s) will be the same for the PFMA and risk analyses; however, there may be occasions that a different facilitator or facilitators are used from the one(s) used to facilitate the PFMA. For example:

1. The PFMA facilitator may not be comfortable or may lack the requisite training and experience to facilitate the Level 2 risk analysis.
2. Because of the complexity of certain project features requiring specialized technical expertise, a separate facilitator may be used to facilitate certain parts of the Level 2 risk analysis (e.g., highly complex mechanical systems with large incremental consequences).
3. Because of the complexity and size of the project, different facilitators than those used for the PFMA may be used for different components of the project.

18-5.3 Qualifications

In general, the qualifications of the facilitator and core team members are similar to those for the PFMA, as described in Chapter 17 of the FERC Engineering Guidelines, with the notable exceptions described in this section. In addition, the criteria for selecting the core team members (technical disciplines, etc.) should be similar to the criteria described for the PFMA core team in Chapter 17 of the FERC Engineering Guidelines.

The qualifications of the risk analysis facilitator include:

- Be a licensed professional engineer or licensed engineering geologist with a minimum of ten years of experience in the design, construction, monitoring, and operation of dams.
- Have experience in dam safety and in participating in risk analyses (semi-quantitative or quantitative) similar to that described in this guidance.
- Have attended a FERC-sponsored semi-quantitative training workshop (or equivalent SQRA training). FERC will periodically provide training opportunities to help develop risk facilitators.
- Have limited prior project experience with respect to examining the particular dam’s operation and history. This is considered an advantageous situation with respect to providing a fresh and vigorous look at the structure.
- Possess good communication and group leadership skills.

Chapter 17 of the FERC Engineering Guidelines provide additional qualifications for a facilitator. In addition to those, the risk facilitator should have previous experience, or be a co-facilitator serving under the supervision and training of an experienced facilitator. They must fully understand the objective and requirements of the Level 2 risk analysis. This ensures that the person leading the risk analysis process knows not only how the process is carried out, but also is aware of what can be accomplished. This is especially critical if the Core Team members have not been through a Level 2 risk analysis. It is also recommended that the risk analysis facilitator have understanding, experience, and training in quantitative risk analysis methods, similar to those described in Best Practices for Risk Analysis in Dam and Levee Safety (BOR/USACE, 2018).

Group dynamics can become even more important in the risk analysis session than in the PFMA session. There is a greater opportunity for heuristics and bias to enter into the process through the estimate of risks. These concepts are discussed in Chapter 17 of the FERC Engineering Guidelines. The facilitator should have the ability to recognize and understand these concepts and the ability to lead the risk team to mitigate these occurrences when they occur.

The Part 12D Independent Consultant and the Level 2 risk facilitator should not be from the same organization.

In general, only those individuals that believe they have sufficient knowledge and understanding of the technical aspects of the potential failure mode should provide risk estimates. It is expected that not all core team members will provide risk estimates for every PFM. Depending on the personalities and self-awareness of the core team members, the facilitator may need to take a more active role in limiting participation of risk estimators for certain types of failure modes.

It is suggested that individuals that provide risk estimates have the following qualifications (in addition to the qualifications of a core team member for a PFMA described in Chapter 17 of the FERC Engineering Guidelines):

- Attended a FERC-sponsored semi-quantitative training workshop (or equivalent SQRA training).
- Have understanding, experience, and training in quantitative risk analysis methods, similar to those described in Best Practices for Risk Analysis in Dam and Levee Safety (BOR/USACE, 2018).

It is important to understand that if the risk analysis facilitator, working with the assembled risk analysis team, does not accomplish the goals of the Level 2 risk analysis, the Level 2 risk analysis may be required to be supplemented or redone entirely.

18-6 LOADING

18-6.1 General

For most dams the likelihood (frequency) of the reservoir loading under normal (static) conditions is typically high. For static or normal loading potential failure modes, the likelihood of reservoir loading can be developed from past reservoir operation records**. If the reservoir is full or nearly full for the majority of the year, a value of one (1) can be conservatively used**. Additional guidance on developing estimates of reservoir loading can be found in the Best Practices in Dam and Levee Safety Risk Analysis, Chapter B-1 Hydrologic Hazard Analysis (BOR/USACE, 2018).

For floods or earthquakes, the likelihood (frequency) of the loading could be small. Therefore, the likelihood of the loading needs to be considered in the risk assessment.

18-6.2 Hydrologic Hazard

Hydrologic hazard curves for Level 2 risk analyses are usually developed from simplified screening processes and typically take the form of annual chance exceedance (ACE) for increasing reservoir levels or flood inflows. An example is shown on Figure 2. In some cases, ACE as a function of release flows, such as for spillway erosion potential failure modes, is also developed. Hydrologic hazard curves should extend far enough out to a frequency that captures the full range of response and project risk. This may require portrayal of the hydrologic hazard curve to frequencies less than what is represented by the Probable Maximum Flood (PMF) – in other words, events more remote than the PMF. More often it is sufficient to truncate the hydrologic hazard curves at a flood representing the threshold of overtopping or to a flood approaching the PMF if the dam does not overtop under such an event, provided the estimated consequences are low.

There are various ways in which such curves can be developed. They typically rely on statistical evaluation of historical information and some method to estimate loading levels for more extreme flood events, possibly performing some limited flood routing using reservoir operating rule curves. **The estimated ACE of a flood that is likely to cause failure indicates the approximate likelihood of hydrologic failure**; however, for reservoirs where there is the potential for large increases in reservoir elevation (i.e., flood risk management dams), it may be necessary to subdivide the entire range of reservoir loading to identify the critical load level (see Section 8.3 for further discussion on critical load level). For qualitative assessments, flood loading is typically limited to existing information or information that can be easily obtained from sources such as the US Geological Survey websites (although data from the USGS websites will be limited to a flood with an ACE of about 1/500).

Guidance on developing hydrologic hazard curves for a Level 2 risk analyses is included in Appendix A. Supplemental information on hydrologic hazard loading can be found in the Best Practices in Dam and Levee Safety Risk Analysis Chapter B-1 Hydrologic Hazard Analysis (BOR/USACE, 2018).

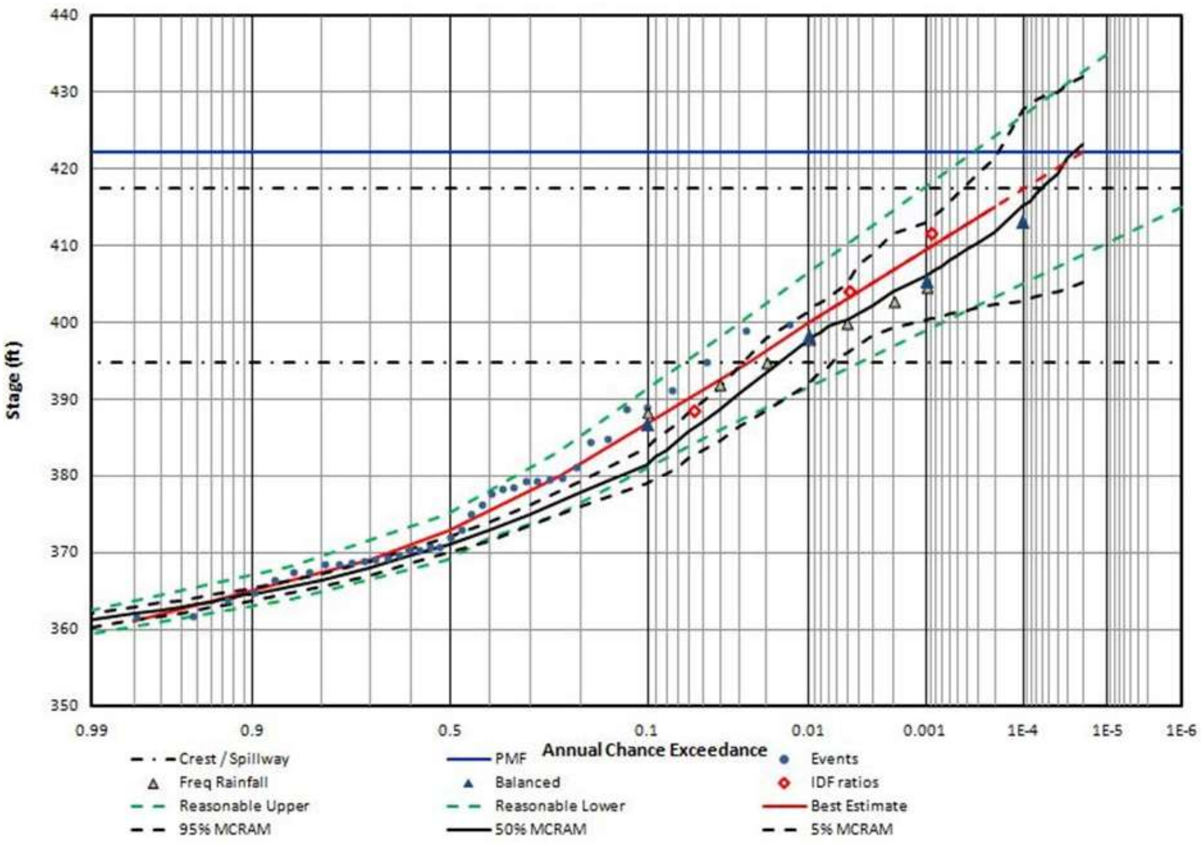


Figure 2: Example of a Stage-Frequency Hydrologic Hazard Curve

18-6.3 Seismic Hazard

An estimate of the seismic hazard at a dam site is typically needed to assess the probability of earthquakes that are likely to lead to dam failure. If a detailed probabilistic seismic hazard study is available for a site, it would be used in the assessment. However, if such a study is not available, simplified seismic hazard curves such as those available from the USGS website are used. Typically, seismic hazard curves with annual exceedance probabilities out to 1/10,000 to 1/50,000 are needed, with the more remote values needed for higher consequence projects. An example probabilistic seismic hazard curve is shown on Figure 3. Seismic hazard curves representing peak horizontal ground acceleration are typically considered. For some concrete and steel structures, seismic hazard curves corresponding to the spectral acceleration at the natural period of the structure may be more useful. **The estimated annual exceedance probability of an earthquake that is likely to cause failure indicates the approximate likelihood of seismic failure**.

For some flood risk management projects, water supply projects, irrigation projects, and other facilities where the reservoir level can vary significantly throughout the year, the probability of the initial reservoir level at the time of the earthquake must also be considered. This information should be obtained from a reservoir stage-duration relationship; for these projects, the approximate likelihood of seismic failure is a function of the joint probability of exceeding a particular reservoir elevation and seismic acceleration.

A general description of probabilistic seismic hazard analyses can be found in Chapter 13 – Evaluation of Earthquake Ground Motions of the FERC Engineering Guidelines. Additional guidance on developing estimates of seismic hazard loading can be found in the Best Practices in Dam and Levee Safety Risk Analysis Chapter BI-2 Seismic Hazard Analysis (BOR/USACE, 2018).

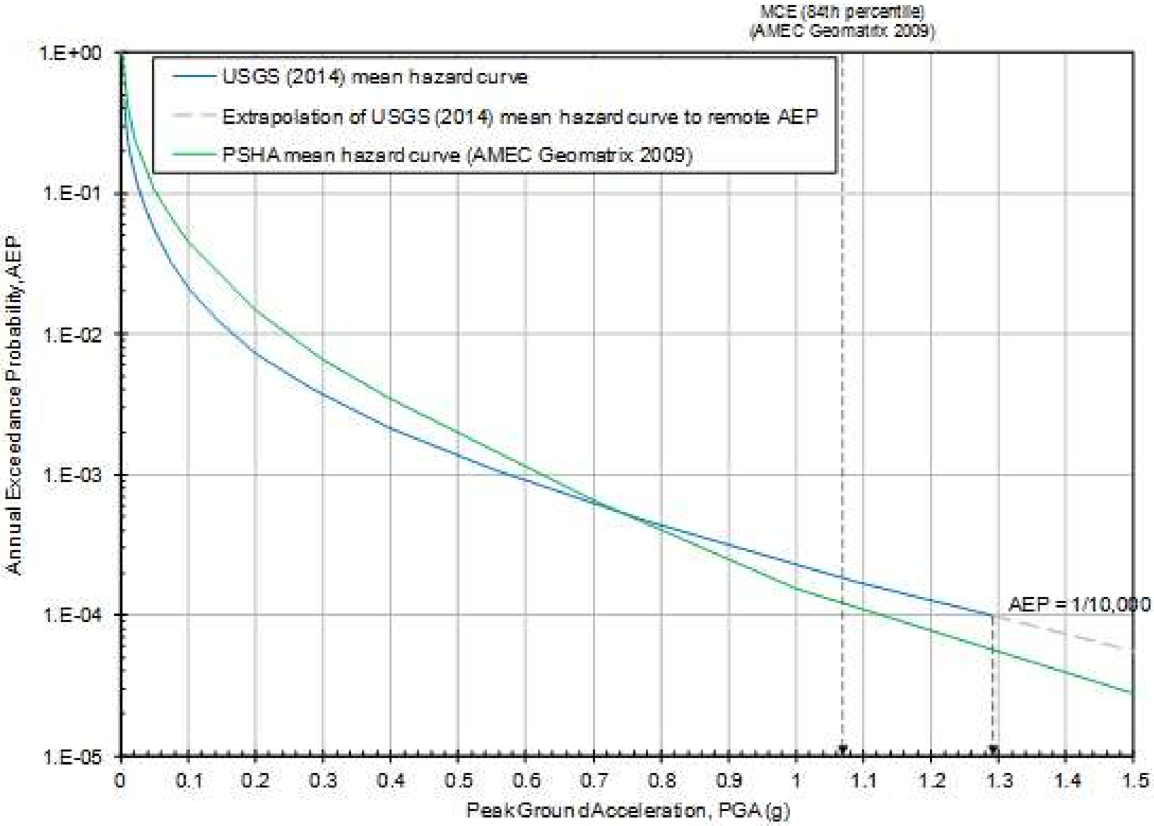


Figure 3: Example of a Probabilistic Seismic Hazard Curve

18-6.4 Other Loading Conditions

The magnitude and frequency of other loads may also be required. These might include environmental conditions such as ice loads, the use of dewatering bulkheads or caissons, and other operational conditions such as changes to reservoir or flood loading due to extended duration maintenance activities or other special circumstances.

18-7 POTENTIAL FAILURE MODES

18-7.1 Identification and Evaluation of Potential Failure Modes

The foundation of the Level 2 risk analysis is the identification and development of a clear and comprehensive list of all of the project's PFMs based on the project's vulnerabilities. If this first step is not diligent and thorough, it can have a significant adverse impact on the results of the risk analysis and may lead to inappropriate or incorrect conclusions and subsequent actions. Missing PFMs, particularly those PFMs that are critical to the estimation of risk, and PFMs that are unclear or are ambiguous have the potential to jeopardize or nullify the results of the risk analysis.

The process of identifying, developing, and evaluating PFMs is documented in Chapter 17 of the FERC Engineering Guidelines.

Candidate potential failure modes that are developed in a PFMA that are considered "credible" – including those considered "credible" and "urgent" – are the potential failure modes that initially are carried forward into a Level 2 risk analysis. Other PFMs, including "ruled-out PFMs" or "clearly negligible PFMs" are not included in a Level 2 risk analysis.

This potential failure mode screening process described in Chapter 17 is shown on Figure 4.

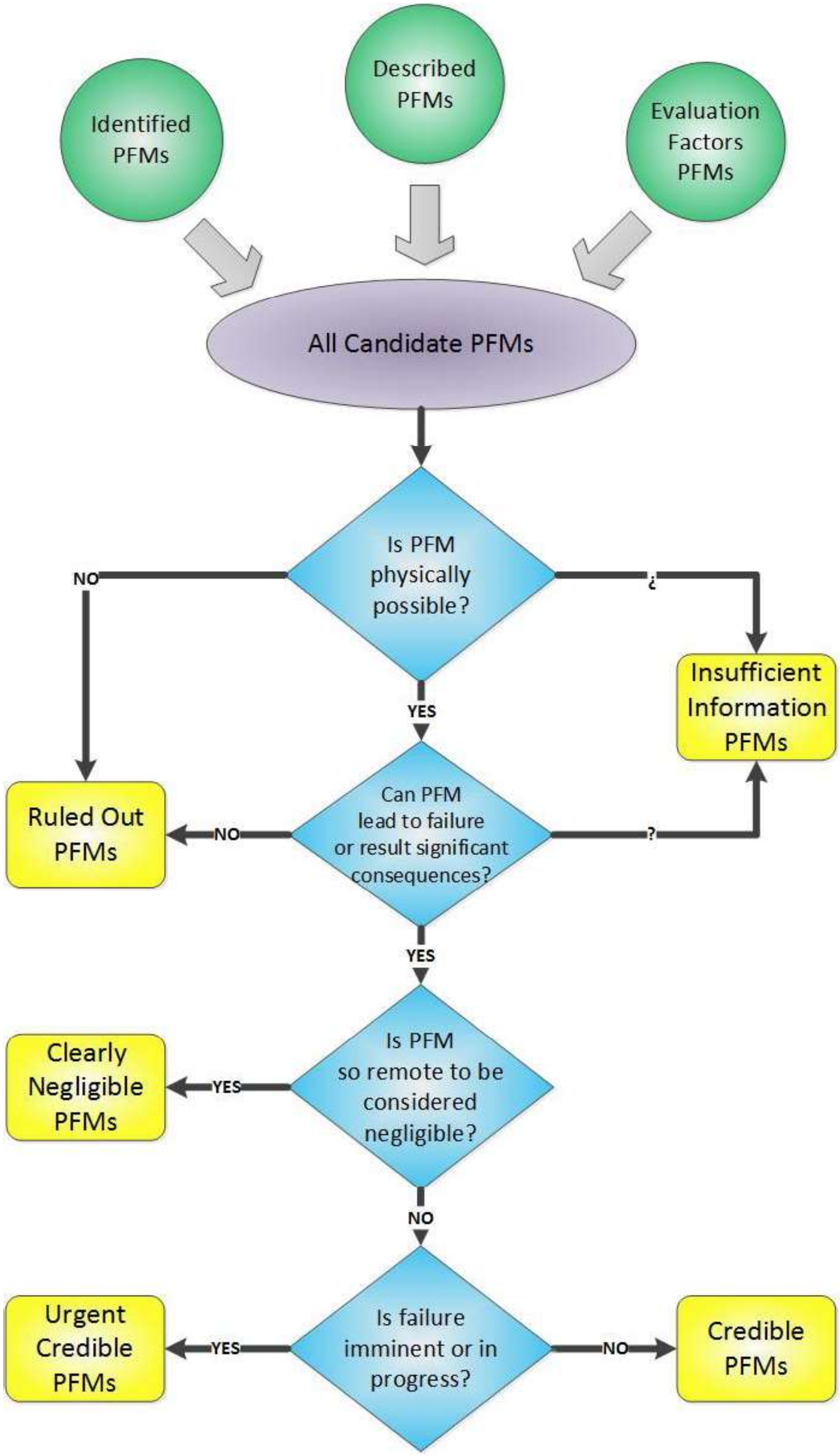


Figure 4: Potential Failure Mode Screening Process

18-7.2 Screening of Potential Failure Modes for Risk Analysis

For most projects the results of the PFMA will generate a large number of credible PFMs. In most cases, not all of these credible PFMs need to be evaluated in a risk analysis. Only those PFMs that substantially contribute to the risk profile of the project need to be evaluated in a risk analysis. This requires that the credible PFMs identified from the PFMA be screened. The goal is to identify those PFMs that need to go into the risk analysis process versus those that do not, which allows the participants to focus their efforts on the PFMs that contribute to the risk profile.

In addition to the information gained from the PFMA, this screening of credible PFMs requires knowledge and understanding of:

1. the estimated loading frequency for the PFM (discussed in Section 6.0),
2. the estimated likelihood of failure for the PFM (discussed in Section 8.0), and
3. the estimated consequences of the PFM (discussed in Section 9.0).

The refined screening of credible PFMs will generally result in the PFMs further differentiated into potentially significant, minor, and insignificant. Potentially significant PFMs are those that contribute substantially to the total project risk while minor PFMs don't significantly contribute to the total project risk. Minor PFMs are those with low consequences – for potential life loss, generally less than 10, as defined in Section 9.0 – that also have likelihood of failure less than 1×10^{-6}, as defined in Section 8.0. Insignificant PFMs are those that after additional evaluation and discussion are considered to be so remote as to be considered negligible (see Chapter 17 of the FERC Engineering Guidelines for additional information). In some cases, after further evaluation and discussion, it may also be possible that a credible PFM may be revised to an urgent, insufficient information, or ruled out PFM based on the definitions included in Chapter 17 of the FERC Engineering Guidelines. The overall PFM screening process is shown in Figure 5.

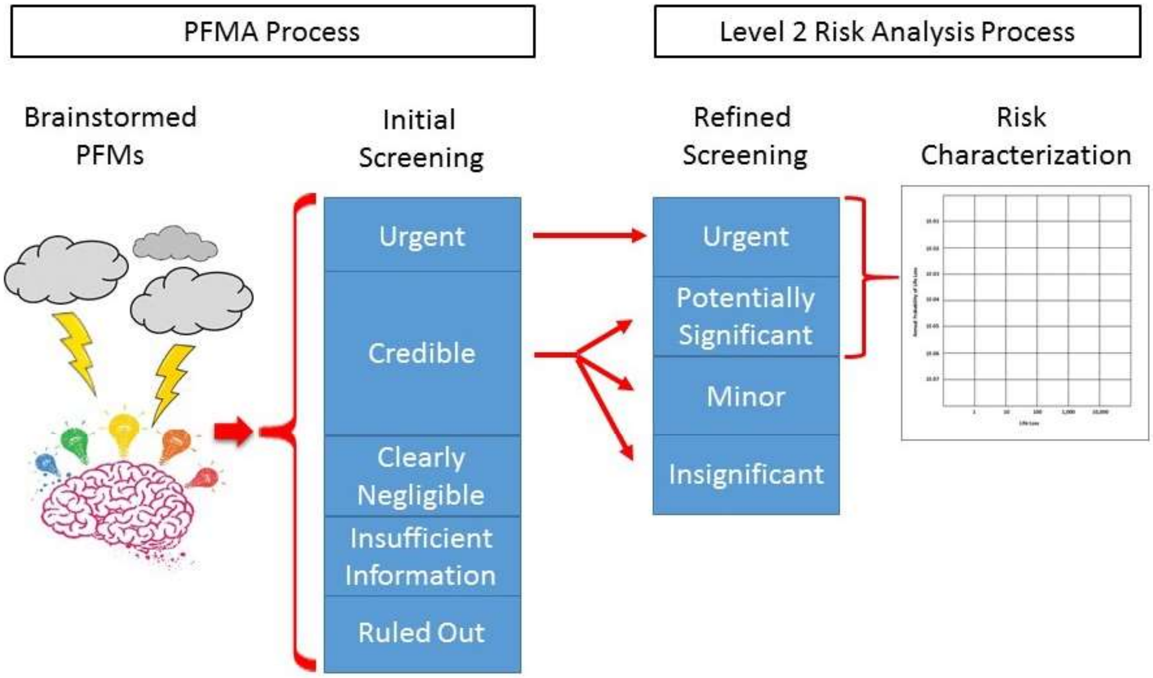


Figure 5: Overall Process of Screening PFMs

Urgent and potentially significant PFMs are carried into the risk analysis. The rationale for why PFMs are classified as minor and are not carried forward into the risk analysis is documented. The following are some example write-ups of the justification of minor credible PFMs:

1. This potential failure mode is considered minor. The combination of a series of highly unlikely events (high reservoir pool, extreme seismic loading, and greater than 20 feet of embankment deformation) and the very limited potential consequences (little to no expected life loss) would result in minor contribution to the overall project risk.
2. This potential failure mode is considered minor. The likelihood of failure of this PFM is considered very low to remote. The rock fractures at the contact with the embankment core material were treated with blanket grouting and slush grout. Dental concrete was used to provide a relatively uniform foundation surface. The first few lifts of embankment core material were placed just wet of optimum moisture content and compacted with a rubber tired roller. The potential consequences of failure would result in little (0 to less than 5 potential life loss). Therefore, the contribution of this PFM to the overall project risk is considered minor.
3. This potential failure mode is considered minor. The likelihood of a landslide mass large enough and traveling fast enough into the reservoir to cause a large,

> rapid generation of a wave that could travel across the reservoir surface and overtop and fail the dam given the large normal freeboard (20 feet) is very low. The consequences of failure for this PFM is less than five individuals. Therefore this PFM would result in minor contribution to the overall project risk.

The rationale for why PFMs are classified as insignificant and are not carried forward into the risk analysis is documented similar to the approach used to document clearly negligible PFMs from the PFMA process (see Chapter 17 of the FERC Engineering Guidelines for more information and examples).

18-8 FAILURE LIKELIHOOD

One component of estimating risk is the probability or likelihood of failure. The likelihood of failure is an estimate of the annual probability of failure (APF) based on the strength and weight of the evidence. Dam failure is often characterized by the sudden, rapid, and uncontrolled rapid release of impounded water. Failure likelihood also includes partial or operational failures that may not lead to an uncontrolled release of the reservoir, but can still result in major consequences. The likelihood of failure is a function of both the probability of the loading condition that could lead to failure (described in Section 6.0) and the likelihood of failure given the loading condition, described below.

18-8.1 Influence Factors

Part of the effort in developing the information to support the failure likelihood for each PFM carried into the risk analysis is identifying the presence of features or susceptibilities that may lead to vulnerabilities for the dam. A susceptibility is a condition or state of nature (e.g., material can crack, internally unstable gradation, continuous uniform fine sand, untreated foundation contact, steep abutment slope with overhangs). Vulnerability can be a process. For example, an embankment that is susceptible to cracking may become vulnerable to concentrated leak erosion (scour).

Factors that may exacerbate or may mitigate vulnerabilities associated with PFMs are identified and evaluated using 'more likely' and 'less likely' factors, and presented in influence tables. Chapter 17 of the FERC Engineering Guidelines provides guidance on developing 'more likely' and 'less likely' factors for each PFM.

For PFMs from previous PFMA reports, these 'more likely-less likely' tables, should be reviewed, revised, and expanded, as necessary. For new PFMs these factors must be developed, including providing analytical results where applicable, and identifying the key factors, in accordance with the guidance provided in Chapter 17 of the FERC Engineering Guidelines.

Some examples of critical information related to factors that may lead to vulnerabilities include the following:

- Internal erosion failure mechanisms and considerations
    - <u>Concentrated leak erosion (scour)</u>: plasticity index, placement moisture content, measured settlement, foundation profile, observed cracking, filters, annual chance exceedance of a flood to reach the elevation of an expected crack or top of filter, etc.
    - <u>Backward erosion piping</u>: continuous fine to medium uniform sand, unfiltered exit, hydraulic gradients, roof material, toe drain or relief well condition, filter compatibility, etc.

  - Suffusion/suffosion: broadly-graded materials with a flat tail of fines, gap-graded material, material within Sherard's unstable band.
  - Erosion into open rock defects: size of the defects, effectiveness of foundation treatment, hydraulic gradient into the foundation, pressurization, etc.

- Instability failure mechanisms and considerations
  - Slope instability: as-built slopes, design factor of safety, seepage and shear strength assumptions, normal freeboard, normal phreatic surface, etc.
  - Foundation or embankment liquefaction: seismicity, peak ground acceleration, cohesionless soils (gravel, sands, or very low plasticity silts), in-situ index (SPT, CPT, BPT, Vs), fines content, normal freeboard, normal phreatic surface, saturation, etc.
  - Monolith instability: design factor of safety, uplift and drain efficiency, foundation conditions, seismic considerations, etc.

- Hydrologic-related failure mechanisms and considerations
  - Overtopping erosion (flood water level plus wind setup exceeds crest elevation): annual chance exceedance of reservoir elevation, overtopping duration, wind setup, crest width, protection, embankment material, knickpoints, etc.
  - Overwash erosion (flood water level plus wind setup does not exceed crest elevation and results in intermittent wave overtopping): annual chance exceedance, threshold flood, freeboard, wave run up, see also overtopping erosion.
  - Unlined spillway erosion: annual chance exceedance of control elevation or damage threshold, weir/sill, erodible materials, headcut distance, armoring, velocity, duration, timing of breach, etc.

Uncertainties should not be listed as 'more likely' or' less likely' factors. Uncertainties should be discussed separately, as discussed in Section 10.2.

18-8.2 Likelihood of Failure Approaches

Three approaches are available for estimating failure likelihood in Level 2 risk analyses:

1. A descriptive approach in which a relative comparison is made to an anchoring annual probability of failure,
2. A critical load approach that involves a more explicit estimation of the annual probability of failure, and
3. A quantitative approach that uses event trees, fault trees or other quantitative methods more typical of quantitative risk analyses.

Each approach is described in the following sections. In all approaches, the 'best estimate' of the failure likelihood is sought. In some cases the range of the 'best estimate' can be provided; however, in these cases the estimates should be clearly identified as such.

18-8.2.1 Descriptive Approach

Examination of historical dam failure rates indicates that dams have failed at a rate of approximately 1 in 10,000 per dam year of operation (for both concrete and embankment dams), depending on the failure mode and age of the structure: Douglas et al. (1998), Foster et al. (1998), Hatem (1985), Von Thun (1985), and Whitman (1984). Using this approach, the likelihood of failure is assessed relative to the historical failure rate. For example, if the key factors affecting the potential failure mode are weighted toward adverse (more likely), the annual failure likelihood is probably greater than 1/10,000. If weighted toward favorable (less likely), then the annual failure likelihood is probably less than 1/10,000.

For this approach the failure likelihood should be estimated using the information contained in Table 1. **For non-dam structures, it may be appropriate to modify the descriptors and annual failure likelihood, tailoring them to the project being evaluated.**

Failure likelihood descriptors in Table 1 include both the frequency of the load **AND** the likelihood of failure given the load.

This approach requires less rigor and may be appropriate for potential failure modes where the likelihood of the loading is high (e.g., during normal operating conditions for dams) or hydrologic potential failure modes where a certain flood is very likely to cause failure, as well as making rapid assessments with appropriately facilitated teams. However, it is difficult to assess potential failure modes where there is not a well-defined flood trigger or threshold to initiate and progress to breach. In this case one of the other approaches may be better suited to assess the likelihood of failure.

Table 1: Failure Likelihood Descriptors

Descriptors/Evidence	Annual Failure Likelihood
There is direct evidence or substantial indirect evidence to suggest it certain to nearly certain that failure is eminent or extremely likely in the next few years.	more frequent (greater) than 1/10
There is direct evidence or substantial indirect evidence to suggest that failure has initiated or is very likely to occur during the life of the structure.	1/10 to 1/100
There is direct evidence or substantial indirect evidence to suggest that failure has initiated or is likely to occur.	1/100 to 1/1,000
The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "more likely" than "less likely."	1/1,000 to 1/10,000
The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "less likely" than "more likely."	1/10,000 to 1/100,000
The possibility cannot be ruled out, the fundamental condition or defect is postulated. Evidence indicates it is very unlikely.	1/100,000 to 1/1,000,000
The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to initiation.	1/1,000,000 to 1/10,000,000
Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood such that the failure likelihood is negligible.	more remote (less) than 1/10,000,000

It should be noted that the verbal descriptors in Table 1 do not work well for estimating the likelihood of failure of electrical and mechanical components. One alternate method to estimate the likelihood of failure of mechanical and electrical components would be to consider the reliability of the critical components in more quantitative terms as described in Section 8.2.3.

For further clarification, a more remote (less than 1/10,000,000) likelihood would be appropriate for the following conditions:

- Remote loading is needed to initiate the potential failure mode. For example, overwash erosion due to inadequate freeboard with the following facts:
  - PMF elevation is within 3 feet of a 30-foot-wide crest
  - The duration of the PMF peak elevation is only 6 hours
  - ACE of the PMF is less than 1/100,000

- Joint-loading probability is remote (e.g., likelihood of a large earthquake resulting in slope instability with large crest deformations in conjunction with a large storm approaching the PMF).
- Several events must occur in series to cause failure, and the likelihood of those events is remote (e.g., undermining of stilling basin slab, downstream toe erosion, progressive slope failure, and overtopping).

The failure likelihood for each potential failure mode can be estimated by an individual or in a team environment, although a team environment is usually preferred. Table 2 illustrates these two processes.

Table 2: Team vs. Individual Failure Likelihood Development Process

Team-Based	Individual-Based
○ After initial discussions, ask each team member to make their individual estimate of the failure likelihood prior to further discussion, considering whether the evidence is weighted more toward likely or unlikely, and then discuss.	○ The individual makes an estimate of the failure likelihood, considering whether the evidence is weighted more toward likely or unlikely.
○ Elicit failure likelihood from each team member, along with the reasoning behind their estimate. This typically prompts discussion among team members. After the discussion has died down, the facilitator summarizes what has been said, proposes a "consensus" likelihood and the reasoning why it makes sense, and then asks if there are any objections. If objections are raised, additional discussion ensues, and the process is repeated. If a consensus cannot be reached, the range of descriptors is captured along with the reasons for each.	○ N/A
○ The facilitator or designated recorder captures the information, including the likelihood and the rationale for its assignment. The confidence in the rating is also captured, along with the rationale for its assignment and what additional information could be gathered to improve the confidence rating, if applicable.	○ Document the information, including the likelihood and the rationale for its assignment. The confidence in the rating must also be documented, along with the rationale for its assignment and what additional information could be gathered to improve the confidence rating, if applicable.

18-8.2.2 Critical Load Level Approach

In developing estimates for the likelihood of failure, it can be important to determine the critical load level (annual chance exceedance) for the potential failure mode being evaluated. This is particularly important for potential failure modes where the frequency of the load varies (flood, seismic, etc.). The likelihood of failure is a function of both the likelihood of the loading condition that could lead to failure and the likelihood of failure given the loading condition. For normal operating conditions, the likelihood of the loading is high. However, for floods or earthquakes, the likelihood of the loading could be small. Therefore, the failure likelihood estimate can be improved by considering the likelihood of the loading. This requires identifying the critical loading level for the potential failure mode under consideration. For seismic potential failure modes, the probability of the earthquake and the coincident water level must be considered. At high annual chance exceedance, the performance of the dam might be expected to be very good; however, as the ACE decreases and the magnitude of the load increases, the performance of the dam may decrease to the point where failure could become likely. Where this expected performance indicator changes is a critical load level.

For example, tailwater can significantly affect the critical load level. The maximum high pool may result in a lower differential hydraulic head for initiation of a potential failure mode and breach at that reservoir level and may result in lower incremental life loss due to warning and evacuation of the population at risk (PAR) for uncontrolled spillway releases prior to breach. In this case, a reservoir level at the spillway crest may be more critical for differential hydraulic head and result in higher incremental life loss. If the ACE of the flood for the critical load level (from a reservoir stage-frequency relationship) is virtually certain to cause failure, then the annual probability of failure is essentially equal to the ACE of that flood.

It is suggested to start the failure likelihood with the ACE of the critical load level, and then reduce that probability based on the likelihood of the step-by-step progression leading to failure (i.e., subsequent nodes in an event tree have probabilities less than one). With this approach a more precise estimate of the range of APF can be made than the semi-quantitative/descriptive approach. However, estimating the critical loading level can be difficult, especially when the performance is not well understood for the full range of loading and there is not a well-defined trigger or threshold to initiate and progress to breach.

For example, the ACE becomes smaller at higher and higher reservoir water surface elevations. An overtopping potential failure mode is typically not a concern until the reservoir elevation approaches the dam crest elevation or some other critical elevation. This may occur before the reservoir elevation reaches the PMF elevation. More frequent floods than the PMF may result in overtopping, erosion, breach, and failure of the dam.

The following is an example. Consider a potential failure mode of foundation liquefaction for an embankment dam. The probability of the seismic load from a probabilistic seismic hazard analysis (PSHA) is shown on Figure 6. Seismic and deformation analyses have been performed for the dam for various seismic loads and the results indicate that for levels of ground shaking below 0.2g, liquefaction is very unlikely. For ground shaking above 0.9g liquefaction and dam failure is very likely. For ground shaking of 0.5g, liquefaction and dam failure is likely. From this information the probability of failure given certain levels of shaking was estimated and is shown on

Figure 7. So the question is, what is the critical load level that should be considered in the risk analysis?

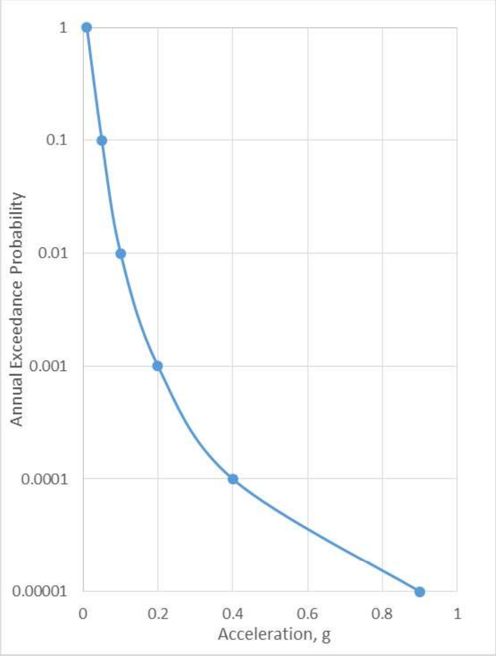


Figure 6: Probabilistic Seismic Hazard Loading Curve

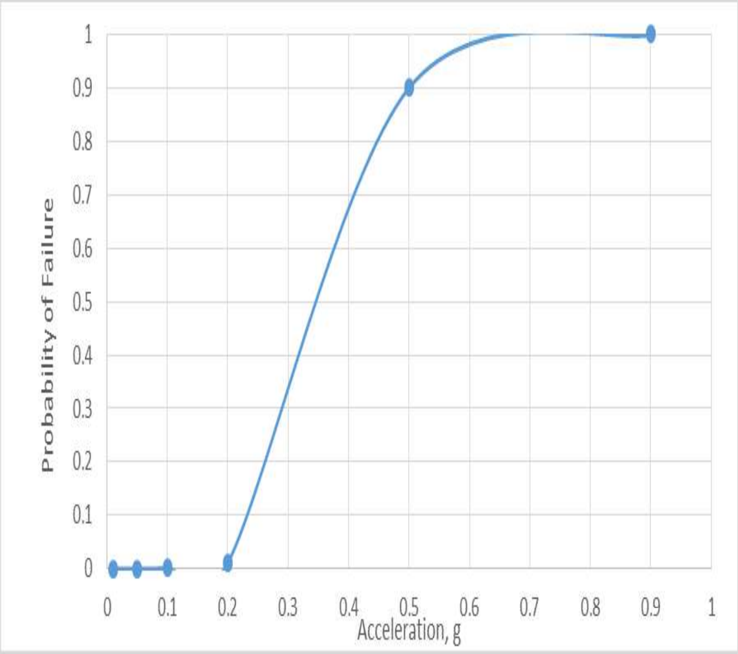


Figure 7: Probability of Embankment Failure for Various Levels of Seismic Shaking

By inspection of the curves on Figures 6 and 7, the answer to that question may not be immediately obvious. Is the critical load case a result of the highest level of shaking or is it for a lower level of shaking?

Starting at the highest load level, the annual exceedance probability (AEP) is 1 x 10^{-5}. The likelihood of failure at this load level is 1, so the approximate annualized probability of failure (between 1 x 10^{-5} and 1 x 10^{-4}) is 8.6 x 10^{-5}. The next lowest load level the AEP is 1 x 10^{-4}. The likelihood of failure at this load level is 0.9, and the approximate annualized probability of failure (between 1 x 10^{-4} and 1 x 10^{-3}) is 4.1 x 10^{-4}. This can be done for each load level as shown in Table 3. This quick evaluation shows that the second to the highest load level is the critical load level.

Table 4 shows the various load levels used in the example and the resulting failure likelihood ranges indicating a higher failure likelihood for the critical load level in bold text.

Table 3: Critical Load Level Example

AEP	Acceleration, g	Emb. Failure Estimate	Incremental AEP	Avg. Prob. of Failure	Annual Prob. of Failure	Comments
1	0.01	0				
			0.9	0	0	
0.1	0.05	0				
			0.09	0.0005	4.5 x 10^{-5}	
0.01	0.1	0.001				
			0.009	0.0055	5.0 x 10^{-5}	
0.001	0.2	0.01				
			0.0009	**0.455**	**4.1 x 10^{-4}**	**Critical Load Level**
0.0001	0.5	0.9				
			0.00009	0.95	8.6 x 10^{-5}	
0.00001	0.9	1				

Table 4: Critical Load Level Example with Failure Likelihood

AEP	Acceleration, g	Embankment Failure Estimate	Annual Probability of Failure	Failure Likelihood Range
1	0.01	0		
			0	None
0.1	0.05	0		
			4.5 x 10^{-5}	1 x 10^{-4} to 1 x 10^{-5}
0.01	0.1	0.001		
			5.0 x 10^{-5}	1 x 10^{-4} to 1 x 10^{-5}
0.001	0.2	0.01		
			4.1 x 10^{-4}	**1 x 10^{-3} to 1 x 10^{-4}**
0.0001	0.5	0.9		
			8.6 x 10^{-5}	1 x 10^{-4} to 1 x 10^{-5}
0.00001	0.9	1		

The information and rationale for determining the critical load level for each potential failure mode should be captured and documented in the report.

18-8.2.3 Quantitative Approach

If one finds difficulty estimating the failure likelihood using the previously discussed approaches, then an alternate approach could be to use event trees or fault trees. Event tree analysis is a commonly used tool in dam safety risk analysis to identify, characterize, and estimate risk. Quantitative estimates for probability of breach or failure and the resulting consequences can be obtained using event trees. Qualitative depictions of potential failure modes and consequences can also be developed using event trees.

For some it is common practice to develop detailed event trees for individual potential failure modes to clearly identify the full sequence of steps required to obtain failure or breach. If the potential failure mode description is complete, then construction of an event tree should be relatively straight forward. A logical progression of events is represented by the event tree beginning with an initiating event and continuing through to a set of outcomes. A typical progression might include an initiating event (flood or earthquake) followed by a system response (breach or non-breach) resulting in potential consequences (life loss, economic). Additional contributing events such as inoperable spillway gates (initiating event), flood fighting (system response), and exposure (consequences) should also be considered in the event tree. In the case of using an event tree for the failure likelihood the consequence part of the event tree would not be included.

An event tree consists of a sequence of interconnected nodes and branches. Each node defines a random variable that represents an uncertain event (a crack forms in the embankment) or state of nature (existence of adversely oriented joint planes). Branches originating from a node represent each of the possible events or states of nature that can occur. Probabilities are estimated for each branch to represent the likelihood for each event or condition. These probabilities are conditional on the occurrence of the preceding events to the left in the tree. Nodal estimates can be estimated by subjective probability using Table 5.

Table 5: Subjective Probability Descriptors

Descriptor	Associated Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

Risks are typically annualized (e.g. probability of breach per year or annual life loss) in the event tree by using annual probabilities to characterize the loading conditions. The conditional structure of the event tree allows the probability for any sequence of events to be computed by multiplying the probabilities for each branch along a pathway. The branching structure of the event tree, which requires that all branches originating from a node be mutually exclusive and collectively exhaustive, allows the probability for any combination of events (e.g. total failure probability for a potential failure mode) to be computed by summing branch probabilities across multiple pathways.

Event trees can be developed for individual potential failure modes to clearly identify the full sequence of steps required to obtain failure or breach. Each potential failure mode is decomposed into a sequence of component events and conditions that all must occur for the breach to develop. This ensures that due consideration is given to each event in the failure sequence. It also supports the identification of key issues contributing to the risk. A typical event tree structure for an internal erosion potential failure mode is illustrated in Figure 8. A challenge with estimating probabilities for event trees is remembering that each branch is conditional on predecessor branches.

Additional guidance on use of event trees for dam safety risk analysis is provided in Best Practices in Dam and Levee Safety Risk Analysis, Chapter A-5 Event Trees (BOR/USACE, 2018).

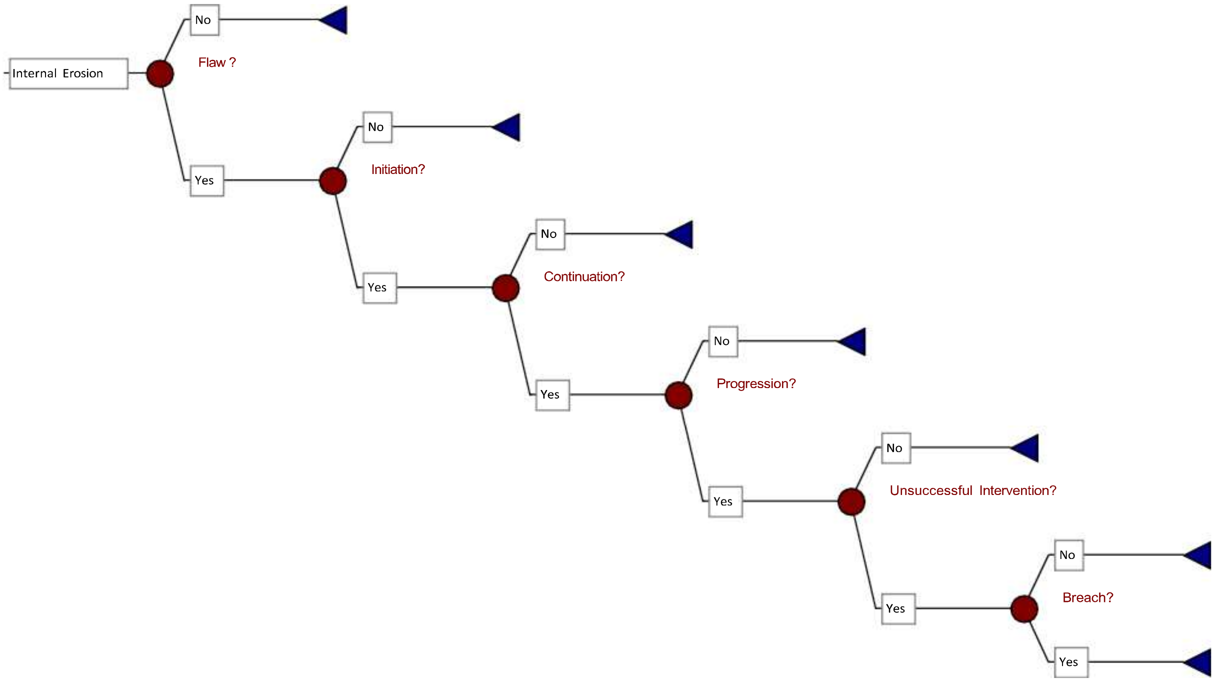


Figure 8: Example Internal Erosion Potential Failure Mode Event Tree (BOR/USACE, 2018)

18-8.3 Intervention

The potential for intervention to reduce the likelihood of failure must be considered when estimating the failure likelihood. In some cases it may be appropriate to consider cases with and without intervention. The likelihood that intervention is successful should be based on realistic estimates, considering whether procedures are in place, materials are available, and personnel are adequately trained, among other factors. Successful intervention is not guaranteed even with the most qualified responders.

18-8.4 Failure Likelihood Justification

The rationale for the selected failure likelihood for each potential failure mode should be synthesized from the pertinent information from the background, performance, and more likely/less likely table to build the case for the failure likelihood. The rationale should include critical information related to susceptibilities (discussed above) that may lead to vulnerabilities. This should also include a discussion of the key pieces of evidence that drove the team's assigned descriptor for failure likelihood. The rationale should clearly document the team's assumptions and understanding so that future reviews of the information and discussion can understand what the team was thinking and whether there are changed conditions, improved knowledge, or improved state of practice that would affect the risk assessment.

18-9 CONSEQUENCES

18-9.1 General

An evaluation of dam failure case histories (Graham, 1999) indicates that the number of fatalities is primarily dependent on:

1. The population at risk (PAR) within the dam-break inundation boundary,
2. The severity of the flooding, and
3. The amount of warning time the PAR has to evacuate the area.

Other significant considerations include the degree to which the PAR understands the seriousness of the potential flooding and the availability and clarity of possible evacuation routes. The PAR can be broadly categorized by the size of the towns and development within the inundation zone as well as transient activity (e.g., seasonal campgrounds). The severity of flooding is a function of the potential destruction to structures and infrastructure within the floodplain. The warning time is a function of when the warnings are issued and the time it takes for the flood wave to reach the PAR.

Additional guidance on developing consequence estimates can be found in the Best Practices in Dam and Levee Safety Risk Analysis Chapter C-1 Consequences of Flooding (BOR/USACE, 2018).

18-9.2 Life Safety Consequences

Considering all of these aspects of consequence evaluation, the broad consequences used for Level 2 risk analyses are shown in Table 6. For non-dam structures, it may be appropriate to modify the descriptors, tailoring them to the project being evaluated.

Similar to the failure likelihood process described in Section 8.3, this process is repeated to arrive at a consequence estimate for each potential failure mode. It is especially important during this process to note differences between the likely breach flows associated with a potential failure mode and what has been assumed in the breach inundation studies. In many cases, the breach outflow associated with a potential failure mode would be considerably less than assumed in the inundation studies.

The potential for evacuation must be considered when estimating the life loss consequence. In the case of breach risks, incremental consequences (consequences over and above those that would occur without failure) are considered when assigning the consequences. For non-breach risks associated with planned operational releases, total consequences drive the consequence estimates.

Table 6: Life Safety Consequences

Incremental Life Loss	Description
None expected	No significant impacts to the downstream population other than temporary minor flooding of roads or land adjacent to the river
Less than 1	Although life-threatening releases occur, direct loss of life is unlikely due to severity or location of the flooding, or effective detection and evacuation
1 to 10	Some direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travelers and small population centers
10 to 100	Large direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/ travelers and smaller population centers, or difficulties evacuating large population centers with significant warning time
100 to 1,000	Extensive direct loss of life can be expected due to limited warning for large population centers and/or limited evacuation routes
1,000 to 10,000	Extremely high direct loss of life can be expected due to limited warning for very large population centers and/or limited evacuation routes
Greater than 10,000	Catastrophic direct loss of life can be expected due to little to no warning for very large population centers and/or limited evacuation routes

The case for consequences must be built as rigorously as for the failure likelihood and for this level of risk analysis, an order-of-magnitude of estimated life loss is more important than discrete values.

The essential elements of building the case for consequences include the following:

- Initial distribution of people
    - Primary impact areas: communities, residential / commercial / industrial, state / county
    - Estimated population at risk
    - Distance downstream from dam
    - Spatial location and population density

- Redistribution of people (evacuation effectiveness)
    - Warning: flood forecast or breach detection, communication lag, warning issuance time (relative to breach initiation), initial non-breach warning (double warning scenario), warning dissemination system (EAS, sirens, reverse 911 and effectiveness but also improvements by word-of-mouth due to dense urban environment, sheriff door-to-door or drive-by announcement)
    - Response (mobilization): clarity of warning message; similar warnings or experiences in past; physically unable; kids, pets, livestock, valuables, etc.; desire to protect home and property; nowhere to go; evacuation plan, etc.
    - Evacuation potential (ability to get to safety before water arrives): distance to clear inundation limits, special evacuation assistance facilities, available road network or routes, traffic density and jams, etc.

- Flood characteristics
    - Flood wave arrival time, depth, and velocity (all from hydraulic model) if available

- Shelter provided by final location
    - Potential for vertical evacuation and shelter in-place: number of stories
    - Survivability: structure damage, human stability, and vehicle stability

Similar to the failure likelihood, the rationale for the consequences selected should be synthesized from the pertinent information from the background, performance, and more likely/less likely table to build the case for the consequences selected. The rationale should clearly document the team's assumptions and understanding so that future reviews of the information and discussion can understand what the team was thinking and whether there are changed conditions, improved knowledge, or improved state of practice that would affect the risk assessment.

18-9.3 Economic and Environmental Consequences

Separate bins for economic consequences are used where the economic consequences may be the deciding factor on taking action or not. These economic consequences are shown in Table 7. These are relative rankings and are not tied to tolerable risk guidelines. **They are in no way to be equated to the life loss descriptors to arrive at a value for human life.** In a general sense, each descriptor represents an order of magnitude range in consequences.

18-9.4 Other Consequences

Other types of consequences should be considered and evaluated in the risk estimates. These include cultural, historic, and other non-monetary consequences. Qualitative impacts from these types of consequences should be identified and described and, where possible, qualitatively estimated. Examples of these types of consequences include:

- Historic sites and landmarks
- Culturally significant sites
- Unique or regionally- or nationally-significant sites

Table 7: Economic and Environmental Consequences

Incremental Economic Loss ($)	Description
None expected	No significant economic or other impacts.
Less than 10M	Downstream discharge results in limited property and/or environmental damage.
10M to 100M	Downstream discharge results in moderate property and/or environmental damage.
100M to 1B	Downstream discharge results in significant property and/or environmental damage.
1B to 10B	Downstream discharge results in extensive property and/or environmental damage.
10B to 100B	Downstream discharge results in extremely high property and/or environmental damage.
greater than 100B	Downstream discharge results in catastrophic property and/or environmental damage.

18-10 OTHER CONSIDERATIONS

18-10.1 Confidence

An essential part of the evaluation is to capture the confidence in the selecting the failure likelihood and consequences. Confidence is a qualitative measure of belief that the information, engineering analysis results, and risk estimate is reasonable. Confidence is used to describe how sure the risk analyst/team is about the risk estimate. Confidence estimates are used by decision makers to inform the potential need to take (or not take) action to reduce risk or to reduce sources of uncertainty.

Factors that influence confidence include:

- Quantity and quality of the information available
- Representiveness of the information
- Information/analysis results accurately capture the expected performance

Confidence categories and qualitative descriptors should be provided for both the failure likelihood and consequence categories using the categories and descriptors provide in Table 8.

Table 8: Confidence Categories

Confidence Category	Description
High	The individual/team is confident in the assigned order of magnitude descriptor and it is unlikely that additional information would change the estimate.
Moderate	The individual/team is relatively confident in the assigned order of magnitude descriptor, but key additional information might possibly change the estimate.
Low	The individual/team is not confident in the assigned order of magnitude descriptor and it is entirely possible that additional information would change the estimate.

A potential failure mode rated with ‘low’ confidence, particularly if risk-reduction actions are indicated, would probably require additional investigations or analyses before taking risk-reduction action. However, if it is rated with ‘high’ confidence, it may be appropriate to go directly to interim risk-reduction actions or in some cases long-term risk reduction actions. In some cases, the team will have ‘low’ confidence in an assigned descriptor but cannot think of any additional information that could be collected to improve their confidence. These cases are documented. The lack of information is not low confidence. When assigning confidence descriptors, the reasoning behind the descriptor and the information that could be gathered to improve the rating should also be captured in the documentation.

18-10.2 Accounting for Uncertainty

Uncertainty is the result of imperfect knowledge. Uncertainty is used to portray variability or a range of values for loads, consequences, failure likelihoods, and risk estimates. All risk estimates must provide a qualitative assessment of uncertainty.

It is acknowledged that given the limited information and resources available for risk estimates and the qualitative nature of these estimates, uncertainty about the risk estimates can be high. The estimates of risk are provided for the expected value/mean value of risk for each PFM. Likewise, the uncertainty about the expected value/mean value of risk is what should be provided and not the overall uncertainty that would be provided by the wider range of all possible outcomes.

Sources of uncertainty and potential actions that could be taken to reduce that uncertainty should both be identified.

18-10.3 Potential Dam Safety Management Activities

After the confidence and uncertainty has been assessed, potential dam safety management activities should be discussed and documented for each PFM. These dam safety management activities include:

- Potential Risk Reduction Measures,
- Inspections,
- Surveillance and Monitoring,
- Emergency Action Plan,
- Follow-up Studies, and
- Other.

Each of these are discussed in more detail in Section 4.7.10 of Chapter 17 of the FERC Engineering Guidelines.

18-10.4 Close-out Activities

Similar to conducting only a PFMA, at the end of the risk analysis session, the facilitator should ask the participants to reflect on what they learned during the risk analysis process. After a few minutes the facilitator should ask the participants to state what were the Major Findings and Understandings (MFU) they gained during the risk analysis session. Typically, this is done by going around the room and asking each participant to provide an MFU and then starting again with the first person until all participants have had the opportunity to express their findings. MFUs may relate directly to a PFM or may reflect a more general understanding about the dam or the risk analysis process.

If any MFU describes a serious dam safety issue, this should be immediately brought to the attention of the FERC-D2SI Regional Office.

The "Major Findings and Understandings" should be documented immediately after the session. The items noted during the session are typically abbreviated and should accurately reflect what the individual participants stated as their major finding or understanding gained during the session. Where the MFU relates to a PFM, a brief discussion (3 to 5 sentences) relating the MFU to the PFM should be prepared and included with the MFU. The write up of the major findings and understandings is then sent to the facilitator and the other core team members for review.

See Chapter 17 of the FERC Engineering Guidelines for an example write-up of major findings and understandings.

18-11 ESTIMATING AND PORTRAYING RISKS

18-11.1 Risk Estimates

Risk estimates for each of the risk measures are portrayed and assessed as described in the following sections.

18-11.1.1 Societal Incremental Life Safety Risk

A Level 2 risk matrix has been established to portray the societal incremental life safety risk (due to failure) associated with the identified potential failure modes, with likelihood of failure on the vertical axis (using cell divisions corresponding to the failure likelihood previously described) and the associated incremental consequences on the horizontal axis (using cell divisions corresponding to the consequences previously described). The matrix is similar to the f-Ñ/F-N diagram used to portray societal incremental life safety risk estimated from quantitative risk assessments (see Chapter 3 of FERC's RIDM Risk Guidelines). Figure 9 illustrates the societal incremental life safety risk matrix.

Cells of the societal incremental life safety risk matrix, defining the failure likelihood and consequences, correspond to order of magnitude divisions on the f-Ñ/F-N diagram. Societal risk guidelines are not portrayed on the Level 2 risk matrix as generally the results of a Level 2 risk analysis are not sufficiently robust to evaluate the tolerability of risk.

Potential failure modes with no life safety consequences can be excluded from the risk matrix or plotted as a line on the vertical axis at the far left end of the matrix.

Likelihoods of failure less than 1E-08/yr are not explicitly represented on the incremental risk matrix.

Using the appropriate failure likelihood and consequences, each significant potential failure mode is plotted on the risk matrix, as shown on Figure 10. For those instances when the risk analysis team could not reach consensus on a single order of magnitude descriptor, then the range of estimates of the best estimate is plotted on the matrix and the rationale for that range is provided in the report.

The total societal incremental life safety risk is also plotted on the risk matrix. The total societal incremental life safety risk is the sum of the risks from each of the individual potential failure modes plotted on the risk matrix. The methodology for determining the total societal incremental life safety risk should be in accordance with SQRA Calculation Methodology (USACE, 2018).

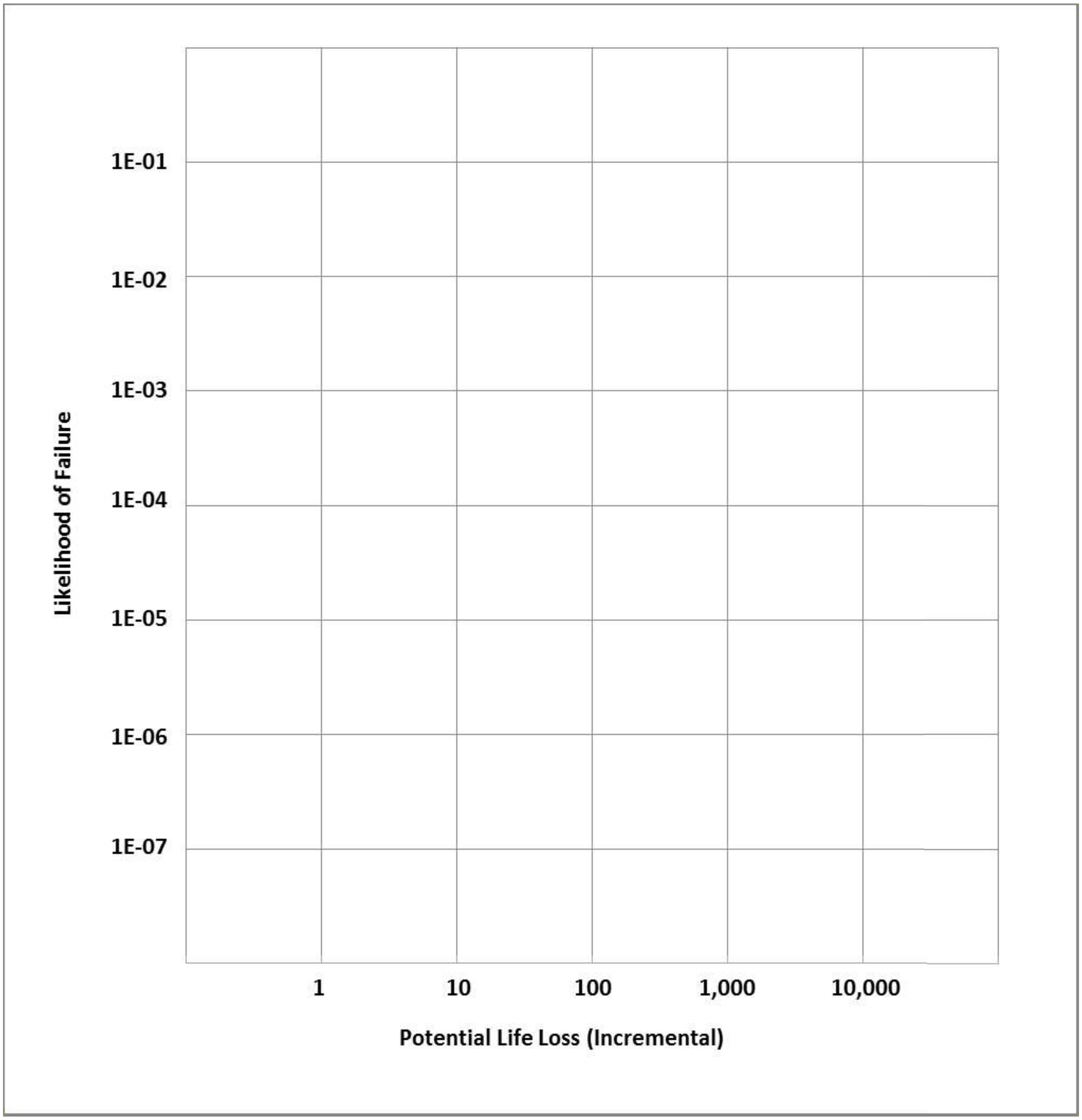


Figure 9: Risk Analysis Matrix for Societal Incremental Life Safety Risk

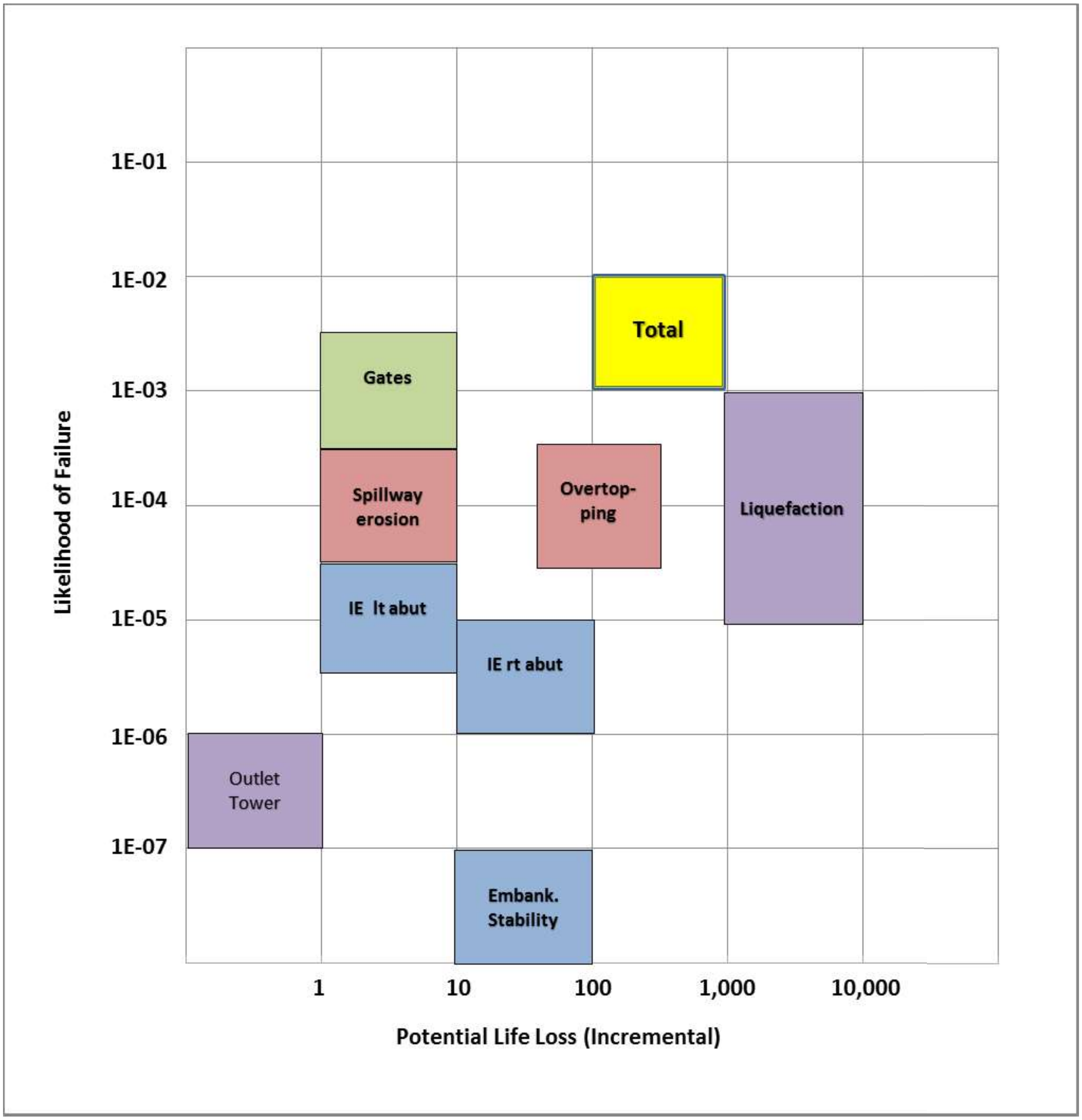


Figure 10: Example of a Risk Analysis Matrix for Societal Incremental Life Safety Risk

18-11.1.2 Non-Breach Life Safety Risk

Non-breach risks are associated with operations, typically involving release of large quantities of water through spillways in order to prevent the dam from overtopping. In some cases, the planned releases are large enough to cause damage and threaten lives. However, risks associated with these conditions are smaller than if the dam were not there (i.e., in the absence of a breach, the peak regulated discharge is most likely less, and rarely more, than the unregulated discharge).

The AEP when the public would begin to experience flooding due to spillway release and the AEP when life loss would start to occur are important to understand and communicate. The AEP for flooding is typically related to spillway releases. However, the annual probability of when life loss would start to occur depends on the specific situation but is typically less than the AEP for flooding. Failure to consider these larger, less frequent flood events results in an underestimation of the non-breach risk (USACE, 2018).

Warnings that would go out prior to impacting the PAR with planned releases must be taken into account in assessing the consequences. Total consequences are typically estimated. Thus, the incremental risks of comparing to the case of no dam are not captured. The results are plotted on a separate non-breach life safety risk matrix, as shown on Figure 11. This is similar to the societal incremental life safety risk matrix described previously, but the vertical axis is labeled “Likelihood of Life Loss” and no tolerable risk limit lines are shown since they are not applicable to non-breach conditions. An example plot is shown on Figure 12. The likelihood of life loss or AEP when life loss begins to occur is plotted on the vertical axis of the non-breach risk matrix. For non-breach risks, the same consequence categories in Table 6 are used. Consequences associated with planned operational releases typically drive the non-breach consequence category.

If there is downstream flood risk management or water supply infrastructure (e.g., dams or levees) that could be overtopped by operational spillway releases, the frequency of the flood that would overtop those structures and the consequences resulting from overtopping (but not due to failure) of those structures are included. Further guidance on estimating non-breach risks is provided in SQRA Calculation Methodology (USACE, 2018).

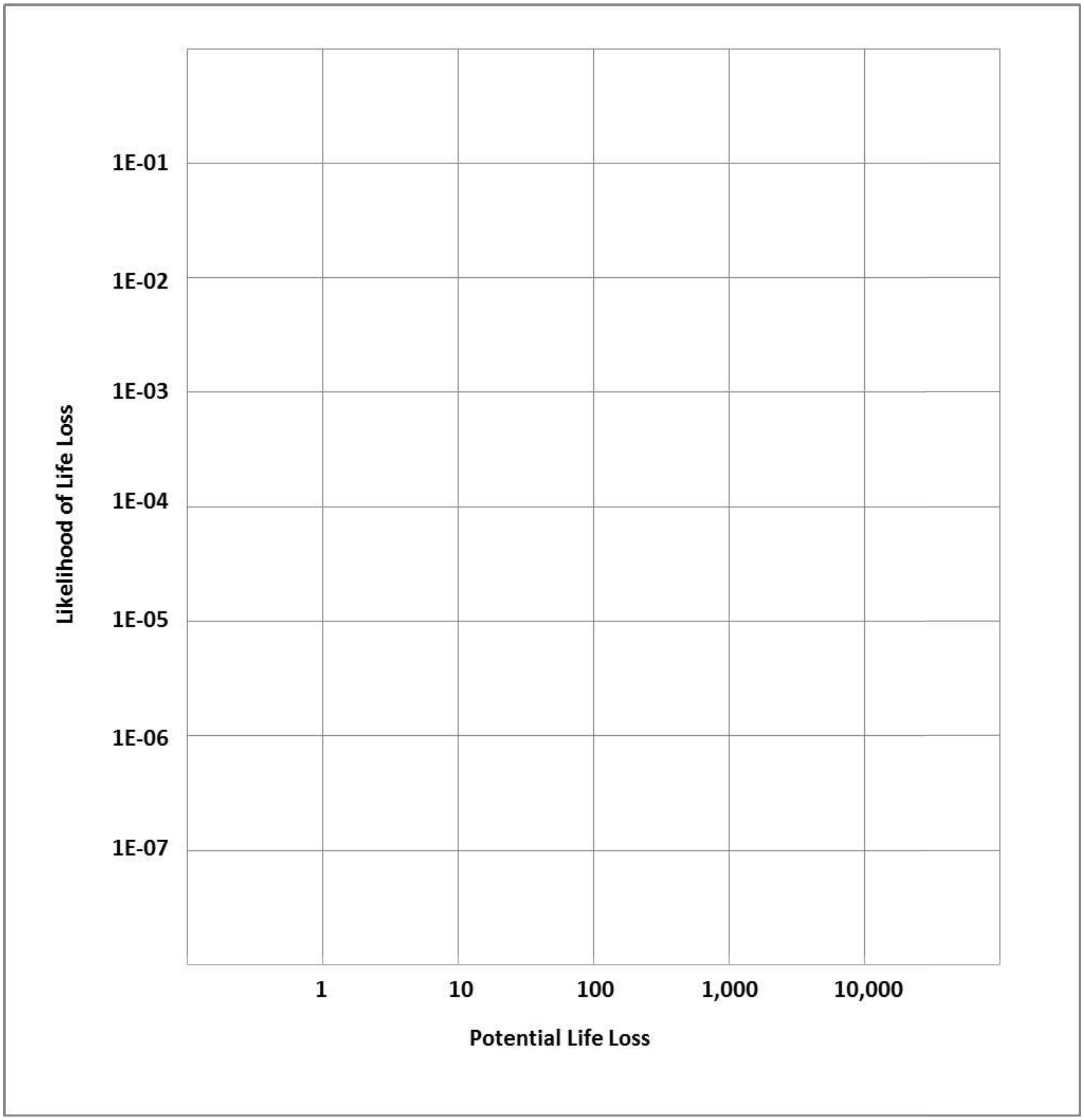


Figure 11: Risk Analysis Matrix for Non-Breach Life Safety Risk

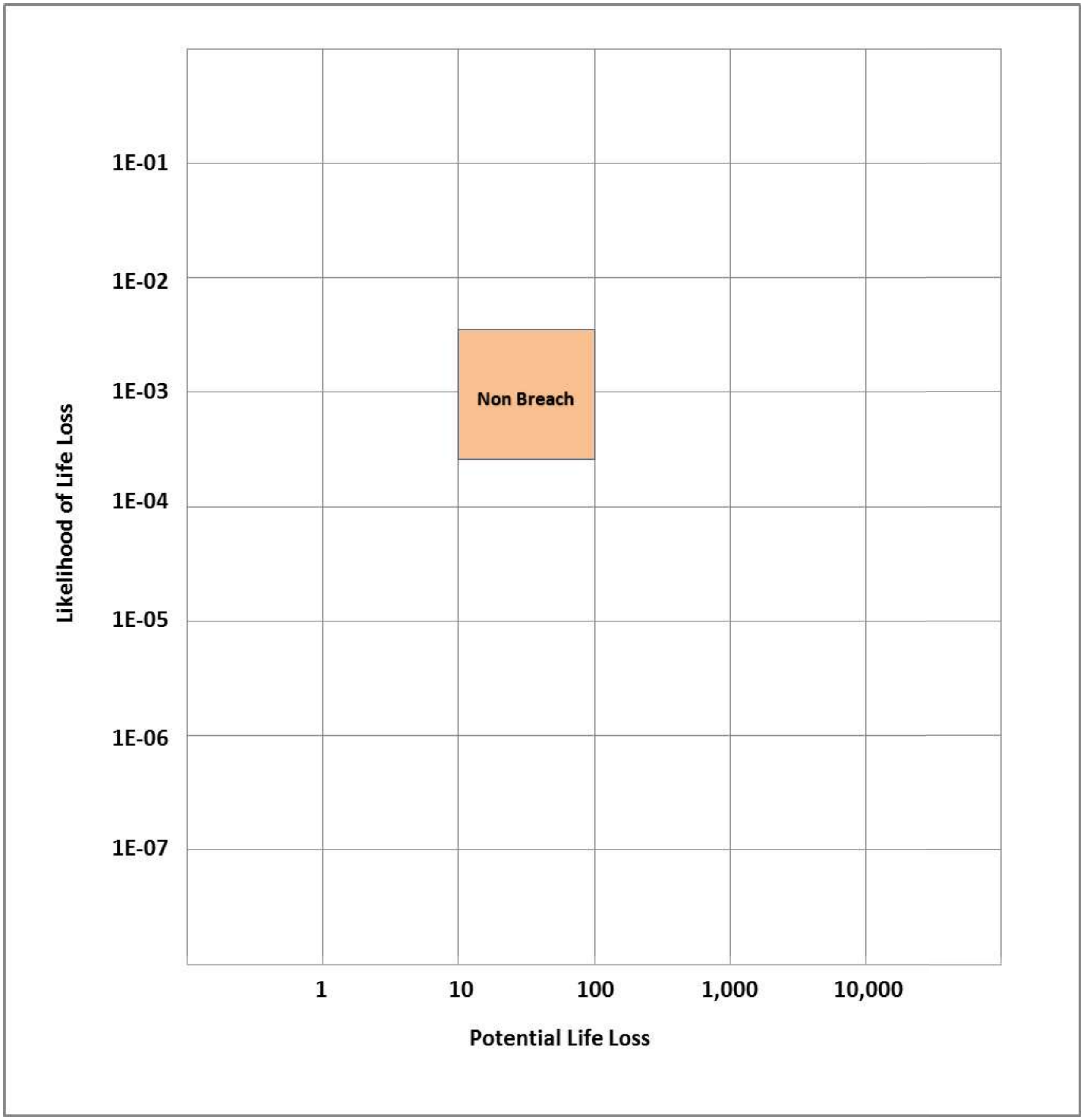


Figure 12: Example of a Risk Analysis Matrix for Non-Breach Life Safety Risk

18-11.1.3 Annual Probability of Failure

Annual probability of failure (APF) is estimated for those potential failure modes associated with the incremental risk. Annual probability of failure is estimated from all potential failure modes associated with all loading or initiating event types. Although the combined annual probability of failure of all potential failure modes is to be provided, it is important that the contributions to the APF from the individual potential failure modes, loading types, and loading ranges, etc., are analyzed.

Annualized probability of failure is approximately represented by the likelihood of failure.

18-11.1.4 Economic, Environmental, and Other Consequences

Economic, environmental, and other consequences are evaluated on a case-by-case basis. Additional discussion of economic, environmental, and other consequences can be found in Chapter 2 of the FERC RIDM Risk Guidelines.

Economic risks, when estimated, are plotted using the risk matrix on Figure 13.

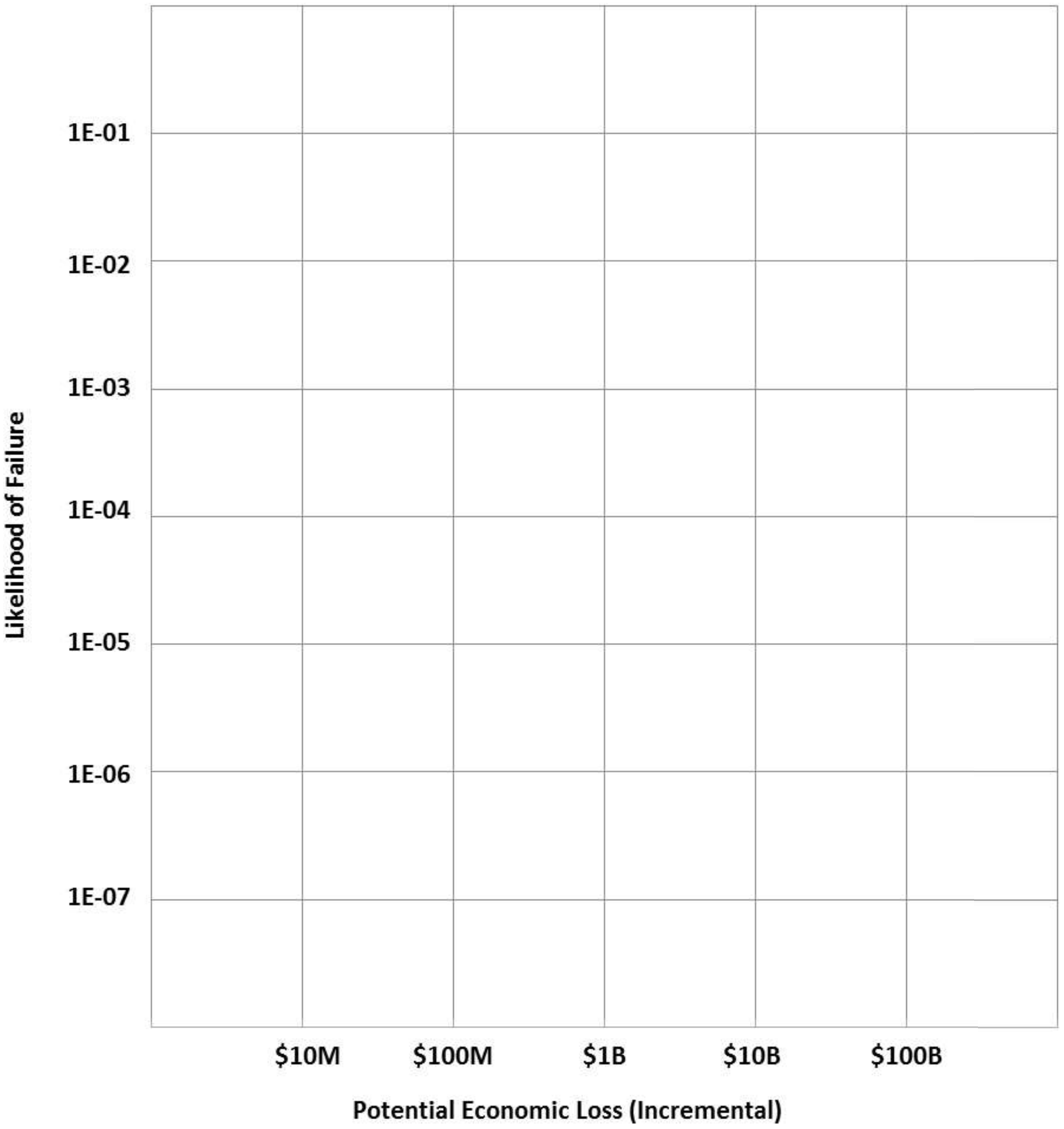


Figure 13: Risk Analysis Matrix for Incremental Economic Consequences

18-11.1.5 Individual Incremental Life Safety Risk

Individual incremental life safety risk (assuming that the most exposed individual is exposed all the time) is approximately represented by the likelihood of failure and represents the concept that everyone deserves some minimum level of safety regardless of the magnitude of the consequences. Additional information on individual incremental life safety risk can be found in Chapter 2 of the FERC RIDM Risk Guidelines.

18-12 DOCUMENTATION

The objective of the Level 2 risk analysis report is to present clear, thorough, logical, and rational documentation of the assumptions, evaluations, and results that accurately portray the risk estimate and recommended course of action in a manner and style that is to be read and understood by both the dam owner and FERC. The three basic risk components, (i.e., load, response, and consequences) should reflect the dam's existing condition and ability to withstand future loading, the risk estimates, and provide the basis for the recommended actions.

A general risk analysis report outline is provided in Appendix B. The outline should be revised to reflect the project-specific components and evaluations performed for developing the risk estimates.

The documentation for each PFM carried into the risk analysis should follow the template provided in Appendix C. Example PFM documentation is included in Appendix D.

The results of the risk analysis are used to place each potential failure mode in the appropriate failure likelihood and consequence box. This requires a clear and complete description of the potential failure modes and an evaluation of the adverse factors that make each potential failure mode “more likely” to occur as well as the favorable factors that make it “less likely” to occur. The rationale and key factors affecting the assigned failure likelihood are documented. Similarly, for consequences, the potential incremental consequences are evaluated and assigned to the appropriate consequence, and the rationale for the assignment is documented. The confidence (and their rationale) as well as the uncertainty are assigned to each, and then each potential failure mode is plotted in the appropriate cell of the risk matrix.

When assigning confidence categories, the reasoning behind the category, and the information that could be gathered to improve the rating should also be captured in the documentation.

The risk estimate documentation should also include the following:

- Portraying the results for all potential failure modes in a summary table. This provides an easy way to identify and compare the likelihood estimates for each potential failure mode. Use the risk estimate summary table for this purpose.
- The results should also be plotted on the risk matrix chart, a copy of which can be found as an MS Excel file on the FERC internet site [reference].

Other key information to present and discuss in the report include:

- Describe the estimated incremental risk for the project and the potential failure modes driving the incremental risk along with their likelihood and key evidence.

  Describe the primary consequence center(s) including proximity to the dam, population at risk, and life loss potential.
- Describe the impacts of planned spillway releases on the primary consequence center(s).
- Describe the confidence in the incremental risk estimate and any major uncertainties related to failure likelihood or incremental consequences.

The basis for the recommended actions should be documented in an objective, transparent manner, portraying the data, evaluations, findings and any associated uncertainties in data or analysis on a factual basis.

REFERENCES

Baecher, G.B and J. T. Christian (2003), "Reliability and Statistics in Geotechnical Engineering," John Wiley and Sons.

BOR/USACE (2018). Bureau of Reclamation and U.S. Army Corps of Engineers, "Best Practices in Dam and Levee Safety Risk Analysis", Denver, Colorado, July 2018. Available at: http://www.usbr.gov/ssle/damsafety/Risk/methodology.html

Douglas, K.J., M. Spannagle, and R. Fell (1998), "Analysis of Concrete and Masonry Incidents," UNICIV Report No. R-373, The University of New South Wales, Sydney, Australia.

FEMA (1979). Federal Emergency Management Agency, "Federal Guidelines for Dam Safety", prepared by the ad hoc Interagency Committee on Dam Safety, Federal Coordinating Council for Science Engineering and Technology, Washington, DC, June 25, 1979. Available at: https://www.fema.gov/media-library/assets/documents/2639

FEMA (2015). Federal Emergency Management Agency, "Federal Guidelines for Dam Safety Risk Management", FEMA P-1025, Washington, DC, January 2015. Available at: http://www.fema.gov/media-library-data/1423661058965-58dfcecc8d8d18b7e9b2a79ce1e83c96/FEMAP-1025.pdf

FERC (2017), Federal Energy Regulatory Commission, Engineering Guidelines for Hydropower Projects, Chapter 14, Dam Safety Performance Monitoring Program. Available at: https://www.ferc.gov/industries/hydropower/safety/guidelines/eng-guide.asp

FERC (2016), Federal Energy Regulatory Commission, Risk-Informed Decision Making Guidelines, March 2016. Available at: https://www.ferc.gov/industries/hydropower/safety/guidelines/ridm.asp#guide

Foster, M.A., R. Fell, and M. Spannagle (1998), "Analysis of Embankment Dam Incidents," UNICIV Report No. R-374, The University of New South Wales, Sydney, Australia.

Graham, W.J. (1999), "A procedure for estimating loss of life caused by dam failure." Report DSO-99-06, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado.

Hatem, G.A. (1985), "Development of a Data Base on Dam Failures in the U.S. – Preliminary Results," Thesis, Stanford University, Palo Alto, CA.

U.S. Army Corps of Engineers (2011), "Safety of Dams – Policy and Procedures," ER 1110-2-1156, Washington, DC.

U.S. Army Corps of Engineers (2018), "SQRA Calculation Methodology," RMC-TN-2018-01, Lakewood, CO.

Von Thun, J.L. (1985), "Application of Statistical Data from Dam Failures and Accidents to Risk-Based Decision Analysis on Existing Dams," Bureau of Reclamation, Denver, CO.

Whitman, R.V. (1984). "Evaluating Calculated Risk in Geotechnical Engineering." *J. Geotechnical Engineering,* ASCE, Reston, Virginia, Vol. 110 (2): 145-188.

APPENDIX 18-A: DEVELOPMENT OF HYDROLOGIC HAZARD CURVES

(Currently being reviewed by the USACE, Risk Management Center)

APPENDIX 18-B: RISK ANALYSIS REPORT OUTLINE

The following is the outline for the risk analysis report.

Risk Analysis Report

1.0 Introduction

2.0 Previous Studies

3.0 Hydrologic Loading
3.1 General
    3.2 Background Information
3.3 Reservoir Elevation Frequency
    3.4 Methodology/Approach
    3.5 Results
    3.6 Non-Breach Scenario

4.0 Seismic Loading
    4.1 General
    4.2 Background Information
    4.3 Methodology/Approach
    4.4 Results

5.0 Consequences
5.1 General
5.2 Approach
5.3 Inundation Scenarios
5.4 Description of Inundation Area
5.5 Breach Assumptions
5.6 Life Loss Estimates
5.7 Economic Loss Estimates
5.8 Other Consequences

6.0 Potential Failure Modes
6.1 Previously Identified PFMs
    6.2 PFMs Carried Forward into Risk Analysis

7.0 Risk Analysis
7.1 General
7.2 Methodology/Approach
7.3 PFM ##: Short Title (Include separate section for each PFM)
7.3.1 Description

APPENDIX 18-C: POTENTIAL FAILURE MODE TEMPLATE FOR LEVEL 2 RISK ANALYSIS

Dam Name

PFM Information

Structure	
Loading Condition	
PFM Type	
Location(s)	

PFM Description

PFM No.	
PFM Title	
PFM Description	

PFM Sketch

Event Tree (if used)

Additional Supporting Information (if needed)

Performance Monitoring Information

Influence Factors

Event Tree Node (or other designation)	More Likely	Less Likely

Failure Likelihood Summary

Failure Likelihood	
Justification	
Confidence	
Rationale	

<table>
<tr><th colspan="5">Consequences</th></tr>
<tr><td colspan="5">Life Safety Consequences</td></tr>
<tr><td>Consequence Description</td><td colspan="4"></td></tr>
<tr><td>Estimated PAR</td><td colspan="4"></td></tr>
<tr><td rowspan="5">Inundation Characteristics</td><td colspan="4"></td></tr>
<tr><td>Location</td><td>Time (hr)</td><td>Depth (ft)</td><td>Velocity (ft/s)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Warning/Evacuation Challenges</td><td colspan="4"></td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4"></td></tr>
<tr><td>Justification</td><td colspan="4"></td></tr>
<tr><td>Confidence</td><td colspan="4"></td></tr>
<tr><td>Rationale</td><td colspan="4"></td></tr>
<tr><td colspan="5">Economic and Environmental Consequences</td></tr>
<tr><td>Consequence Description</td><td colspan="4"></td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4"></td></tr>
<tr><td>Justification</td><td colspan="4"></td></tr>
<tr><td>Confidence</td><td colspan="4"></td></tr>
<tr><td>Rationale</td><td colspan="4"></td></tr>
<tr><td colspan="5">Other Consequences</td></tr>
<tr><td>Consequence Description</td><td colspan="4"></td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4"></td></tr>
<tr><td>Justification</td><td colspan="4"></td></tr>
<tr><td>Confidence</td><td colspan="4"></td></tr>
<tr><td>Rationale</td><td colspan="4"></td></tr>
<tr><th colspan="5">Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions</th></tr>
<tr><td>Inspections</td><td colspan="4"></td></tr>
<tr><td>Surveillance and Monitoring</td><td colspan="4"></td></tr>
<tr><td>EAP</td><td colspan="4"></td></tr>
<tr><td>Follow up Studies</td><td colspan="4"></td></tr>
<tr><td>Others</td><td colspan="4"></td></tr>
<tr><th colspan="5">Other Notes/Comments</th></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5"></td></tr>
</table>

APPENDIX 18-D: EXAMPLE TEMPLATE WRITE UPS

Wontoo Dam

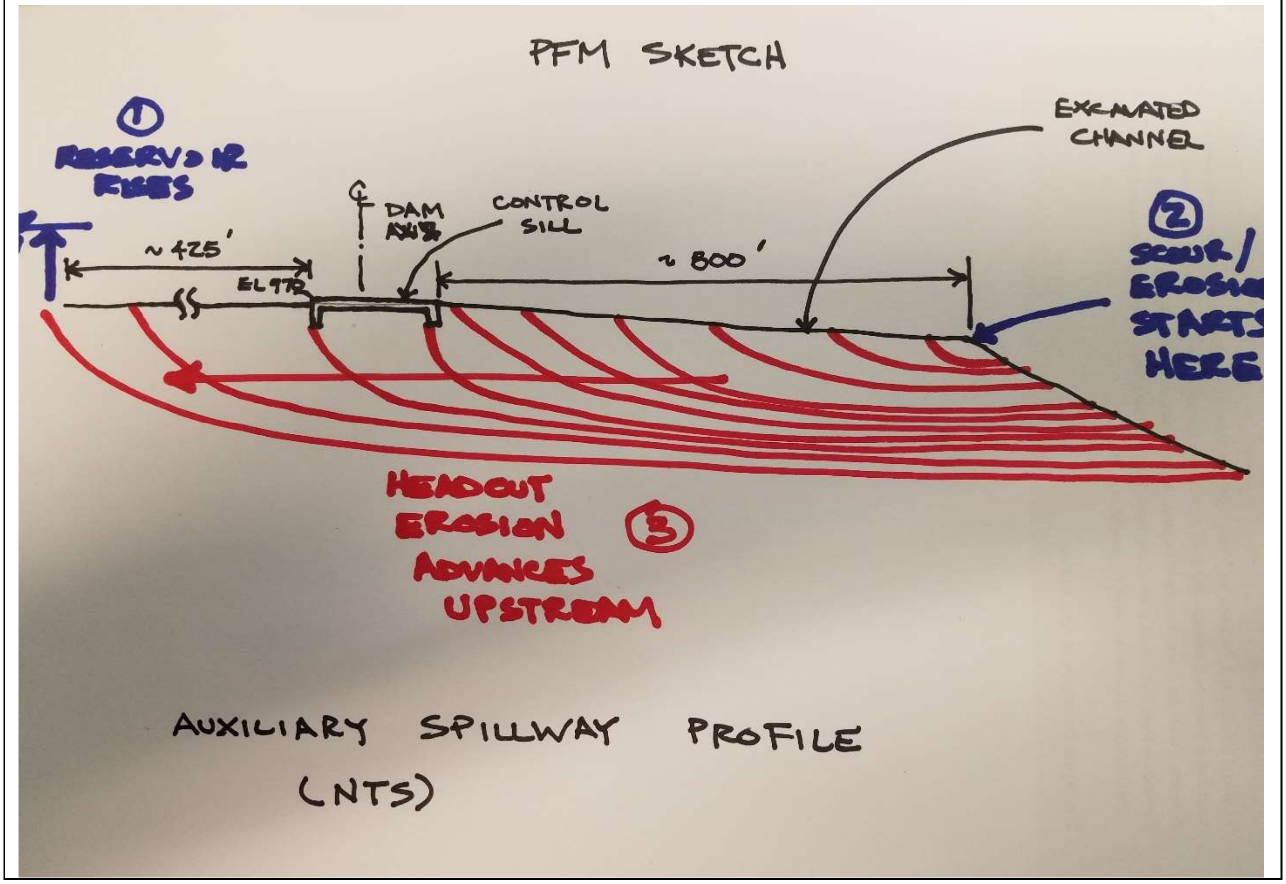
PFM Information

Structure	Auxiliary Spillway
Loading Condition	Flood
PFM Type	Erosion
Location(s)	Auxiliary Spillway

PFM Description

PFM No.	1
PFM Title	Headcutting and erosion of the auxiliary spillway
PFM Description	The reservoir rises above elevation 975 to 980 feet leading to headcut erosion downstream of the spillway control sill. Erosion begins at the knickpoint near the break in slope approximately 800 feet downstream of the control sill. Headcut erosion continues and deepens, undermining the control sill. Headcut erosion continues to advance towards the reservoir leading to breach and partial loss of pool.

PFM Sketch



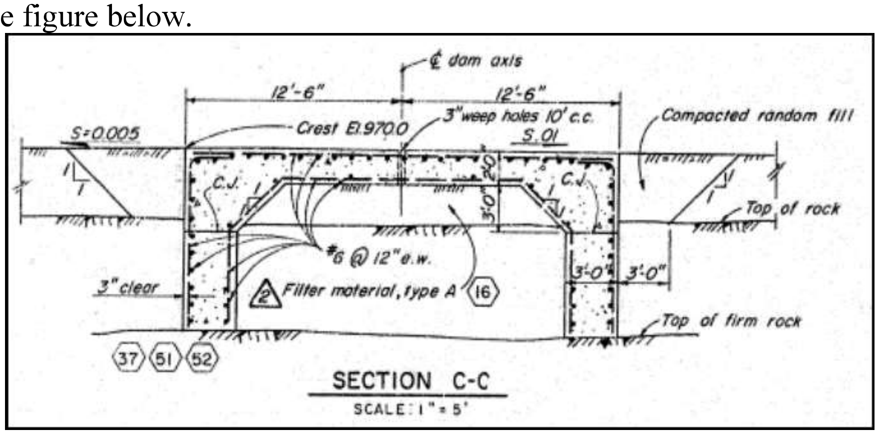
Event Tree (if used)

A sequence of events that can be used in spillway erosion event tree is:

- Hydrologic event occurs and reservoir stage reaches the spillway crest.
- Spillway begins to flow.
- Vegetation is removed (if it is present).
- Concentrated flow erosion begins (downcutting forms headcut).
- Headcut advancement begins (Headcut deepens and advances towards spillway crest/control section).
- Intervention is unsuccessful.
- Headcut advances through crest of spillway and/or headcut undermines control structure/section and flow control is lost.
- Headcut advances into reservoir pool and breaching begins.

Additional Supporting Information (if needed)

The auxiliary spillway is located at the west end of the embankment, with its centerline at dam Station 36+03. The spillway is 300 feet wide with a crest elevation of 970 feet. The length of the excavated spillway is approximately 1,500 feet with 3H:1V side slopes. A retaining wall with a top elevation of 988 feet is located on each side of the spillway and retains the embankment fill. A 25-foot-wide and 300-foot-long concrete slab (i.e., control sill) protects the crest. The slab is turned down at both the upstream and downstream ends to firm rock at a depth of about 8.5 feet, as shown in the figure below.



SECTION C-C
SCALE: 1" = 5'

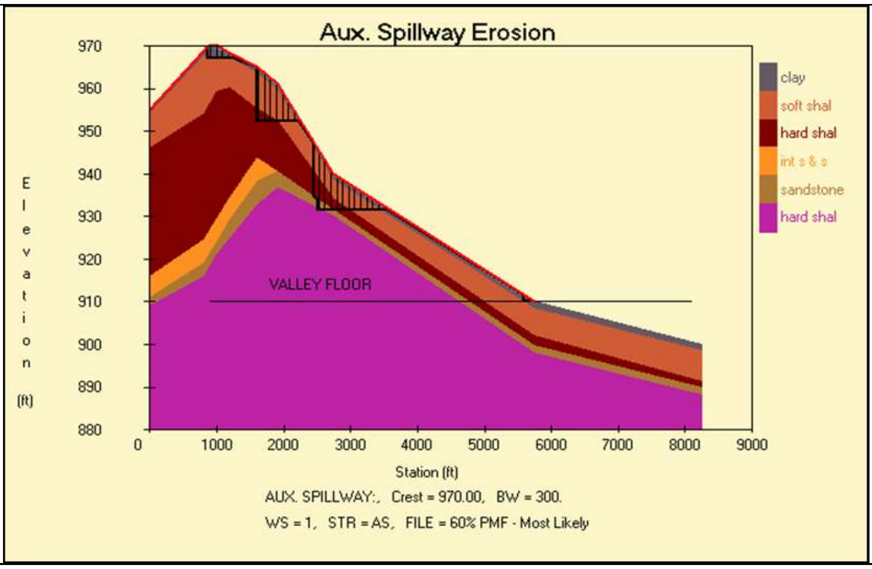
The spillway floor consists of soft to hard shale materials. The firm rock line is approximately at an elevation of about 959 feet. The excavated spillway channel extends approximately 800 feet downstream of the control sill and 425 feet upstream. An approximately 20-foot fall exists within 175 feet beyond the downstream portion of the excavation.

Performance Monitoring Information

The spillway has never experienced flow. The record pool elevation 964.24 feet is approximately 6 feet below the spillway crest. Surface erosion has occurred downstream of the spillway, as shown in the photo below.

		
Influence Factors		
Event Tree Node (or other designation)	More Likely	Less Likely
	The spillway includes erodible near-surface overburden and weathered shale	Infrequent flood for loss of crest control (i.e., AEP = 5E-04/year to 6E-05/year)
		Exit channel length is 800 to 1000 feet.
		An additional 400 feet of natural materials exist at an elevation of 970 feet, resulting in a total length of 1,200 to 1,500 feet which must eroded before partial breach.
		A concrete sill is founded in firm rock with a depth of 8.5 feet, which is not included in the SITES model.
		Infrequent flood for loss of crest control (i.e., AEP = 5E-04/year to 6E-05/year)

Failure Likelihood Summary	
Failure Likelihood	5E-05 to 5E-06
Justification	Based on the spillway erodibility analysis using SITES, the threshold flood for loss of spillway control is approximately 60 to 70 percent of the PMF, as shown in the figure below, which corresponds to an annual exceedance probability (AEP) on the order of 1E-05/year. Therefore, the annual probability of failure (APF) is also on the order of 1E-05/year.

	
Confidence	Low
Rationale	The SITES analysis appears to be conservative and included some sensitivity analyses. The frequency of the PMF seems reasonable. The lower confidence is due to uncertainty associated with the SITES model. Additional boring may improve the geologic profile but would not change the confidence in the estimate.
Consequences	
Life Safety Consequences	
Consequence Description	Wontoo Dam is located on Town Creek, a drainage that joins Lolly Creek approximately 7 miles downstream of the dam. Lolly Creek then flows into Smith Reservoir approximately 26 miles downstream of the dam. Downstream from Wontoo Dam, extending to Smith Reservoir, the valley of Town Creek is narrow with scattered rural residences, seasonal cabins, and much recreation use during the tourist season. The facilities and communities located downstream of Wontoo Dam within the inundation limits include numerous ranches, campgrounds, a dozen or more residences, a Forest Service facility, the Carolina Gulch Picnic Area on the shore of Smith Reservoir, 2.9 miles of railroad track, and 18 miles of roads and trails. Several additional campgrounds and picnic areas exist around Smith Reservoir that could also be affected by potential flooding caused by a breach of Wontoo Dam. Smith Reservoir's flood-surcharge capacity of 21,000 acre-feet and would be able to contain the dam-breach flood volume (up to 15,700 acre-feet) from Wontoo Dam and Reservoir.
Estimated PAR	Wontoo Dam is rated as a high-hazard structure due to the population at risk downstream. It is estimated that about 90 people live within the potentially inundated areas below Wontoo Dam, and a possible total of about 200 people including those seasonally using the campgrounds and other facilities in the floodplain.

Failure of Wontoo Dam has the potential to place many people at risk. The number of people and their location varies substantially depending on the time of year, day of the week, and time of day.

The inundation area for a hydrologic day failure under flood loading conditions would be expected to be slightly higher due to the larger reservoir volume and higher reservoir head available as compared to a sunny day failure. Therefore, the population at risk estimates for a hydrologic failure were increased by 10 percent to account for the larger extent and deeper inundation that would likely be caused by a larger reservoir volume and reservoir head.

An estimated population at risk is provided in the table below.

Reach	Season			
	May-September		October-April	
	Day	Night	Day	Night
Reach 1	44	44	22	22
Reach 2	176	176	77	77
Totals	220	220	99	99
Annualized Total	150			

Inundation Characteristics

Travel times for the leading edge of the flood wave are provided on the inundation maps. The results of that study provide estimates of the leading edge of the flood wave beginning at the time of failure at the dam.

Location	Time (hr)	Depth (ft)	Velocity (ft/s)

Warning/Evacuation Challenges

The area around Wontoo Dam and along the creeks below the dam are popular recreation areas. Based on the inundation maps, the first populated areas and potential dam-failure notification people downstream of the dam appear to consist of several ranches and camps located along the creek within the first 2 miles below the dam. These ranches and camps include both year-round and seasonal residents. There also appear to be some ranches just downstream of the dam that are located above the inundation boundary.

The dam tender is located at Smith Dam, about 25 miles from Wontoo Dam, and visits Wontoo Dam for visual inspections on a regular (at least weekly), year-round basis. The roadway to Wontoo Dam is a good paved highway, except for about 6 miles of gravel roadway near the dam. There is also a locked gate on the access road about 1.6 miles below Wontoo Dam that must be opened. The trip from the dam tenders house to Wontoo Dam takes approximately 30 to 45 minutes, depending on the weather

	conditions. It should be noted that the access road to Wontoo Dam travels up the Town Creek valley below the dam and crosses two bridges over the Creek. The first bridge is located just above the gate and the second bridge is located above the confluence of the creek and the spillway outflow channel. If the spillway is flowing above a relatively low percentage of its capacity, the two bridges and the last 1.7 miles of the access road to the dam could be underwater and impassible, forcing the dam tender to use other routes to reach the dam. Alternate access routes would range from an additional 15 minutes to over 1-1/2 hours to reach the site, depending on what other access routes are also underwater and impassible. Depending on the perceived severity of the situation, other modes of travel to the dam, such as a helicopter, could be used. Telephone communications are available at the dam, and the dam tender has two-way radio communication.
Consequence Likelihood	1-10
Justification	No peak flood flow velocities were provided from the flood inundation studies. Because of the narrow canyon and steepness of the downstream channel, flow depths and estimated flow velocities would likely be high for the majority of the flood flow cross section. Based on crude analyses, it is estimated that the depth-velocity factor for the flood flows for both reaches would be greater than 50. In some places it is likely that the flood severity would be severe. However, due to the steepness of the valley walls and abundant large vegetation, it is likely that the vast majority of the population at risk would be able to make it to higher ground very quickly, therefore only a medium flood severity was used for both reaches. Filling of the reservoir above the current maximum pool would be considered first filling and require 24-hour monitoring of the dam. Therefore, if a failure event occurred during a flood loading, then adequate warning (more than 60 minutes) would be provided prior to failure and breach. Because of the above, fatality rates were estimated to be relatively low with estimated average potential life loss less than 10.
Confidence	Moderate
Rationale	A more detailed life loss study could potentially show slightly higher fatality rates may be justified.
Economic and Environmental Consequences	
Consequence Description	The vast majority of the inundation area is public lands with relatively limited other use (scattered residential). No other major consequences were considered.
Consequence Likelihood	
Justification	

Confidence	
Rationale	
Other Consequences	
Consequence Description	None considered.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Inspect spillway channel after each flow event for signs of erosion.
Surveillance and Monitoring	Consider installing a staff gage in the spillway channel to monitor flow depths. Perform 24-hour monitoring when depth of flow in spillway channel exceeds historic flows.
EAP	Consider preparing inundation maps for breach of the spillway control structure.
Follow up Studies	Consider more detailed life loss studies for breach of the spillway.
Others	
Other Notes/Comments	

New Beaver Dam

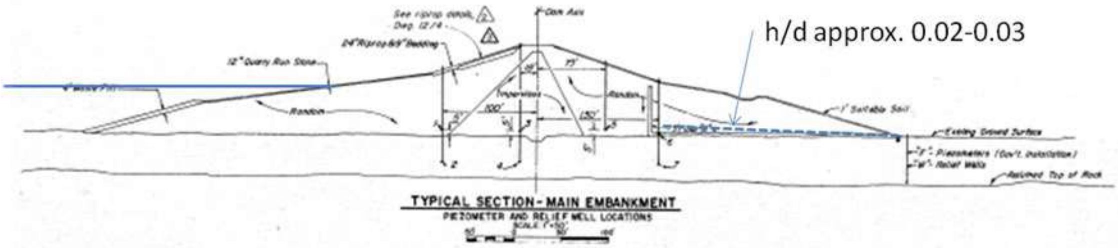
PFM Information

Structure	Main Dam
Loading Condition	Static
PFM Type	Internal Erosion
Location(s)	Sta 14+00

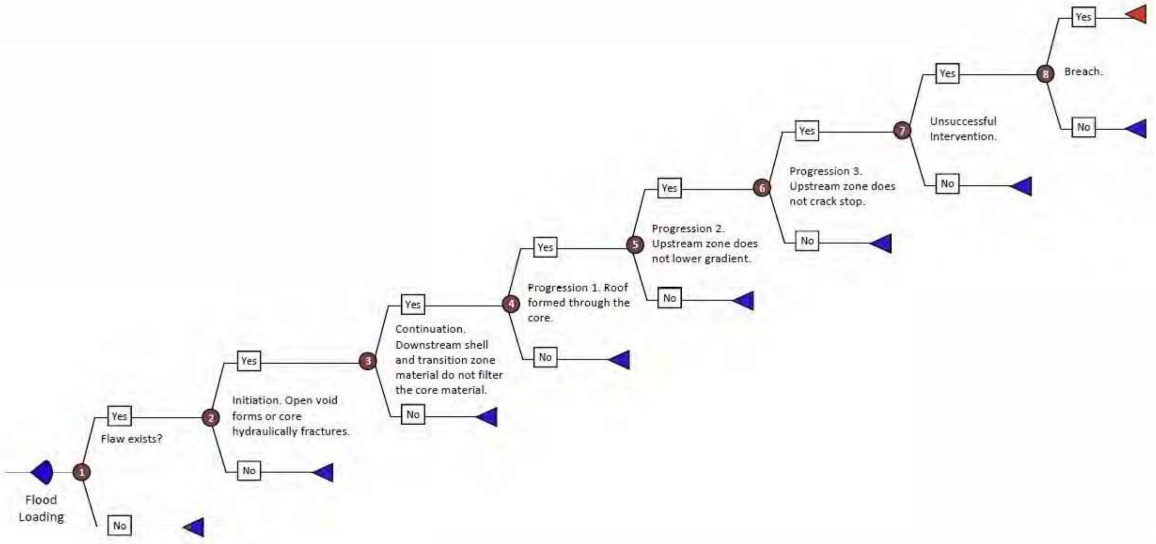
PFM Description

PFM No.	3
PFM Title	Backward erosion piping in foundation near 14+00 (former stream channel)
PFM Description	The reservoir rises above conservation pool of elevation 412 feet overwhelming the capacity of the toe drain system causing foundation pressures to rise to a sufficient level to heave the confining layer, creating an unfiltered exit at the ground surface. Sufficient gradient exists to remove soil particles at the exit initially forming a void. A pipe develops as soil particles are transported into the void as the erosion in the pipe advances upstream towards the reservoir. The fine-grained confining layer supports the roof of the developing pipe. The erosion pipe enlarges as flow increases. Breach initiates as gross enlargement leading to crest collapse and rapid release of the reservoir.

PFM Sketch



Event Tree (if used)



Additional Supporting Information (if needed)
Beaver Creek, just prior to construction of the dam, ran diagonally across embankment footprint from north to south prior to construction from approximately Station 13+00 to 15+00. The thickness of the alluvium was generally 15 to 20 feet pinching out at the abutments. A 5-foot deep inspection trench with 1H:1V side slopes and a 12-foot wide base was located in this section of the dam from Station 11+00 to 17+00. The alluvium consists primarily of fine-grained, plastic soils with more pervious soils classified as SM (silt sands) and SC (clayey sands) with very little to no SP (poorly graded sands) soils. The original design included 7 relief wells and a toe drain system, and 4 more relief wells were added before 1979. To lengthen the potential seepage path, the upstream channel was filled with waste fill from the first stage dike to the second stage dike approximately 1,200 feet along Beaver Creek and approximately 500 feet from the upstream toe. Waste fill was also placed in the downstream channel for a distance of 280 feet up to an elevation of about 900 feet (the top of original ground outside the channel.) The channel bottom was cleaned/de-mucked and widened to 30 feet with 4H:1V slopes. According to as-built drawing C-2-12/5, the channel was backfilled with random fill up to a minimum elevation of 900 feet (bottom of blanket filter). Zoning in the remainder of this section remained as designed with impervious fill placed in the center portion of the dam flanked by random fill. “Boils” were noted on the construction photographs showing de-mucking operation. This operation appeared to extend below the water table in the area and should have resulted in flow into the excavation. Some areas were noted as being backfilled with material placed by D8 dozer to provide stable base for subsequent compacted lifts.
Performance Monitoring Information
Seepage was first noted as “pinhead boils” near Station 11+25 in June 1986 after a significant increase in reservoir pool level during initial filling (weir flow 0.4 gpm). A total of 9 relief wells were installed between Stations 11+25 and 18+58 in June 1990. According to a 1991 Inspection Report, the seepage condition at the downstream toe improved, but seepage was still visible in old channel further downstream. Following installation of the 9 relief wells, piezometric levels dropped 0 to 5 feet. A 1993 Inspection Report describes a high pool in October 1982 with no seepage noted (seepage condition: “no apparent change”). Following the October 1982 high pool, piezometers responded to pool but then remained relatively unchanged (e.g., B-4 and B-6 at approximately 400 feet). A 1995 Inspection Report indicates no seepage in the notes (seepage condition: “no apparent change”). Following the new record pool of 414.14 in May 1994, piezometers responded to pool but remained relatively unchanged (e.g., B-4 and B-6 returned to approximately 400 feet). According to the high pool inspection report, a new boil was noted 150 yards southeast of the embankment toe with bubbles. A “wet area” was noted near Station 17+00 (piezometers B-5), and “bubbles” were noted near Station 18+00 (piezometer B-7). Boils and associated seepage were also noted during a high pool of 414.08 in May 1998. Piezometers responded to pool but then remained relatively unchanged (e.g., B-4 and B-6 returned to approximately 401 feet). During a high pool of 415.25 feet in June 2002, several boils up to 3 inches in diameter were observed in the former Beaver Creek channel, and a small boil was observed in the second toe drain ditch east of the stilling basin. According to Inspection Report (August 2002), the old river channel adjacent to service road was backfilled. During the 2005 record pool of 416.24 feet, a wet area was noted at the downstream toe near Station 12+00 that extended from the right abutment approximately 300 feet towards the east.

Influence Factors		
Event Tree Node (or other designation)	More Likely	Less Likely
	Embankment and/or confining layer can support a roof.	B-5A max reading at 2 feet above the ground surface (401.4).
	“Boils or bubbles” noted near penetrations or in area of potentially thinner confining layer at B-5 and B-6 and at ditch near Station 12+00.	Relief wells and toe drain system regularly maintained and cleaned at an interval less than 5 years.
	Sands beneath the fine-grained confining layer are fine-grained. Limited samples of SM have 100 percent passing the No. 40 sieve, with fines contents ranging from 20 to 40 percent.	Foundation consists predominantly of fine-grained soils.
		Path of channel prior to construction suggests sinuous/lengthened seepage path.
		High tailwater (for pools greater than about 412.6 feet).
		Base width of embankment is about 250 feet and provides an average gradient of approximately 0.1 at 419 feet (PMF).

Failure Likelihood Summary	
Failure Likelihood	1E-06 to 1E-07
Justification	The ratio of head-to-seepage path length (i.e., gradient) indicates low values, as shown in Figure 7.5, and actual data from piezometers indicated even lower values under the downstream portion of the dam. Graphs of piezometric levels during the 2002 high pool were compared. The effect of tailwater on the piezometers was suggested to be more of a factor than previously thought. B-6 indicates a lower pressure head of about 2 to 3 feet at normal pool levels from early readings after initial filling to those recorded lately. This indicates the drainage systems have been improved, or the reservoir has silted in. A record of drain flows would help in determining the cause of this improved condition. The foundation drainage systems (toe drain and relief wells) for the dam as well as several piezometers become submerged during high releases. A more detailed review of the foundation piezometers is needed to verify this finding. The site visit revealed that tailwater currently enters the toe drain system directly at the lowest manhole even though the outfall for the toe drain has a flap gate. During the site visit, water was observed exiting this drain outfall, but no water was entering the inlet on the berm. Photographs from the 2002 high water event revealed that the toe ditch became flooded. Based on the drawings, it would appear that the filter blanket starts to

	become inundated when tailwater at the toe ditch gets above 414.5 to 415 feet. At the PMF of 419 feet, the APF will be less than the AEP of 5E-06/year. Spillway crest is 412 feet, (AEP of 3E-02/year) which had satisfactory performance with no boils noted (i.e., SRP less than 1E-04). Therefore, the APF is estimated to be (5E-03/year)(1E-04) or about 5E-07/year to 1E-06/year. At the conservation pool of 412 feet, the APF is also expected to be less than 5E-07/year to 1E-06/year. Therefore, the total APF is likely to be on the order of 1E-06/year to 1E-05/year.
Confidence	Moderate
Rationale	The team felt moderately confident in the magnitude of the estimate, some key information might possibly influence the estimate.
Consequences	
Life Safety Consequences	
Consequence Description	New Beaver Dam is located on Beaver Creek upstream of New Beaverdale. Beaver Creek is one of three principal tributaries of Scott's River. The breach of New Beaver Dam main embankment would cause a major flood and inundate several towns, with the most significant impacts to New Beaverdale. The flood wave would travel down Beaver Creek to the confluence with Scott's River and then continue to the Monster River where flows would be contained within the banks of the river. Regional impacts of a dam failure would be observed approximately 25 miles downstream to the confluence with the Monster River, with the deepest inundation occurring within the first eight miles downstream of the dam. Potentially impacted facilities include a school, communication facilities, fire and police stations, electrical substations, and a health care facility.
Estimated PAR	PAR was estimated from overlaying the inundation area over GoogleMap images. Limited field truthing was done. Estimated PAR is provided in the table below:
Inundation Characteristics	Beaver Creek downstream of the dam follows an incised channel in the flood plain before discharging into Scott's River. The relatively narrow flood plain includes some farm fields and dense trees. The inundation area downstream of the confluence with Scott's River is a much broader and gently sloping flood plain.

Distance Downstream	Day PAR	Night PAR
0-8 mi.	6	8
8-18	2	1
18-25	1	1

Location	Time (hr)	Depth (ft)	Velocity (ft/s)

Warning/Evacuation Challenges	The dam is not attended full-time. The dam owner visits the site once a day to confirm reservoir elevation, gate settings, and other tasks. The dam is not visited on the weekends or holidays. The dam has no video camera facilities. The first indication of a problem would likely be a reservoir level warning or high flow warning on the stream gage ½-mile downstream of the dam on Beaver Creek. The first inhabited structures are located 2 miles downstream of the dam.
Consequence Likelihood	1-10
Justification	Life loss is anticipated to range between 2 and 6 for this PFM, depending on the time of day and day of the week.
Confidence	High
Rationale	It is very difficult to envision a life loss less than 1 or greater than 10 for this PFM.
Economic and Environmental Consequences	
Consequence Description	Economic consequences were not estimated.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Other Consequences	
Consequence Description	No other consequences were estimated.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Continue to monitor seepage and boils during periods of high pool.
Surveillance and Monitoring	Consider installing recorders on select piezometers that collect and transmit data daily for evaluation. Consider installing a high-level alarm on the seepage collection weir. Consider installing video cameras to observe conditions along the downstream toe of the dam.
EAP	Consider using this PFM during the next table top or functional exercise.
Follow up Studies	Evaluate the need for additional piezometers to evaluate seepage gradients near the downstream toe.
Others	
Other Notes/Comments	

Old Man Dam

PFM Information

Structure	Main Dam
Loading Condition	Static
PFM Type	Slope Stability
Location(s)	

PFM Description

PFM No.	7
PFM Title	Downstream slope instability due to excessive foundation pore pressures
PFM Description	The reservoir rises causing an increase in foundation pore pressure and a decrease in effective stress, resulting in downstream slope instability, deformations and embankment cracks extending across the dam. Overtopping due to failure at crest is thought to be less likely than embankment cracking, and thus cracking is proposed as part of failure. Concentrated leak erosion through the crack initiates with an unfiltered exit above the filter or below the filter if it is severely damaged so that it does not function. Leakage flows and erosion increase, progressively enlarging the crack. Gross enlargement and lateral erosion of the opening occurs until the reservoir is rapidly released through opening, and the dam erodes to the base of the embankment.

PFM Sketch

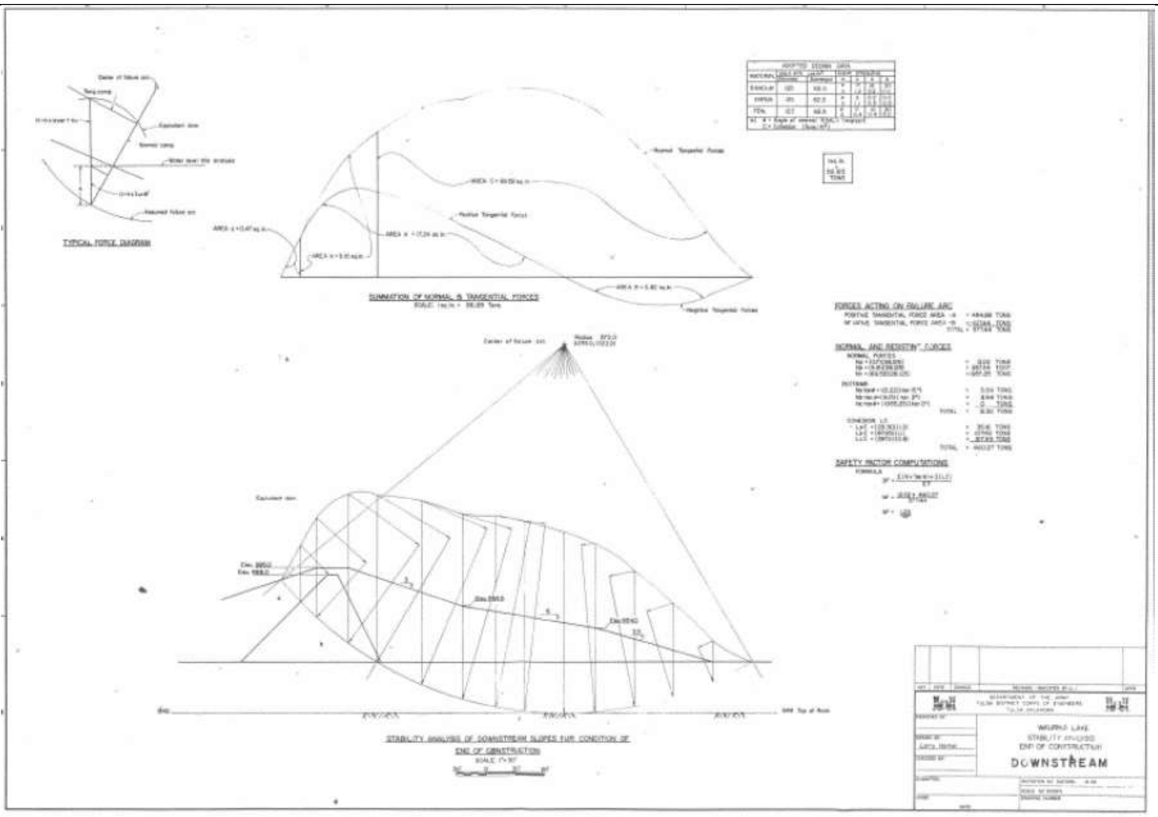
See sketch of failure surface in Additional Supporting Information section.

Event Tree (if used)

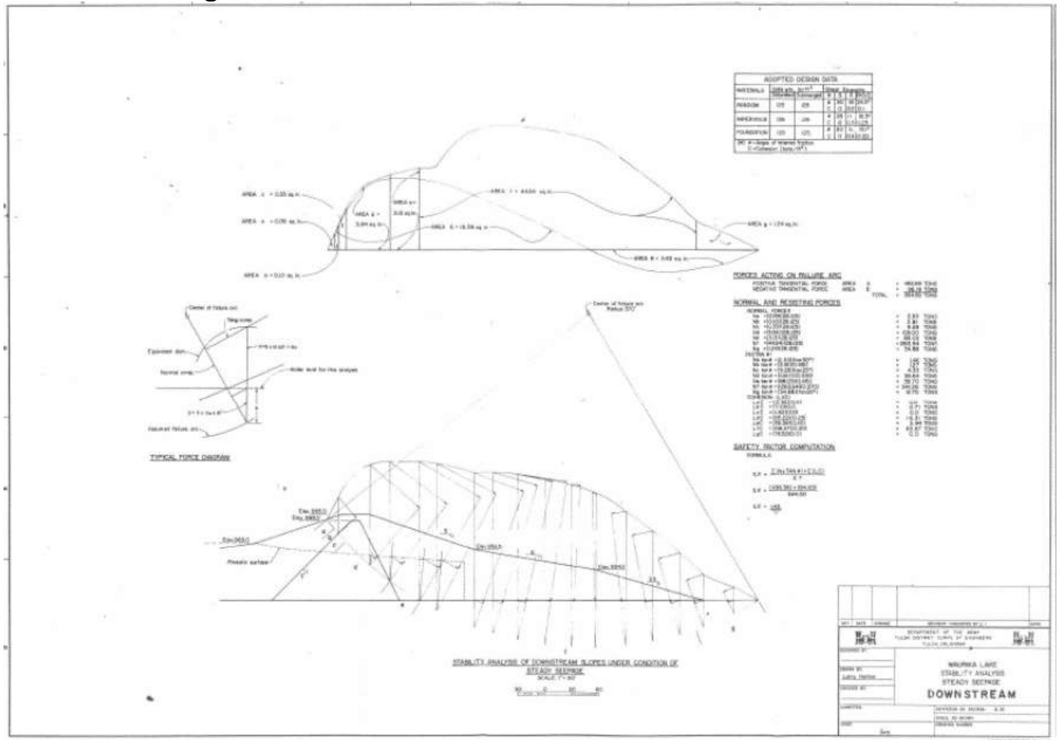
- The reservoir rises
- Foundation pore pressures increase and effective stresses decrease
- Downstream embankment slope fail resulting in deformations leading to embankment cracking
- Concentrated leak erosion through the crack initiates
- Flow continue to erode cracks, progressively enlarging the cracks
- No crackstopper upstream
- Gross enlargement and lateral erosion of the cracks progress until the reservoir is rapidly released through opening
- Intervention unsuccessful
- Dam breaches.

Additional Supporting Information (if needed)

The downstream slopes are 3H:1V to 6H:1V to 3.5H:1V. Internal seepage control features include blanket/chimney drain at the section in the valley bottom and in addition relief wells between Stations 110+00 to 119+00. An updated stability analysis using as-built shear strengths was reported in the 1991 Stability Analysis Report. The factor of safety for the end-of-construction condition was 1.25, as shown in the figure below.



The factor of safety for steady-state seepage with a pool of 963 feet and tailwater of 896 feet was 1.43, as shown in the figure below.



This analysis had the filter in the “as-built” location 120 feet downstream of dam centerline, whereas an earlier analysis had the filter located further upstream and higher.

Performance Monitoring Information
No instability was observed at record pool. Piezometer B-4 increases 5 to 8 feet at 962.5 feet which is about 2 feet above ground surface. Tailwater has an effect on this rise. No instability was noted during or at the end of construction. Instrumentation indicated that construction-related pore pressures were generated in the embankment as well as the foundation in some locations but have since drained and now reflects drained conditions (e.g., B-3 and B-5 in the embankment and B-7 in the foundation). It was noted that foundation pore pressures at Section B (B2 and B4) indicate higher pressures than at sections A, C, or D. This condition has been present since the instruments began responding to initial filling of the reservoir in the late 60's.

Influence Factors

Event Tree Node (or other designation)	More Likely	Less Likely
	There is no cut-off trench to rock.	Significant construction pore pressures were generated with no instability noted.
	Some CH soils are present in the foundation with potentially lower strength.	3H:1V to 6H:1V to 3.5H:1V relatively flat slopes with an intermediate berm.
	Free water has been observed at toe.	No significant movement up to the record pool has been observed.
		The road at the downstream toe appears to be elevated slightly and may provide additional resistance to sliding.
		The filter blanket and chimney, relief wells, and toe drain system provide drainage of embankment and foundation.
		Significant construction pore pressures were generated with no instability noted.

Failure Likelihood Summary

Failure Likelihood	1E-06 to 1E-07
Justification	At the PMF of 988 feet, the APF will be less than the AEP of 5E-06/year. At the record pool of 962.24 feet with an AEP of about 3E-02/year, no instability was observed (i.e., SRP less than 1E-04). Therefore, the APF for record pool is approximately 3E-06/year, and the APF for the full range of loading would be on order of 1E-05/year to 1E-06/year. The key factors for this estimate are the lack of deformation noted to-date under end-of-construction pore pressure conditions as well conditions associated with the record pool which was slightly above the flood control pool; the stability provided by the relatively flat slopes; and the apparent control of pore pressures as a result of the drainage systems and apparent upstream control.
Confidence	Moderate to High.
Rationale	Pore pressure at pools greater than the record pool are somewhat uncertain and might lead to unexpected behavior. Team was not aware of any case histories for this PFM.

Consequences	
Life Safety Consequences	
Consequence Description	Old Man Dam is located on the Timothy Draw drainage, which joins with Ginger Creek approximately four miles downstream of the dam. Ginger Creek then flows into the Gold River approximately 15 miles downstream of the dam. Timothy Draw and Ginger Creek flow through a sparsely to moderately populated area comprised mostly of farm land with the owner's houses. There are no concentrated population centers along the drainage. The inundation area is fairly wide immediately downstream of the dam, but within two or three miles, becomes fairly channelized (1/4 to ½ mile wide) by bluffs located on both sides of Ginger Creek that rise on the order of 90 feet above the creek. The inundation area does not encroach upon the nearby town of Hazel, but passes entirely to the east of the town. The inundation area remains fairly confined to the Ginger Creek drainage until reaching the Gold River. The inundation area flows over state highway 119 just prior to the confluence of Ginger Creek and Gold River, where the flood waters widen considerably. The majority of this area is sparsely populated. From this point downstream along the Gold River, there is no population at risk (PAR) until reaching Elbert, approximately 35 miles downstream of the dam. At this point, the Gold River meets the Whiskey River and the inundation area again becomes fairly broad. Several roads are impacted, as well as the southern portion of Elbert. Beyond this point, the flood waters are minimal and do not present a significant risk further downstream
Estimated PAR	Failure of Old Man Dam has the potential to place many people at risk. The number of people and their location varies substantially depending on the time of day. The overall PAR was estimated by using inhabitable structure estimates based on 2018 GoogleMap files within the estimated inundation limits obtained from the most recent inundation study. Data from the 2010 Census indicates 3.05 residents/house in county. Recent Census data indicates a 4.2 percent population increase in the county from 2010 to 2018, or about a half percent increase per year. Assuming an inhabitable structure estimate from 2018, accounting for a half percent population increase per year, and assuming 3.05 residents/structure results in a PAR of approximately 503 within the downstream inundation limits. This estimate is based on a hydrologic failure mode and would be expected to vary depending on the day of week and time of day. There are no significant transient population areas within the inundation limits (i.e., no fishing, camping, picnic areas) other than regional

<table>
<tr><td></td><td colspan="4">transportation corridors. Therefore, the PAR estimates do not include transient populations.

The inundation area for a sunny day failure under static or seismic loading would be expected to be slightly smaller due to the smaller reservoir volume and lower reservoir head available as compared to a hydrologic failure. However, due to the broadness of the inundation area within the first three miles downstream of the dam, the presence of the greatest PAR within the first three miles downstream of the dam, and the relative small percentage of difference between the reservoir height and volumes between the sunny day and hydrologic failure scenarios, the inundation area for the hydrologic failure was conservatively used to estimate the inundation area for the sunny day failure scenarios.</td></tr>
<tr><td rowspan="5">Inundation Characteristics</td><td colspan="4">Travel times for the leading edge of the flood wave are provided on the inundation maps. The results of that study provide estimates of the leading edge of the flood wave beginning at the time of failure at the dam. This includes a travel time of 4 to 6 hours to reach the Gold River and 15 to 35 hours to reach Elbert.</td></tr>
<tr><td>Location</td><td>Time (hr)</td><td>Depth (ft)</td><td>Velocity (ft/s)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Warning/Evacuation Challenges</td><td colspan="4">District personnel are stationed at the office and maintenance facility located at the downstream toe of the dam on a daily basis. In addition, recreationalists use the reservoir and other facilities at the reservoir on a daily basis during spring, summer, and fall months. In addition, a fairly well traveled state highway is located very close to the left and downstream portions of the dam. However, typically the dam and reservoir area are not occupied during nighttime hours. Therefore, the following assumptions were made in regard to detection of an event leading to failure of the dam. For a slow failure scenario (daytime or nighttime), initial detection would be made at the dam, therefore some warning would be provided prior to failure and breach of the embankment.</td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4">10-100</td></tr>
<tr><td>Justification</td><td colspan="4">For the assumed slower failure scenario and adequate warning, a relatively low fatality rate was applied to the PAR that resulted in an average estimated potential life loss in the range of 15 to 25.</td></tr>
<tr><td>Confidence</td><td colspan="4">High</td></tr>
<tr><td>Rationale</td><td colspan="4">It’s not expected that a more detailed life loss study would yield substantially higher or lower (order of magnitude) estimates for potential life loss.</td></tr>
</table>

Economic and Environmental Consequences	
Consequence Description	Not considered
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Other Consequences	
Consequence Description	Not considered
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Continue weekly, monthly, and annual inspections of the dam looking for cracks, bulges, offsets or other signs of slope instability.
Surveillance and Monitoring	Continue to read piezometers and survey monuments. Consider installing additional piezometers along the maximum section of the dam.
EAP	Signs of slope instability should be apparent prior to a failure and failure is anticipated to develop relatively slowly due to the highly plastic nature of the embankment materials.
Follow up Studies	
Others	
Other Notes/Comments	

Long Draw Dam

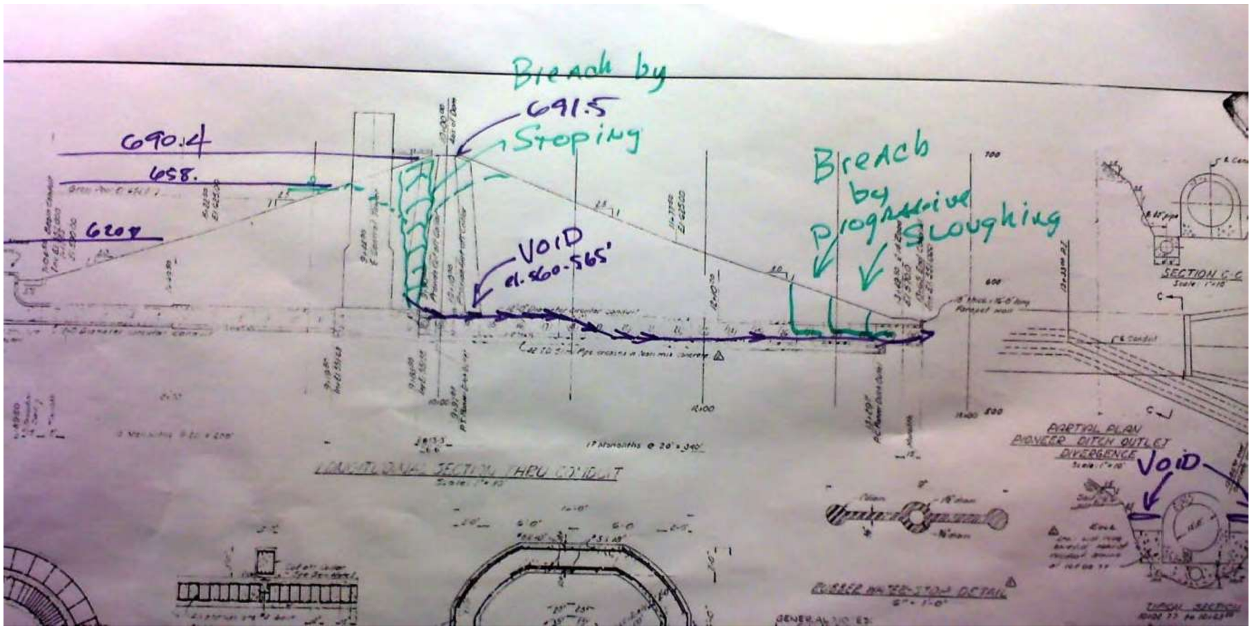
PFM Information

Structure	Main Dam
Loading Condition	Flood
PFM Type	Internal Erosion
Location(s)	At Outlet Works

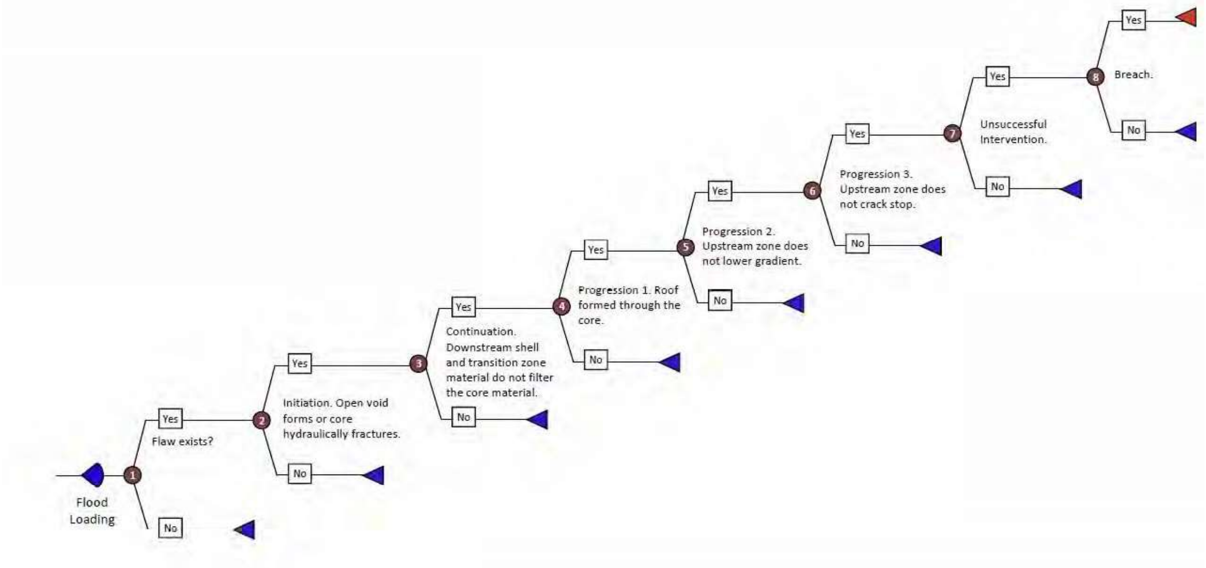
PFM Description

PFM No.	13
PFM Title	Concentrated leak erosion in transverse crack above conduit and filter
PFM Description	The reservoir rises above 951.4 feet (conservation pool). A defect, such as a crack or hydraulic fracture, due to a low density zone exists in the embankment above the conduit. A concentrated leak develops, and an unfiltered exit exists above the top of the chimney filter (also at 951.4 feet). Leakage flows and erosion increase, progressively enlarging the crack. Gross enlargement and lateral erosion of the opening occurs until the reservoir is rapidly released through opening, and the dam erodes to the base of the embankment.

PFM Sketch

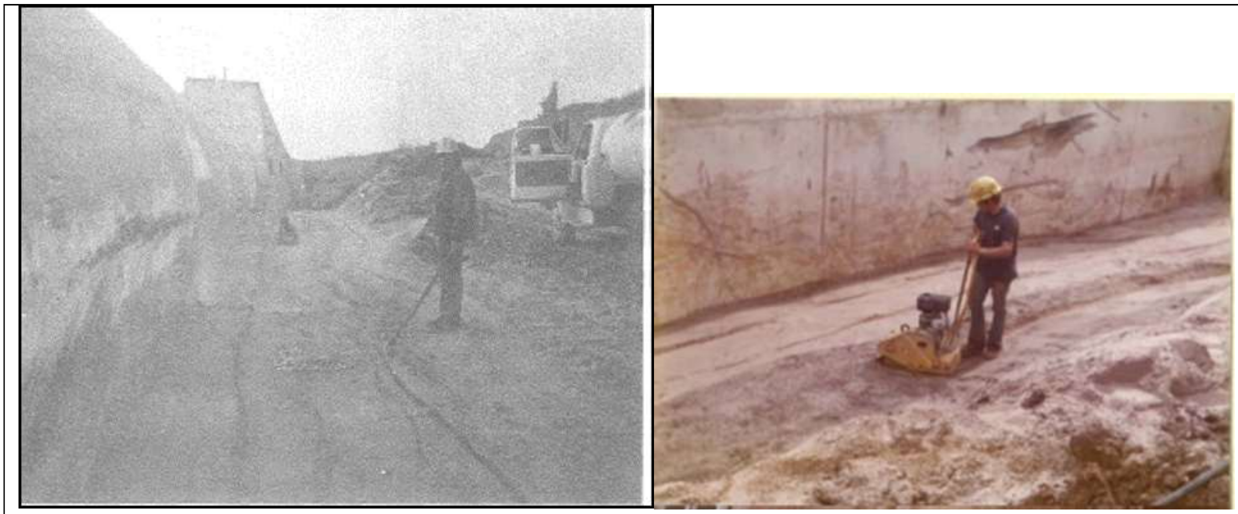


Event Tree (if used)

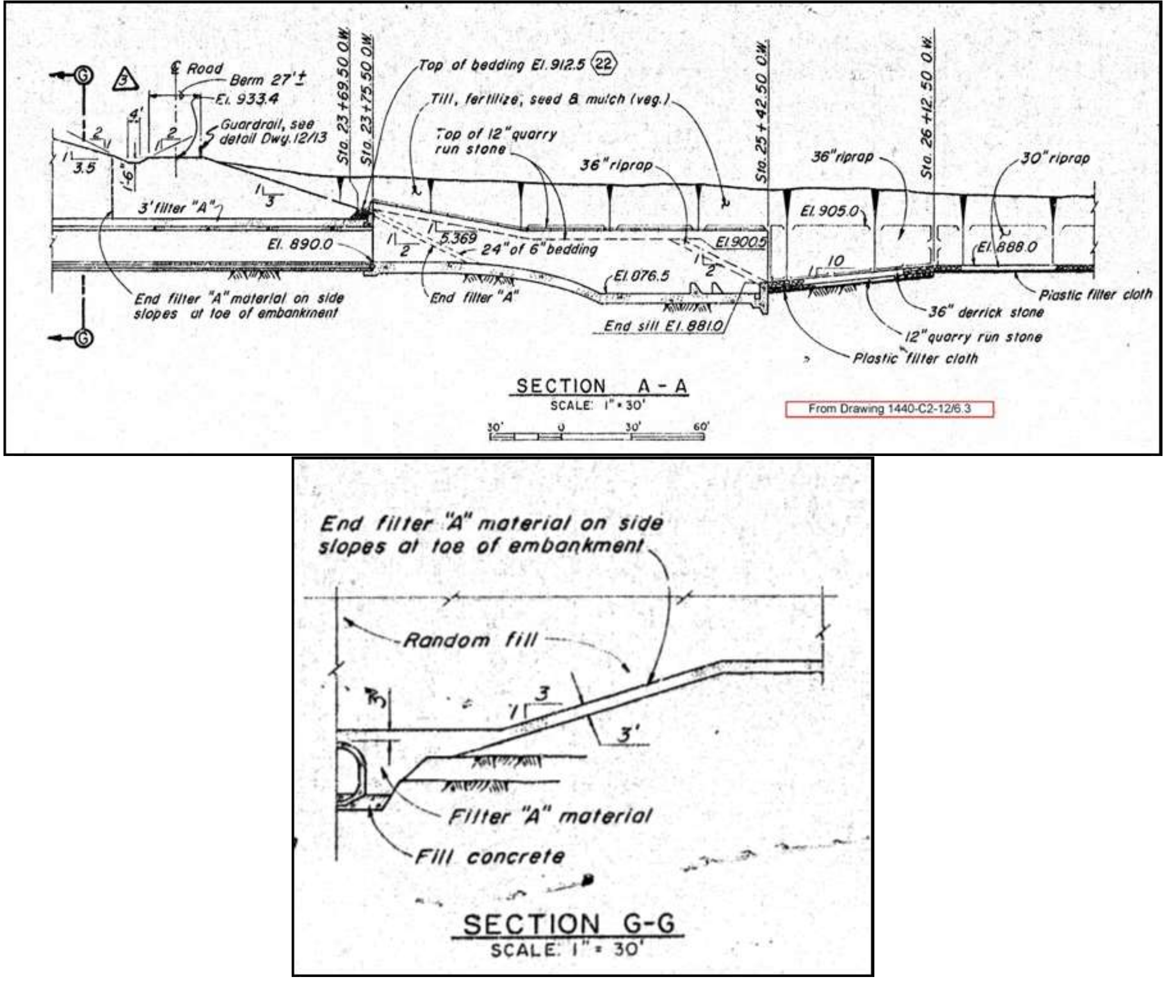


Additional Supporting Information (if needed)

Construction Photograph of Outlet Works Excavation



Construction Photographs of Filter Placement around the Conduit



"As-Built" Details of Filter around the Conduit

Performance Monitoring Information

No instrumentation exists along the conduit. No seepage or leakage has been observed at the downstream toe along the conduit.

Influence Factors		
Event Tree Node (or other designation)	More Likely	Less Likely
	Unfiltered exit exists above 951.4 feet.	Top of the outlet conduit and top of weathered rock are at similar elevations so any differential settlement should be negligible.
		Majority of field moisture contents were wet of optimum (average moisture content).
		Embankment plasticity index is greater than 20, with an average of 20 to 30.
		No seepage was observed up to record pool of 964.24.

Failure Likelihood Summary	
Failure Likelihood	1E-06 to 1E-07
Justification	There is no compelling evidence to suggest that a crack exists. Key evidence is weighted against a crack or hydraulic fracture. The top of the conduit and top of weathered bedrock adjacent to the conduit excavation are at similar elevations, and any differential settlement should be minor. Compaction using a vibratory-plate compactor was specified for Filter “A” material around and over the top of the conduit. The embankment soils were placed wet of optimum with average plasticity index greater than 20. No cracking or seepage has been observed in this area up to the record pool of 964.24 feet, which extended about 12 feet above the top of the filter.
Confidence	Moderate to High.
Rationale	The evidence was fairly compelling for the selection of the likelihood. Since the dispersive characteristics of the clay were unknown, the confidence was extended to moderate.

Consequences	
Life Safety Consequences	
Consequence Description	The primary consequence center is Howard, Texas which is located between the toe of the dam and about 22 river miles downstream along the Mainstem River. In Howard, the northern and western portion of Titan Industrial Park is inundated. Merry, Texas is located about 50 river miles downstream of the dam, but only the MHP breach scenario inundates Merry. Howard has less than 1 hour for the MHP breach flood wave arrival time (2-foot rise), and the flood wave arrival time for Merry is about 7 hours.
Estimated PAR	The PAR for a MHP breach ranges from 280 (day) to 390 (night); the PAR for a TAS breach ranges from 200 (day) to 280 (night); and the PAR for a sunny day breach is about 30 to 120. The majority of the PAR is in Howard. The incremental PAR for MHP breach is 184 (day) and 255 (night).

<table>
<tr><td rowspan="5">Inundation Characteristics</td><td colspan="4">The majority of the single family homes observed during the risk team’s site visit were single story, with most multi-family structures being 2-story buildings. The estimated depth of flooding for MHP breach within Howard typically ranges from 8 to 14 feet but as deep as 20 feet in populated areas. In Merry, the estimated depth of flooding for MHP breach typically ranges from 5 to 10 feet. Based on these depths, single-story structures will not provide safe shelter, and for a depth of flooding of 20 feet, two-story structures will not provide safe shelter either.</td></tr>
<tr><td>Location</td><td>Time (hr)</td><td>Depth (ft)</td><td>Velocity (ft/s)</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Warning/Evacuation Challenges</td><td colspan="4">There are several facilities in Howard requiring special evacuation assistance within the spillway and embankment breach inundation zones including hospitals, schools, and correctional facilities.</td></tr>
<tr><td>Consequence Likelihood</td><td colspan="4">10-100</td></tr>
<tr><td>Justification</td><td colspan="4">The breach parameters compare favorably with the team’s estimated parameters.
Due to the proximity of the large PAR to the dam, the life loss estimates are not sensitive to warning time. The estimated incremental life loss ranged from about 60 (MHP breach) to 10 (TAS breach) to about 13 to 40 (sunny day).
The life loss estimate is based on the Emergency Alert System (EAS) only. The warning effectiveness may be better than EAS for two reasons. The dense urban development facilitates warning dissemination between neighbors and family, and the PAR will likely have heightened awareness of the reservoir filling given its recent storage history and the extended period of drought and near-drought conditions in this part of Texas. Because of the urban environment, numerous evacuation routes are available, many perpendicular to the river in the residential areas, except for those near the toe of the dam and the river. The maximum distance to evacuate is less than 2 miles nearest the confluence of Smith Creek and less than 1 mile for other areas.</td></tr>
<tr><td>Confidence</td><td colspan="4">Moderate to High</td></tr>
<tr><td>Rationale</td><td colspan="4">Given the close proximity of the large PAR to the dam, there is a potential for significant life loss and it is unlikely that the estimated life loss will change by an order of magnitude.</td></tr>
</table>

Economic and Environmental Consequences	
Consequence Description	There are four endangered mussels in the area.
Consequence Likelihood	Environmental consequences were considered qualitatively.
Justification	Loss or reduction in upstream pool would potentially be considered a benefit as the pool is drawn down periodically to allow vegetation to be established to augment the aquatic habitat. If the pool loss occurred in the winter (unlikely since locking does not occur), the potential separation of off channel pools from the river and lower water levels would be an impact to the ability of the aquatic species to survive the winter freezing period.
Confidence	Low
Rationale	
Other Consequences	
Consequence Description	None.
Consequence Likelihood	
Justification	
Confidence	
Rationale	
Potential Interim Risk Reduction Measures/ Potential Dam Safety Management Actions	
Inspections	Continue to inspect along downstream toe where outlet works penetrate the embankment.
Surveillance and Monitoring	Consider installing piezometers along profile of outlet works from the core to the downstream shell to verify the phreatic surface.
EAP	Initial breach might be limited due to effects of outlet conduit. Might also impact use of outlet to drawdown the reservoir in the event the PFM activated at this location.
Follow up Studies	
Others	
Other Notes/Comments	

Document Content(s)