

TECHNICAL NOTE 5
**POTENTIAL FAILURE
MODE ANALYSIS**

GOOD PRACTICE NOTE ON
DAM SAFETY



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This publication received the support of the Global Water Security & Sanitation Partnership (GWSP). GWSP is a multidonor trust fund administered by the World Bank's Water Global Practice and supported by Austria's Federal Ministry of Finance, the Bill & Melinda Gates Foundation, Denmark's Ministry of Foreign Affairs, the Netherlands' Ministry of Foreign Affairs, the Swedish International Development Cooperation Agency, Switzerland's State Secretariat for Economic Affairs, the Swiss Agency for Development and Cooperation, and the U.S. Agency for International Development.

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This Technical Note on Potential Failure Mode Analysis is a supplementary document to the Good Practice Note on Dam Safety. Please cite the work as follows: World Bank. 2021. “Good Practice Note on Dam Safety - Technical Note 5: Potential Failure Mode Analysis.” World Bank, Washington, DC.

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Cover design: Bill Praguski, Critical Stages LLC.

Technical Note 5: Potential Failure Mode Analysis

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Definitions and Origin of the PFMA

Potential failure modes analysis (PFMA) is a process to systematically identify, describe, and evaluate the ways in which a dam and its appurtenant structures could fail under postulated loading conditions.

Since 2002, PFMA has been introduced as part of five-year inspections under the U.S. Federal Energy Regulatory Commission (FERC) regulations¹ for nonfederal hydropower dams in the United States. Chapter 14 of the FERC Guidelines² provides a detailed description of the PFMA process, including key goals and typical outcomes; background information review; site inspection; and facilitated workshops involving “brainstorming” sessions to identify and evaluate potential failure modes, consequences, and mitigation measures.

The PFMA requires dam owners to perform a qualitative risk assessment to identify potential failure modes (PFMs) and assess required remedial works, monitoring instrumentation systems, and others for risk mitigation and safety improvement. The PFMA has established a basis for dam safety performance assessment and provides an opportunity for targeted dam safety enhancements that might be overlooked by traditional standards-based approaches. Monitoring instruments can be installed and dam safety inspections targeted to specifically address failure modes.

PFMA can be carried out at several levels. Several useful guidelines (see References) have been prepared, including the PFMA and other similar type of risk assessment techniques.³ As an adjunct to the standards-based engineering design, a screening or preliminary level, qualitative, or semiquantitative PFMA is a valuable risk-informed dam safety tool.

¹ PFMA is defined under Part 12: Safety of Water Power Projects and Project Works—Subpart D: Inspection by Independent Consultant under the Code of Federal Regulations—Title 18: Conservation of Power and Water Resources—Chapter I: Federal Energy Regulatory Commission, Department of Energy—Subchapter B: Regulations Under the Federal Power Act.

² See <https://www.ferc.gov/industries/hydropower/safety/guidelines/eng-guide/chap14.pdf>.

³ Other similar and equally useful qualitative and semiquantitative risk analyses techniques include failure modes and effect analysis and failure modes, effect, and criticality analyses.

Objectives and Applications of the PFMA

The PFMA is intended to provide an understanding of how and why dams fail by looking at how dams behave normally, learning to identify early signs that something is wrong, understanding the hazards and risks imposed by the dam, and being prepared for the unexpected behavior that leads to failure.

PFMA can be used during both design and operation of dams to:

- Identify applicable PFMs
- Identify where additional defensive measures could reduce the likelihood of failure
- Identify key parameters and provide instrumentation to monitor them
- Prepare operating, surveillance, maintenance, and emergency preparedness plans that take account of PFMs

During the implementation of large water infrastructure projects, such as dams and hydropower schemes, the transition between construction and operation is often a challenging phase. In many cases, the entity that takes over the operation of a project is different from the one that supervised construction activities. The handing-over process entails the transfer of a significant amount of information, including elements pertaining to risk management, as emerged during construction and first reservoir filling. A PFMA workshop is particularly useful in the transition between the construction and the operation phase of a dam project.

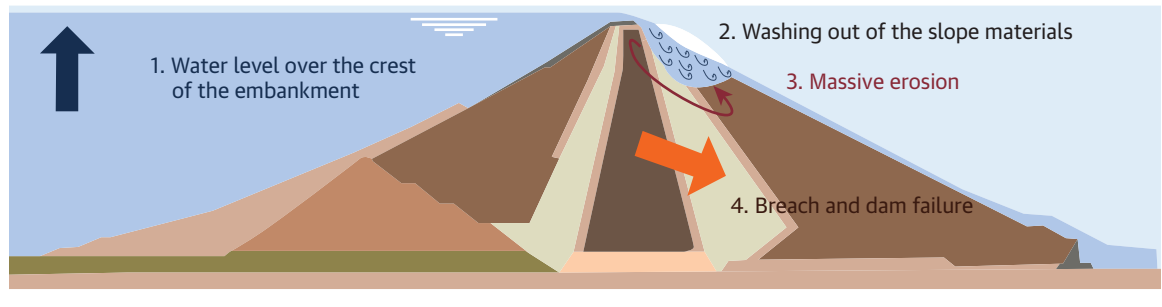
The World Bank has assisted some countries in applying the PFMA for safety review of major existing dams⁴ and found that the tool is useful in prioritizing additional investigations needs and remedial works in coordination with key stakeholders, including owners, operators, and designers.

This Technical Note contains guidance for preparing PFMA terms of reference for: (a) the FERC-based standard approach to PFMA and (b) a simplified PFMA approach. The latter may be appropriate to optimize time and resources or when there is limited knowledge of the dam, which is a frequent problem at smaller and older dams. Depending on results, the simplified approach may or may not be followed by a full-fledged PFMA. Guidance on application of the simplified PFMA to an individual dam and a portfolio of dams is also presented.

Figure 1 provides an example of how a PFM for overtopping of an embankment dam would be developed. A severe flood, inadequate spillway capacity, or inability to open the gates of the spillways causes the water level to rise over the crest of the dam. Flow over the crest washes out the downstream slope materials of the embankment and causes massive erosion that progresses, leading to slope instability, breach, and dam failure.

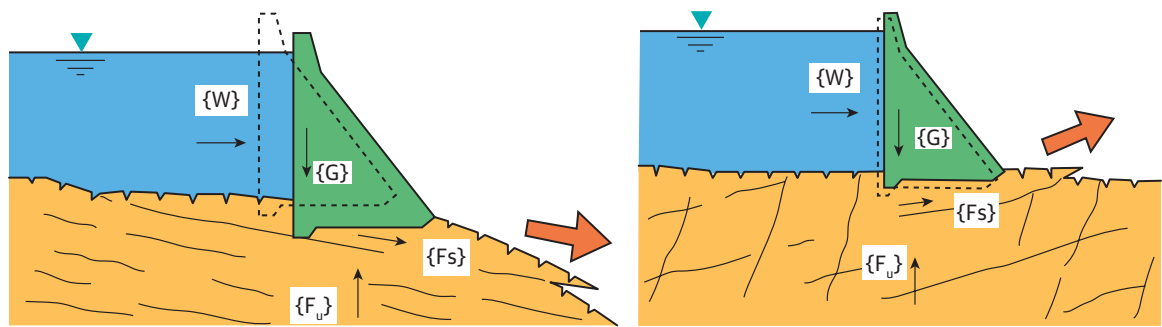
⁴ Legadadi and Dire Dams in Ethiopia; Tuyamuyun Dam in Uzbekistan and Turkmenistan; Valdesia, Jigüey, Aguacate, and Las Barías in the Dominican Republic; Nurek Dam in Tajikistan; Jatiluhur Dam in Indonesia; Swa Chaung Dam in Myanmar; and Poechos in Peru. PFMA trainings were also provided under the Nile Basin Initiative/Eastern Nile Technical Regional Office dam safety program for the then four riparian countries.

FIGURE 1. Failure Mode—Overtopping of an Embankment Dam



Source: CWC (2019).

FIGURE 2. Failure Mode—Sliding of a Concrete Gravity Dam on Foundation Joint



Source: Wittke (2014)

Note: F_s = Sliding Force; F_u = Uplift Force; G = Gravity Force; W = Water Pressure.

Figure 2 provides another example of a PFM for sliding of a concrete gravity dam along unfavorably oriented joints in the foundations. Gravity dams are particularly sensitive to uplift pressures, and the presence of structural features in the foundation must be checked carefully. Small deformations may be enough to trigger failure if foundation discontinuities are unfavorably oriented. Foundation weathering and undetected uplift pressure buildup are concomitant issues to be carefully considered.

Critical Assessment of the PFMA after the Oroville Incident

After the Oroville Dam spillway incident in February 2017, FERC required the California Department of Water Resources to engage an Independent Forensic Team (IFT) to develop findings and opinions on the causes of the incident. The IFT concluded that:

... although PFMA is a very useful tool, which is likely quite adequate for a majority of dams, the current PFMA process can have difficulties in properly characterizing risks for large or complex systems, including accounting for human and operational aspects in failures. By defining failure modes as a linear chain of events, there can be a tendency to oversimplify complex failure modes involving

multiple interactions of system components. Knowledge of the full range of dam safety risks resulting from all operational aspects is required for an organization's managers to decide on appropriate actions to manage those risks.

In addition, the current PFMA process does not explicitly consider how broader organizational factors, such as culture and decision-making authority and practices, can contribute to failure. For such situations, it may be necessary to supplement the typical PFMA process with other approaches as used in other industries, which can possibly better address these complexities and operational aspects.

The PFMA process described in this Technical Note is based on the process as defined by FERC, but it is also supplemented by recommendations put forward by the IFT aimed at elimination or moderation of shortcomings of the original PFMA.

Standard Potential Failure Mode Analysis

Scope of work

The PFMA exercise aims to identify PFMs relating to dam(s), spillway, foundations, abutments, and so on and to assess those failure modes of enough significance to warrant continued awareness and attention to visual observation, monitoring, and remediation as appropriate. This process will provide opportunities for risk reduction, possible investigations or analyses, means for monitoring and inspecting for the development of PFMs.

The specific purpose of the exercise is to:

- Enhance the dam safety inspection process by helping to focus on the most critical areas of concern unique to the dam under consideration
- Identify operational related PFMs such as failure of discharge equipment to operate
- Consider hazards that might indirectly affect the dam, such as landslides into the reservoir
- Identify structural related PFMs (for example, piping) not addressed by the commonly used (standards-based) analytic methods (for example, slope stability or seismic analysis)
- Enhance and focus the visual surveillance and instrumented monitoring program
- Identify shortcomings or oversights in data, presentation of data, information, or analyses necessary to evaluate dam safety and each PFM
- Help identify the most effective risk reduction measures, including emergency preparedness

The requirements of the PFMA exercise are to:

Collect all data, studies, and information on the investigation, design, construction, previous dam safety assessments and analyses, performance, and operation of the project, history of repairs, and their performance. All studies and investigation reports that relate to the ongoing safety of the dam must be

included, reviewed, and evaluated. A listing should be made of the data and information available for review and considered in the PFMA and included in the subsequent PFMA report. It is extremely beneficial if all documents are made available before the workshop and adequate lead time to review documentation is available. That approach allows the participants to request additional information if documentation is incomplete, and it also shortens the duration of the workshop.

Have technical experts visit the project site with an eye out for PFMs, structural, and geologic conditions; identify instrumentation; review operations; and interview owners and operators for their input on PFMs.

Review all the background information for general understanding and with these specific questions in mind:

- How could this dam fail? (site-specific consideration of geology, loadings, structure condition, and project past and anticipated operations)
- What would happen if the dam fails? What would be the consequences of failure, considering the number of people at risk, environmental damage, and economic impacts?
- How could a large unplanned discharge occur even if the dam does not fail (for example, uncontrolled gate opening or overtopping wave from a landslide into the reservoir)?
- Are any other reservoirs present in the upstream river basin that could pose a risk to the subject dam?
- Are the identified PFMs recognized and appropriately monitored by visual surveillance or instrumental monitoring?
- What actions (immediate or in the long term) can be taken to reduce dam failure likelihood or unplanned discharge or to mitigate failure consequences? These actions could include data collection, analyses or investigations, operational changes, communication enhancement, monitoring enhancement, or structural remediation measures.

A core team of four, five, or more people (table 1) is recommended to conduct the PFMA exercise for a high-risk or hazard/consequence dam.

In addition to the technical experts, attendance of the PFMA workshop should also include:

- Dam operators (main actors)
- Operators of other dams that can affect the operation of the dam undergoing PFMA
- Representatives of stakeholder institutions

Methodology of the PFMA Workshop

- The site visit is intended to provide: (a) a general orientation on the dam and related facilities, and (b) an understanding of the conditions of the dam. Digital photos should be taken for use in the workshop.

TABLE 1. Composition of PFMA Team

PFMA core team member	Main tasks
Facilitator—international expert familiar with the PFMA process	Site inspection, facilitation of the PFMA session
Independent dam safety specialist—international expert in dam safety evaluation who is familiar with dam failure mechanisms	Site inspection; delivery of expert input to PFMA
Engineer geologist/geotechnical engineer—national expert	Site inspection, providing site-specific knowledge during PFMA
Hydrologist/hydraulic engineer—national expert	Site inspection, providing site-specific knowledge during PFMA
Hydro mechanical engineer—national expert	Site inspection, testing, and expert review of discharge gates and valves, their controls, and backup systems

Source: Original table for this publication

Note: PFMA = potential failure mode analysis.

- The data review sessions should involve the definition by the facilitator of key data required.
- The PFMA team should be diverse and adequately cover all relevant technical disciplines involved in the analysis and with sufficient specialized expertise.
- The PFMA workshop sessions should involve the systematic identification of PFMs for normal, flood, and earthquake conditions. The dam site(s) are considered as several discrete components and analyzed one at a time. For complex dam systems, the PFMA team should be divided into specialized groups for different components of the system, but the coordination among the groups should be established to ensure that the interactions among components are adequately addressed.
- PFMs and failure scenarios are brainstormed within a team of people most familiar with design, analysis, performance, and operation of the dam. Records will include the identified PFMs, the reasons each PFM is likely to occur, and any possible actions related to each mode of failure that could help reduce risk (monitoring enhancement, investigation, analysis, and remediation).
- If a voting process is used, qualifications should be included that are needed to be able to cast a vote for particular PFMs, and silent voting could be used so that participants are not influenced by the votes of others. Alternatively, PFMs can be assigned to categories based on consensus, with outlying opinions recorded appropriately if a full consensus is not achieved.
- It is important to specifically identify possible performance monitoring enhancements for each PFM for consideration of the owner and periodic inspectors.
- The PFM should be expressed as a sentence easily interpreted by others (for example, “excessive settlement resulting in transverse cracking across the dam and, with no compatible filters, leading to internal erosion developing into piping failure through the dam core”).
- It is important to document the analysis by recording the major findings and understandings from the brainstorming session. An interim report is prepared, containing results as collected directly from the workshops and addressing these items.

The core team prepares summary tables as the discussions progresses. These tables include key parameters pertaining to the following elements:

- PFM
- Scenario/initiating events/sequence/consequences
- Negative factors affecting the likelihood of the PFM
- Positive factors that could reduce the likelihood of the PFM
- Monitoring/risk reduction opportunities/data and analysis
- Gaps/emergency plans
- Action items
- Categorization of the PFM

PFM categorization is carried out according to the FERC system (table 2).

The resulting tables are attached as Appendixes to the PFMA report. On completion of the tables, a round table review is held with all participants identifying key findings and understandings that were recorded. Findings are then prioritized by the group.

The final report should include a recommended action plan on the identified remedial measures, along with specific inputs for the preparation and upgrading of dam safety plans, including instrumentation plans and Emergency Preparedness Plans (EPPs). The EPP should include updating or preparing the Response Level Matrix (see Sample terms of reference for EPPs in the Good Practice Note [GPN], Appendix 4).

TABLE 2. Potential Failure Mode Categorization According to the U.S. Federal Energy Regulatory Commission

Category	Characterization	Description
I	Highlighted PFM	Considers potential for occurrence, magnitude of consequence, and likelihood of adverse response (physically possible, fundamental flaw or weakness identified, conditions reasonable and credible)
II	Potential PFM considered, not highlighted	Of lesser significance and likelihood than category I
III	More information or analyses needed to classify	Lacked information for confident judgment and because action may be required, these may be highlighted
IV	PFM ruled out	May be that physical possibility does not exist, information eliminated concern, or so remote a possibility as to be noncredible or not reasonable

Source: FERC (2005)

Note: In many cases, it is a single person, or maybe two, who makes such a judgment, but the responsibility is hidden behind the PFMA team. In such cases, the report should state who exactly ruled out the failure mode and on what basis. PFM = potential failure mode; PFMA = PFMA analysis.

Follow-up actions after PFMA

The intent of PFMA is to provide guidance for the future operation and maintenance (O&M) plan, including surveillance and monitoring of the dam, and help the owners and operators make informed decision on required remedial measures in structural and nonstructural items. The following provides some general guidance on the required follow-up actions.

Additional investigations and enhanced monitoring

Category III PFMs may require more information based on additional survey, investigations, and analyses to assess the potential risks and potential required measures. The owner may also need to enhance regular surveillance and introduce some additional monitoring instruments for some targeted areas that have exhibited some potential safety issues.

Maintenance and repairs priorities

Category II PFMs may require the owner to consider undertaking prioritized maintenance and repair works and enhanced inspection and monitoring instrumentation of the dam. This requirement could also involve changes in the O&M plan of the dam, including possible drawdown of the maximum water supply level of the reservoirs.

Guidance for rehabilitation decisions

Category I PFMs may require the owner to assess the urgency of remedial works and prioritize rehabilitation decisions to use limited funds for most critical remedial works. The owner may need to communicate with an emergency office and other stakeholders to ensure the EPP, in particular the Response Level Matrix (see a sample in GPN Appendix 4) in place and update it as needed including training/dissemination works, and so on. Also, a more detailed risk assessment may be needed to allow the decision makers to make an informed decision.

Table 3 also provides a general matrix of risk categories and potentially required actions. Although the four categories of urgency of action do not directly correspond to categories I through IV, the table would give some general idea of required actions to address identified risks according to their urgencies.

Duration and deliverables

The following are approximate indicators of time required for each activity; however, these are specific to the project under consideration:

- Data collection and study: one week
- Site visit: one day
- PFMA workshop: two days (highly complex cases may require longer time)
- Summary findings: one day

TABLE 3. Risk Categories and Potentially Required Actions

Urgency of action	Characteristics	Potentially required measures
Very high urgency	Critically near failure under normal operating conditions within a few years or under floods less than 10 years return period	Undertake immediate risk reduction measures to avoid failure, communicate risk to affected people, enhance monitoring, ensure EPP is in place, and so on
High priority	High risk (failure could occur under normal operations or initiated by an unusual event (for example, earthquake or flood) less than design standard, and so on)	Undertake interim risk reduction measures, expedite investigation enhance monitoring, ensure EPP is in place, and so on
Priority	Moderate risk (significant and unacceptable dam safety issues)	Prioritize detailed investigations, risk assessment, and proposed phased remedial measures, and so on
Normal	No significant dam safety issues identified	Ensure regular surveillance, monitoring, and periodic safety inspection program in place, and so on

Source: Original table for this publication
Note: EPP = Emergency Preparedness Plan.

- Draft report: three days to one week (or longer depending on the volume of information relevant to the PFMs that should be assembled)
- Final report: two days

Deliverables include:

- Technical archive, preliminary version stating contents and identified gaps
- PFMA workshop draft report documenting the analysis and the major findings and understandings from the brainstorming session
- Final report, including an action plan, input to dam safety plans (Response Level Matrix in the EPP in particular), and recommendations on training needs for dam operators and other relevant stakeholders

Annex B contains an example of PFMA for an individual dam, including a list of identified PFMs and category I PFMs that required more-detailed analyses, investigations, and remedial works.

Simplified PFMA

In several cases, it is necessary or appropriate to undertake a quick assessment of PFMs in a way that follows the general principles of FERC’s PFMA process, but optimizes time and resources. This assessment leads to simplified processes, which may find their legitimacy in the quantity and quality of information available. A simplified PFMA may be used in combination with a risk index system to assess risk and prioritize action for a portfolio of dams.

Two simplified PFMA procedures⁵ are described in the following for application to:

- Individual dam

⁵ The methodology described here is based on Dam Rapid Assessment and Prioritization Tool (DRAPT) User Guide - Issue 2, a report prepared by Damwatch Engineering Ltd (2018).

- Portfolio of dams

Individual dam

A simplified application of PFMA entails three essential steps:

- Site visit and scoping meeting with dam operators and designers to identify PFMs and the condition of the dam relevant to them
- Consideration of the most likely failure modes for the type of dam and applications of scores for each PFM. These findings can be used as a component of a risk index system.
- Presentation of assumptions and results to the dam operator or designer to critically review and revise results as necessary

For an embankment dam made of earthfill, clay core/rockfill, or upstream-faced rockfill dams, the common failure modes (based on historical dam failures) are:

- Overtopping of dam crest eroding slope of dam (resulting from insufficient spillway capacity)
- Internal erosion or foundation piping
- Slope instability or cracking of the dam face
- Operational issues that can lead to failure (for example, poor maintenance or low capability of dam operators)
- Geological hazards (earthquake shaking and landslide instability)

This information is overall in line with the analysis of 232 embankment dam failure cases (figure 3).

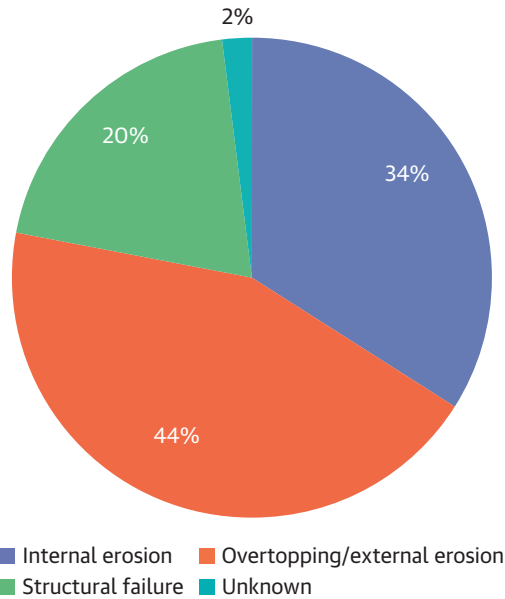
For a concrete dam, the common failure modes are:

- Flood overtopping eroding toe of dam
- Sliding on a plane of weakness in the foundation or at the dam/foundation interface
- Structural failure of the dam body
- Operational issues that can lead to failure (for example, poor maintenance or low capability of dam operators)
- Geological issues (abutment slope failure, earthquake shaking, and landslide instability)

This information is also overall in line with the statistical analyses result of 59 concrete and masonry dam failure cases (figure 4).

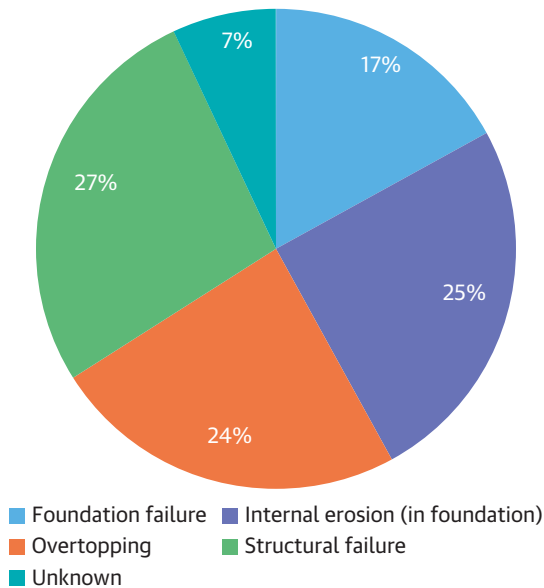
Also, the assessment team needs to realize that a specific dam may have an important but unusual failure mode and the process should be able to accommodate such a variation. It should be noted that

FIGURE 3. Failure Causes of Embankment Dams



Source: ICOLD (2019).

FIGURE 4. Failure Causes of Concrete/Masonry Dams



Source: ICOLD (2019).

flood overtopping requires some understanding of catchment characteristics and dam spillway dimensions to route the flood through the dam reservoir and understand its effects on the structure.

Furthermore, it is important to identify and assess “hidden” failure modes beyond just the extreme flood event. For example, failure of electrical-mechanical system, gate jamming, and so on under flood

flows significantly less than the design flow can cause far greater risk than flood flows exceeding the design flood. As discussed for Question 97 - Spillway⁶ (ICOLD 2015), BC Hydro undertook an assessment of their discharge facilities and identified a number of deficiencies that could lead to single-point failures including: i) aging and obsolete equipment which increases the risk of failure, ii) lack of consistent maintenance in the past, iii) limited scope and frequency of testing and inadequate testing procedures, and iv) limited staff operating familiarity and knowledge of standby arrangements. It also raised a concern over the safety issue of jammed gates. The report further introduced the root cause analyses of gate failure cases as shown in Table 4. Had these operational deficiencies occurred during even a moderate flood event, there could have been a risk of overtopping. However, many of these operational deficiencies and causes of gate failures are difficult to be identified by traditional standard-based approach, and the likelihood of such situations may be more prevalent in the borrowing countries of World Bank-funded projects.

PFMs can be rated with a scoring system such as the one shown in table 5. Higher scores indicate priorities for undertaking remedial actions. For those who are interested in more details of PFMs and contributing factors, refer to Annex A: Contributing Factors to PFM Development based on the most common five failure modes for embankment dams.

With engineering judgment being necessary to make these assessments, the process requires a highly experienced dam expert, preferably supported by one or more experts in the disciplines required (structural engineering, hydrology, hydraulics, geotechnical engineering, and electrical-mechanical engineering). The process can be completed in two to three days.

Using event or fault tree techniques to estimate probability of failure

As mentioned, the objectives of a PFMA are to: (a) identify the site-specific credible PFMs, and (b) provide a complete description of the PFMs and the progression of steps leading to an uncontrolled release of the reservoir. The risk assessment achieves the latter objective using an event tree analysis to determine the probability of failure. The perspective of local office personnel, including dam operators and inspectors, is of fundamental importance in conducting the exercise.

TABLE 4. Root Cause of Gate Failures

Root cause of gate failures	Number of reviewed failure cases	Share (percentage) of failure cause
Debris	10	27
Hoist failure	10	27
Failure to operate on demand (typically power failure)	9	24
Structural failure	5	14
Jammed gate	3	8
Total	37	100

Source: Lewin et al 2003

⁶ ICOLD 25th Congress in Stavanger, Norway 2015

TABLE 5. Contributing Factor Score

Contributing factor score	Description
10	Contributing factor means that the potential failure mode has been initiated, is in progress, or is expected to progress under normal operating or design loading conditions.
9	
8	
7	Contributing factor indicates that the potential failure mode is likely to develop or progress under normal operating or design loading conditions.
6	
5	
4	Contributing factor indicates that the potential failure mode is unlikely to develop or progress under normal operating or design loading conditions.
3	
2	
1	Contributing factor indicates that the potential failure mode is very unlikely to develop or progress under normal operating or design loading conditions.
0	Contributing factor is not relevant to potential failure mode development

Source: Damwatch Engineering Ltd. (2018)

Annex C contains an example of a simplified PFMA for an individual dam that uses the event (of fault) tree technique to estimate probabilities of failure.

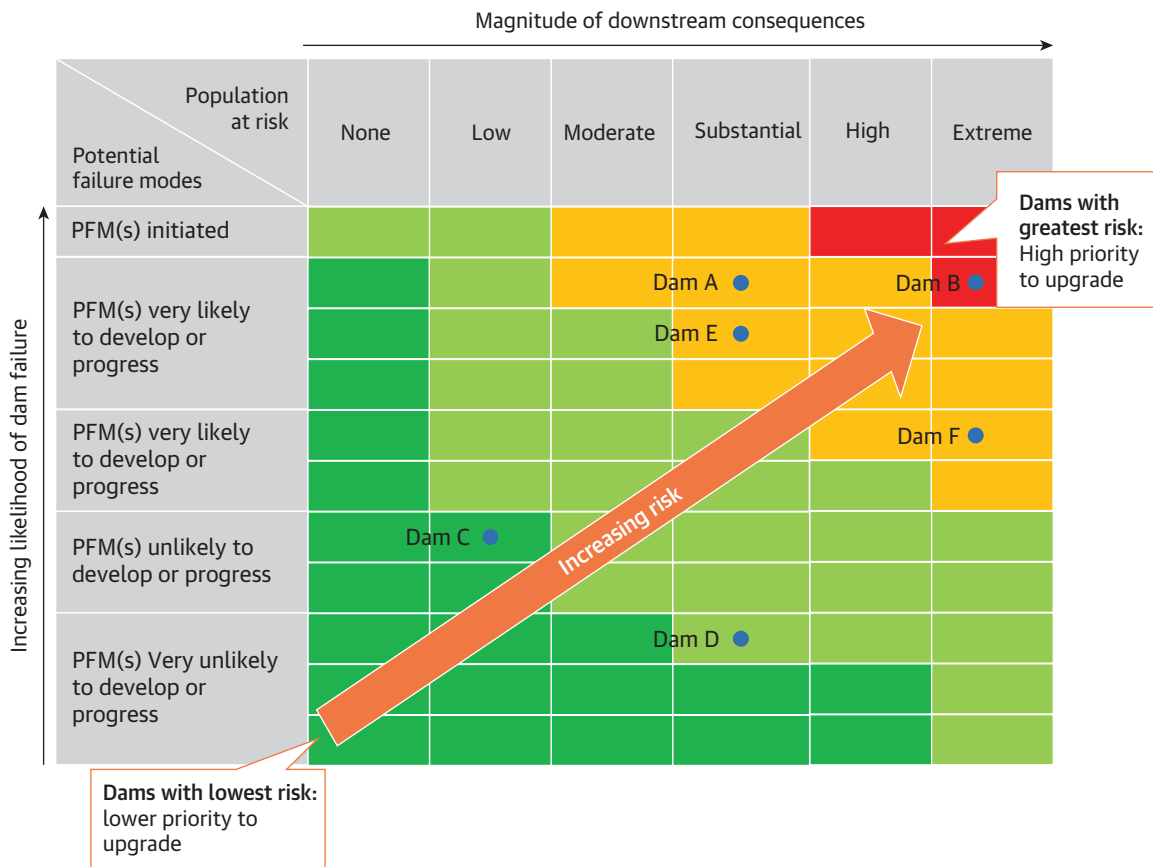
Portfolio of dams

PFMs for a portfolio of dams can also be assessed with a rapid method as described earlier for individual dams. This assessment provides the opportunity to identify common problems across the portfolio and therefore prioritize the most urgent remediation and avoid unnecessary interventions. Costs to remediate can potentially be more efficient. If possible, the same team of experts is recommended to carry out the portfolio assessment to achieve consistency and reduce the potential for bias. There is also an opportunity to build local capacity by utilizing the experts in mentoring and training roles over multiple dams.

As mentioned, this portfolio approach (under simplified PFMA) focuses on the most common failure modes.

The assessment is carried out by a team of experts, in consultation with dam operators and designers. The process involves assigning scoring contributing factors to each PFM on a scale of 1 to 10. The score for each contributing factor is assigned based on the dam site inspection and the user’s experience and judgment. This system is most useful as a contribution to a risk index method of prioritization, in which the results of a portfolio of dams can be shown (table 6). The figure can also be used in a manner that each dam can be represented by more than one dot corresponding to various failure modes. The magnitude of downstream consequences should be adjusted to local context using population at risk or potential loss of life and possibly considering other economic, environmental, and social factors. The eventual results may be categorized as in four groups from red (highest risk) to green (lowest risk) as an example.

TABLE 6. Risk Classification Matrix



Source: Damwatch Engineering Ltd. (2018)

Note: PFM = potential failure mode.

Accuracy of probability estimates is less critical than for an individual dam because relative values are used for portfolio risk assessment and management.

Key components of the PFMA scope of work are:

- Organize the “dam archive” containing as built design documents, quality control tests during construction, instrumentation and monitoring records, independent safety reviews, and so on
- Define PFMs and complete the required follow-up actions (see the previous section for Follow-Up Actions after PFMA) including the review and update of the Response Level Matrix (RLM) (see a sample EPP framework and RLM in GPN Appendix 4).
- Provide guidance on how to update the dam safety plans including instrumentation, O&M, and EPPs.
- Identify the date for conducting the next PFMA workshop, which will depend on the importance of the project and the associated hazard level; it may be about five years, but sometimes 10 years.

Annex A: Contributing Factors to PFM Development

TABLE A.1. An Example List of Contributing Factors to Potential Failure Mode Development

PFM	Contributing factor to PFM development in embankment dams	Maximum contributing factor score
Flood	Insufficient spillway capacity	10
Overtopping	Dam freeboard reduced due to excessive settlement or modification of the embankment	10
	Spillway blockage	8
	Spillway condition	8
	Spillway gate reliability (if applicable)	8
	Internal Erosion	Seepage carrying fines
Internal Erosion	Uncontrolled seepage	10
	Sinkholes and depressions	10
	Surface cracking on crest or upstream face	10
	Sand boils in channel downstream of embankment	5
	Animal burrows	5
	Decaying tree roots	5
	Slope Stability	Vertical displacement (settlement) leading to zero freeboard
Horizontal displacement (lateral deformation)		5
Slope movement upstream face (slips, cracking)		8
Slope movement downstream face (slips, cracking)		8
Erosion or failure of upstream slope protection		6
Operational	Poor ability to inspect dam	6
	Poor access to dam for machinery	6
	Physical modifications to dam that could reduce dam safety or stability	8
	Frequency of visual dam inspections	4
	Operation and maintenance systems (including Emergency Preparedness Plan)	4
Geological	Strong seismic ground motions lead to dam instability	5
	Fault rupture through the dam	4
	Fault rupture through the reservoir	3
	Landslides that enter reservoir followed by seiche wave with potential for dam overtopping	8
	Landslides and slope failures in dam or spillway vicinity with potential to disrupt structure or lead to failure	6
	Geological feature In dam foundations, presence of which could lead to dam failure	6
	Landslides or slope failures that could prevent access to dam	4

Source: Damwatch Engineering Ltd. (2018)

Notes: PFM = potential failure mode.

Annex B: An Example of PFMA (Qualitative Analyses)–Individual Dam

In this example, a team of experts, a professional facilitator, dam’s owner and operator, and so on participated conducted a joint site visit and a PFMA workshop. They have identified and classified PFMs, first in a long list as in table B.1 and then a short list as in table B.2 considering the following:

Identification and Classification of PFMs:

- Normal conditions and operation events (normal water level, structural instability, and so on)
- Aging or deterioration of initiated events (concrete alkali-aggregate reactions, corrosion, internal erosion, and so on)

TABLE B.1. A Long List of PFMs Based on Brainstorming

Events/categories	I	II	III	IV	Total
Normal conditions	1	1	6	1	9
Aging initiations	–	1	7	–	8
Flood conditions	3	–	2	–	5
Earthquake initiation	2	1	4	–	7
Other conditions			2	–	2
Total	6	3	21	1	31

Note: – = not available.

TABLE B.2. A Short List of Identified Category IPFMs

Events	Structure	Potential failure mode	Potential Consequences
Normal condition	Bottom spillway	Abutment landslide shearing the bottom spillway tunnel and filling the tailrace under normal conditions	Tailwater level rises, machine hall floods, and hydropower generation stops Significant reduction in spillway discharge capacity Overtopping of the dam during normal inflow
Flood condition	Surface spillway	Inability to open one or more spillway gates during flood discharge conditions less than inflow design flood resulting from electrical or mechanical failure	Overtopping of the dam leading to dam failure
Flood condition	Surface spillway	Overtopping with all gates available for flood exceeding the design flood	Cannot pass the probable maximum flood
Earthquake initiated	Tailrace channel	Earthquake-triggered landslide blocking the tailrace channel	Tailwater level rises, machine hall floods, and hydropower generation stops Inability to discharge water because of a total loss of spillway capacity and overtopping of the dam
Earthquake initiated	Surface and bottom spillways	Loss of operation of the spillway gates because of a loss of hydropower supply or damage to the gate equipment	Spillway not available for a long time during which the core can be overtopped and eroded by floods less than design flood, possibly leading to dam failure

- Flood conditions events (high water levels, spillway discharge, overtopping, and so on)
- Earthquake-initiated events (during and after an earthquake event)
- Other significant conditions (for example, debris accumulation, siltation, human factors, and so on)

Categories of Identified PFMs:

- Category I-Highlighted as of greatest significance and which are reasonable and credible
- Category II-Credible PFMs considered but not highlighted
- Category III-More information and analyses are required to classify these PFMs
- Category IV - PFM ruled out if it is not physically possible or so remote a possibility as to not be credible

Annex C: An Example of PFMA (Semi-Quantitative Analyses)–Individual Dam

In this example, a team of experts, a professional facilitator, and dam owner and operator, and so on conducted a joint site visit and a PFMA workshop. Each PFM was subject to an event tree analysis to assess relative probabilities and, based on those, to define priorities and actions. The following conventions were used to associate descriptive risk categories to probability values (table C.1).

The following event tree analyzes the failure mode of highest probability (figure C.1).

Results for the other failure modes are summarized in table C.2.

Comparison of failure modes clearly indicates that PFM1 (piping through spillway-core contact) entails the highest risk level. PFM1 is followed by PFM3, PFM4, and, to a lesser extent, PFM2. PFM5 and PFM6 have negligible risk levels compared with the others. In dam safety terms, the findings in table C.2 have the following implications:

- Immediate actions should be directed at reducing the risk associated with PFM1.
- Measures to mitigate risks associated with PFM3 and PFM4 should be urgently implemented.
- Further studies are necessary to define preventive and remedial actions pertaining to PFM2, 5, and 6.

TABLE C.1. Risk Categories and Probability Values

Category	Probability range (per year)
Negligible	Indistinguishable from 0
Very low	$< 10^{-4}$, except 0
Low	10^{-3} to 10^{-4}
Medium	10^{-2} to 10^{-3}
High	10^{-1} to 10^{-2}
Very high	$> 10^{-1}$, not 1
Certain	1

FIGURE C.1. Event tree analysis for piping through spillway-core contact

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

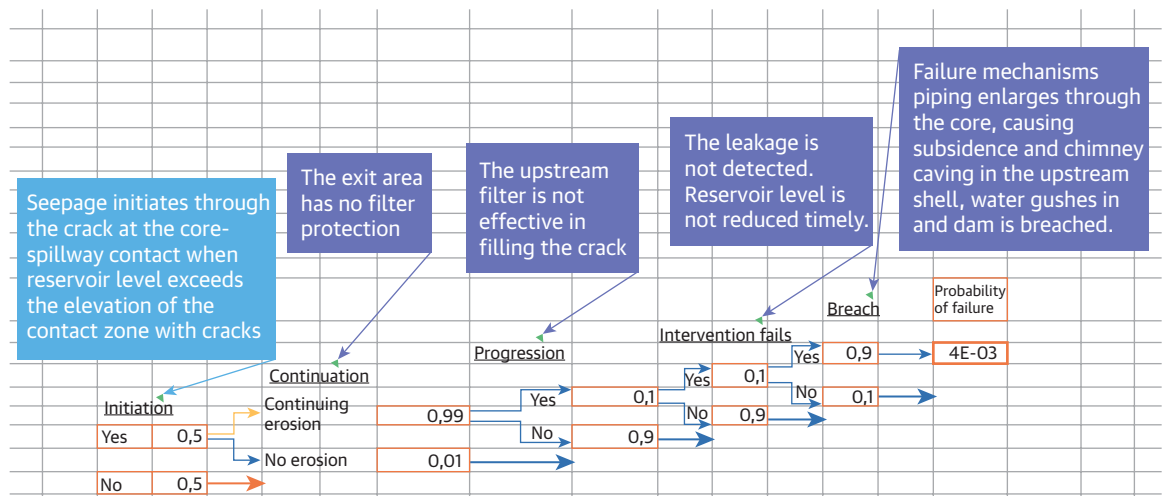


TABLE C.2. Event Tree for Highest PFM

Potential failure modes	Probability of failure	Risk level
PFM1 Piping through spillway-core contact	4E-03	Medium-high
PFM2 Progressive erosion of core or foundations	9E-06	Very low
PFM3 Impulse wave caused by right bank mass movement	2E-04	Low
PFM4 Foundation erosion in the chemically grouted fault area	1E-04	Low
PFM5 Right bank mass movement obstructs outlet works	5E-07	Negligible
PFM6 Large rockfall obstructs spillway chute	5E-07	Negligible

Note: The inverse of failure probability may be convenient in some cases when non-experts participate in the exercise.

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