Shedding Some Light on this Thing Called Risk Assessment

PART THREE

PUTTING IT ALL TOGETHER

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Introduction

This is the third part in a 3-part series on Risk Assessment. Part I of this article was published in Volume 8, Issue 1 of the Journal (Scott, April, 2010) and covered the basics of performing risk analyses and the process of developing risk estimates. Part II of this article was published in Volume 8, Issue 3 of the Journal (Scott and Fiedler, July, 2010) and presented an example that illustrated the risk analysis process.

So, you have completed a risk analysis and have some results, now what? Part III describes how the risk assessment process is used to make risk-informed decisions on dam safety issues and how to prioritize future activities.

Risk Guidelines

As discussed in previous articles in this series, the risk analysis process involves the estimation of two elements of risk. *Annualized failure probability* is the estimated annual likelihood of failure, and is a product of the probability of the load and the probability of failure of the structure given the load. *Annualized life loss* is simply the annualized failure probability multiplied by the estimated life loss.

In order to use estimated risks to help formulate dam safety decisions, there needs to be a framework or set of guidelines that establish whether the estimated risks for a particular dam justify taking actions to reduce risk of dam failure. Reclamation has developed Dam Safety Public Protection Guidelines to indicate general threshold guidelines when risks would justify additional studies and potentially lead to dam safety modifications. Originally developed in 1997 and modified in 2003, a recently released version (Reclamation, 2011) is in interim usage. In addition to describing the risk process and threshold values, these guidelines also include the portrayal of risks, building the dam safety case, and a prioritization system. Each of the latter three topics is explained in additional detail below.

Portraying Risks

Risks can be portrayed and compared to guidelines through the use of an f-N chart. Reclamation's f-N chart is shown on Figure 1. The "f" on the vertical axis refers to the estimated annualized failure probability while the "N" on the horizontal axis refers to the estimated number of lives lost in the event of failure.

Within Reclamation, a guideline value of $1x10^{-4}$ (shown as a horizontal dashed line on Figure 1) is defined as the threshold annualized failure probability value. Annualized failure probability can be equated to individual risk if the most exposed individual is in harm's way most of the time, and the threshold value represents a risk level that will not significantly increase the background risk from everyday hazards for most individuals. Estimated annualized failure probabilities above this value indicate increasing justification to pursue actions to reduce the risk or to better understand (define) the risk. Annualized failure probabilities below this threshold value generally indicate a decreasing justification to take further actions.

Annualized life loss is shown by plotting an "f-N pair" which simply means portraying both the annualized failure probability and the expected life loss as a single point. Reclamation's threshold value for annualized life loss is $1x10^{-3}$, shown as the diagonal dashed line in Figure 1. This threshold value is generally consistent with other countries and industries that deal with hazards that affect the public and reflects society's general aversion to disasters that result in

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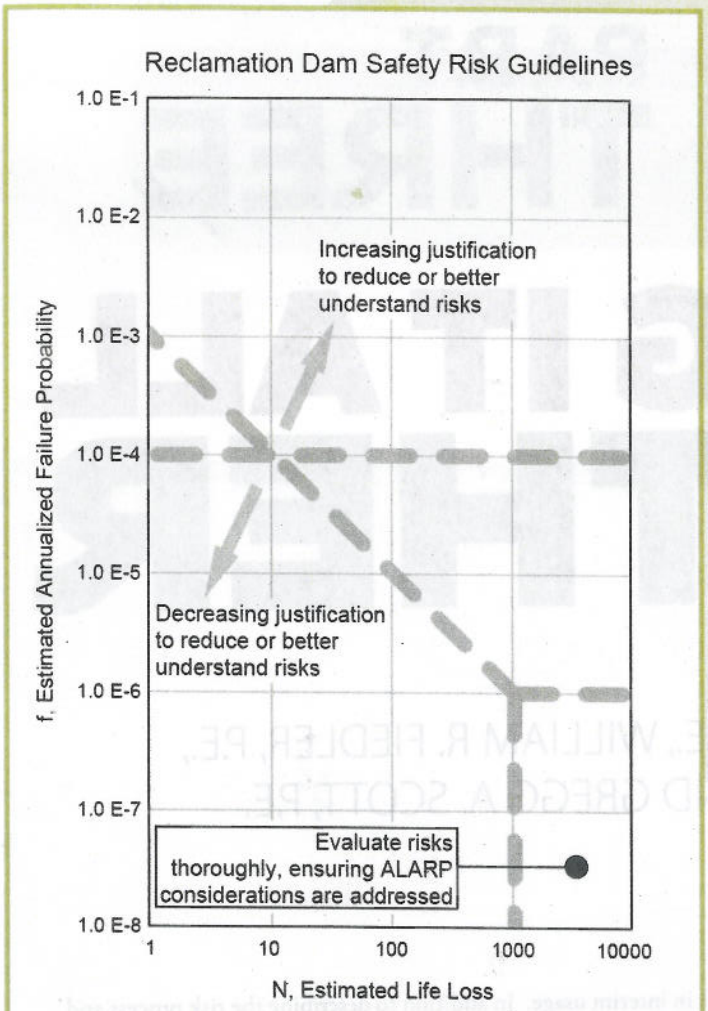

Figure 1. Reclamation Dam Safety Risk Guidelines (f-N) Chart

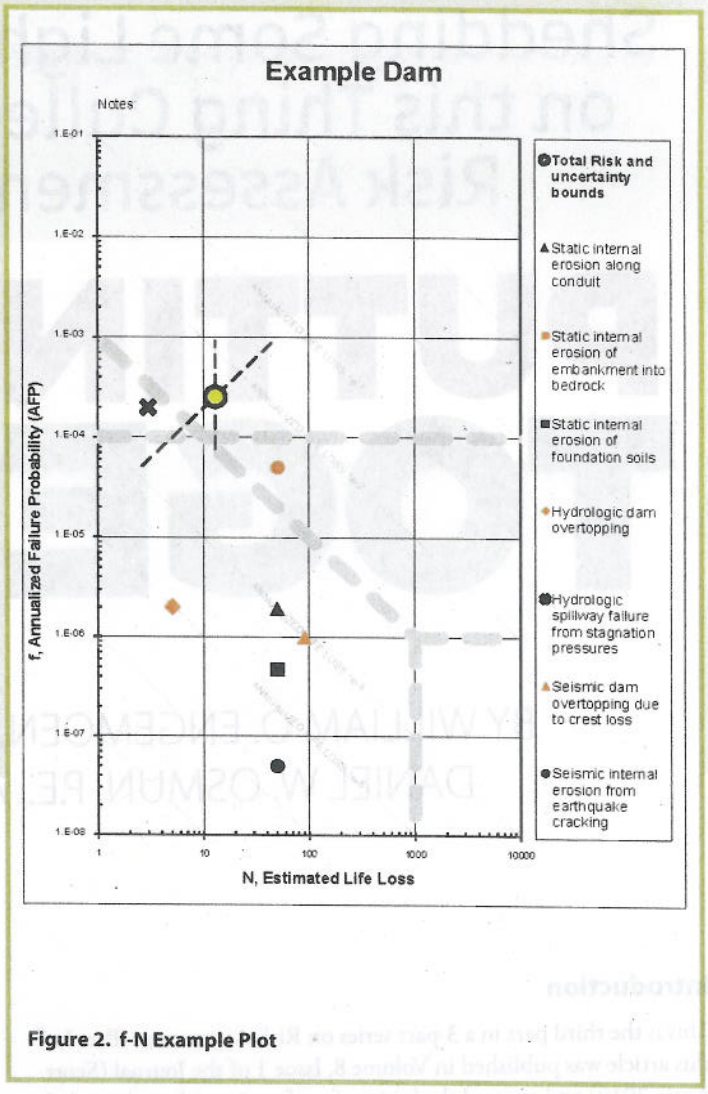

Figure 2. f-N Example Plot

significant loss of human life. That is, as the consequences become larger, society in general expects the likelihood of those failures to become smaller. Estimated annualized life loss above this value indicate increased justification to pursue actions to better define the risk or reduce the risk; values below this threshold generally indicate a decreasing justification to take further actions.

Typically, a risk analysis will generate estimated annualized failure probabilities and annualized life loss risks for several potential failure modes. The total risk for a particular dam is the summation of all the risks for various potential failure modes (under various loading conditions). It is important that both total risks and the risks associated with individual failure modes are understood and portrayed. In this way, decision makers can focus on which failure modes are driving the overall risk and determine whether additional study or corrective actions are needed for only one failure mode or several failure modes.

An example f-N chart is shown in Figure 2. As shown in this figure, the risks associated with several different failure modes are presented. The total risk, portrayed as a yellow circle, plots above the threshold for both guidelines. The dashed lines radiating from the total risk point indicate the uncertainty bounds for the annualized failure probability (the vertical line) and the annualized life loss (the diagonal line). In this particular example, two failure modes display estimated risks that are in the category of increasing justification to reduce, or better define, risks. The probability of a spillway failure from stagnation pressures under flood loading exceeds the annualized failure probability threshold, while the probability of internal erosion into untreated bedrock joints and fractures exceeds the annualized life loss threshold. Thus, based solely on risk numbers, an argument could be made for taking actions to better define or reduce the risks of these two failure modes. The remaining failure modes appear to have risks sufficiently below guidelines values such that no additional actions appear necessary to better understand, or mitigate for, these failure modes.

Worth noting is the box in the lower right hand area of Figures 1 and 2. It represents a unique set of conditions (very low annualized failure probability estimates but with very high loss of life estimates) where Reclamation applies ALARP, or "as low as reasonably practicable" principles. Estimated risks in this region have annualized failure probabilities less than $1x10^{-6}$ and life loss greater than 1,000. Predicting events or failure probabilities that are expected to be less probable than one in a million, or how many fatalities will occur when large populations are subject to a dam failure flood, is very difficult, and uncertainty in results becomes an even bigger concern than when risks are not in the ALARP area. Thus, when risks fall in this area, Reclamation strives to not only estimate risks but to ask, "Are the risks as low as reasonably practicable?" In other words, are there redundant or robust design features that are essentially state-of-the-practice? Are emergency management practices well conceived and practiced? Has everything reasonable been done to characterize

the risk? Would it be reasonably cost-effective to reduce risks further? Are there reasonable and prudent actions that should be taken? These types of questions indicate whether conditions at a site are generally up to expected standards and/or whether risks could reasonably be reduced.

Using Risk to Build the Dam Safety Case

It is important to recognize that estimating annualized failure probabilities and expected life loss from dam failure is difficult and involves significant uncertainty. Although a risk analysis provides a quantification of risks, the estimated risks are by no means precise numerical results. Rather, they reflect the quantified judgment of the risk estimating team based on available information and analyses (sometimes probabilistic), or the "degree of belief" in a particular outcome. For this reason, Reclamation does not solely rely on the risk estimates to drive a dam safety decision. Risk teams are required to "build the case" for the risk estimates (and subsequent recommendations) by providing justification in the form of listed statements or arguments that support a given conclusion or case.

The dam safety case is thus a logical set of reasons that support the position that additional dam safety studies and/or risk reduction actions are needed, or that no additional action is justified at this time. As part of the case, three elements must be addressed: (1) whether the estimated risk justifies action, (2) if so, the urgency of taking action, and (3) the confidence in the estimates and whether additional information is likely to change perception of the need and urgency to take action. When making the case, usually it is informative to demonstrate where the highest contributions to risk are coming from and to highlight the strongest evidence to support why this makes sense. The potential failure modes and/or load ranges that contribute most to the risk should be identified, and the reasons why this is believable enumerated. The set of reasons include key evidence that address factors concerning the loadings, the structural response, and the consequences. For example, the following factors might be used in justifying a case to take risk reduction actions for an embankment dam during an earthquake:

- The earthquake loading at this site is particularly severe. The principal source is a subduction zone earthquake within 20 miles of the dam, with the potential for generating long duration, high levels of shaking at fairly frequent annual exceedance probabilities (indicate the annual exceedance probability for a representative earthquake that is thought likely to cause liquefaction).
- Foundation soils beneath the embankment footprint consist of relatively loose sands and silts in continuous layers, with corrected SPT blow counts less than 10, making liquefaction and strength loss likely when subjected to reasonably frequent earthquakes as indicated above (indicate number and distribution of SPT tests).
- Post-earthquake stability analyses using low strengths in the foundation soils indicate safety factors less than 1.0, and deformation analyses indicate crest loss on the order of 20 feet; thus, it is unlikely the remnant embankment will retain the reservoir when subjected to this level of ground shaking (indicate key assumptions that went into the analyses and why they are believable).

- There is a downstream community of 2,000 people less than 5 miles from the dam, which may get little warning from a sudden dam failure. The town is situated within a canyon and flood depths from a dam break are expected to be on the order of 50 feet, which indicates a severe flooding condition. Therefore, life loss is expected to be high, (for example, an estimated 50 to 300 fatalities).
- These factors result in high annualized failure probability (for example, $2x10^{-4}$), and annualized life loss, (for example, $3x10^{-2}$).

The actions to be taken in any case depend largely on the confidence in the results. Depending on the amount and quality of available data for a risk analysis, as well as loading and model uncertainties and other factors, risk teams may have varying degrees of "confidence" in the risk estimates. For example, teams with good data, reasonable uncertainties, and perhaps sensitivity studies that demonstrate minimal changes in risk estimates when key parameters or assumptions are varied within reasonable limits are likely to have a moderate to high level of confidence that they have correctly portrayed the risks of dam failure. However, risk teams with limited data and significant uncertainties regarding loadings or structure response or consequences may have a relatively low level of confidence in their assessment of risks. In this case, it is important to identify what is driving the risk, and perform sensitivity or parametric studies on those variables. If it turns out that there is justification to reduce or better understand risks for one set of reasonable assumptions but not another, then that would be a good case for obtaining more information to better understand the risks. It is important to include the relative level of confidence in the risk estimates and conclusions about dam safety when building the dam safety case. In the end, the current condition of the dam and its ability to resist future loading, the estimated risks and confidence therein, and the recommended actions need to be consistent in order for the case to be convincing.

Prioritizing Dam Safety Risks within an Inventory

The U.S. Army Corps of Engineers has developed a Dam Safety Action Classification (DSAC) where they rate their dams in terms of urgency of taking actions to address dam safety deficiencies as part of their risk assessment process (U.S. Army Corps of Engineers, 2011). Reclamation has modified that system for use primarily as a means of providing a relative priority ranking of dams in their inventory for dam safety action. Termed the Dam Safety Priority Rating (DSPR) system and shown in Figure 3, it is an additional tool used by Reclamation in determining dam safety actions.

In addition to estimating risks and building the dam safety case, risk teams are also asked to place the dam being analyzed into a DSPR category. The different categories depend on such factors as where the estimated risks plot, whether risks are driven by a summation of many different failure modes or result from a single critical failure mode, the relative confidence in the risk numbers, whether the critical failure modes result from normal operations or would require an unusual loading event, the degree of uncertainties in the risks and the general understanding of critical aspects of the dam and/or

Dam Safety Priority Rating	Characteristics and Prioritization Considerations	Potential Actions
1 – IMMEDIATE PRIORITY **An active failure mode is in process or the likelihood of a failure is judged to be extremely high, such that immediate actions are necessary to reduce risk.**	**TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY IS EXTREMELY HIGH WITH HIGH CONFIDENCE** To assign this category consider if: 1. There is direct evidence that failure is in progress and the dam is almost certain to fail if action is not taken quickly. 2. Both the failure probability and the annualized life loss are extremely high. 3. The annualized life loss or failure probability is driven by a single failure mode. 4. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions.	Take immediate action to avoid failure. Implement interim risk reduction measures including operational restrictions, and ensure that emergency action plan is current and functionally tested for initiating event. Conduct heightened monitoring and evaluation. Expedite investigations and designs to support long-term risk reduction. Initiate intensive management and situation reports.
2 – URGENT PRIORITY **Potential failure mode(s) are judged to present very serious risks, either due to a very high probability of failure or due to very high annualized life loss, which justify an urgency in actions to reduce risk.**	**TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY IS VERY HIGH WITH HIGH CONFIDENCE OR SUSPECTED OF BEING VERY HIGH TO EXTREMELY HIGH WITH LOW TO MODERATE CONFIDENCE** To assign this category, as well as prioritize dams within this category, consider if: 5. Both the failure probability and the annualized life loss are very high to extreme. 6. The annualized life loss or failure probability is driven by a single failure mode. 7. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions. 8. The range in risk estimates is tightly clustered and the mean and median are similar (for detailed uncertainty analysis only) and/or sensitivity studies instill confidence. 9. Risk reduction or confirmation is relatively easy and inexpensive.	Consider implementing interim risk reduction measures, including operational restrictions as justified, and ensure that emergency action plan is current and functionally tested for initiating event. Conduct heightened monitoring and evaluation if appropriate. Expedite confirmation of rating, as required. Give very high priority for investigations and designs to support remediation, as required.
3 – MODERATE TO HIGH PRIORITY **Potential failure mode(s) appear to be dam safety deficiencies that pose a significant risk of failure, and actions are needed to better define risks or to reduce risks.**	**MODERATE TO HIGH TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY WITH AT LEAST MODERATE CONFIDENCE** To assign this category, as well as prioritize dams within this category, consider if: 10. Both the failure probability and the annualized life loss are moderate to high. 11. The annualized life loss or failure probability is driven by a single failure mode. 12. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions. 13. The range in risk estimates is tightly clustered and the mean and median are similar (for detailed uncertainty analysis only) and/or sensitivity studies instill confidence. 14. Risk reduction or confirmation is relatively easy and inexpensive.	Consider whether implementation of interim risk reduction measures is appropriate, which may include ensuring that emergency action plan is current and functionally tested for initiating event; conducting heightened monitoring and evaluation; and in some cases even operational restriction. Prioritize investigations to support justification for remediation and remediation design, as appropriate.
4 – LOW TO MODERATE PRIORITY **Potential failure mode(s) appear to indicate a potential concern, but do not indicate a pressing need for action.**	**LOW TO MODERATE TOTAL ANNUALIZED LIFE LOSS AND TOTAL FAILURE PROBABILITY WITH LOW CONFIDENCE AND THE REALISTIC POTENTIAL TO MOVE THE ESTIMATE INTO "HIGH"; OR MODERATE TO HIGH TOTAL ANNUALIZED LIFE LOSS AND TOTAL FAILURE PROBABILITY WITH LOW CONFIDENCE AND THE REALISTIC POTENTIAL TO MOVE THE ESTIMATE INTO "LOW"** To assign this category, as well as prioritize dams within this category, consider if: 15. The failure probability and annualized life loss are near guidelines 16. The likelihood that refinement of risk may change to a different category (a 3 could fall to a 4, or a 4 could rise to a 3)	Ensure routine risk management activities are in place. For those actions for which the case has been built to proceed before the next comprehensive review, take appropriate interim measures and schedule other actions as appropriate. Determine whether action can wait until after the next comprehensive review of the dam and appurtenant structures.
5 – LOW PRIORITY **Potential failure mode(s) at the facility do not appear to present significant risks, and there are no apparent dam safety deficiencies.**	**LOW TOTAL ANNUALIZED LIFE LOSS AND TOTAL FAILURE PROBABILITY WITH MODERATE TO HIGH CONFIDENCE** The annualized life loss and failure probability are estimated to be low and are unlikely to change with additional investigations or study.	Continue routine dam safety risk management activities, normal operation, and maintenance.

Figure 3. Dam Safety Priority Rating System

foundation, and whether there is evidence that a particular failure mode is in progress. The risk team and reviewers carefully weigh these various factors (and others) in determining an appropriate DSPR assignment for a given dam, as well as a relative ranking with respect to other dams within the same DSPR category. Faced with a finite budget, Reclamation can utilize the DSPR category among dams as a means of determining the priority for funding.

Decision Making

Once a risk analysis has been completed, estimates of risks developed, and a dam safety case outlined, an assessment of the overall risks for a dam can be made. This process generally consists of discussing the conditions at a given dam, the potential failure modes arising from any vulnerabilities and deficiencies at a structure, and the estimated risks.

Reclamation conducts a meeting for this purpose, where participants include the risk team, technical experts, program managers, and decision makers. A report outlining the risk analysis results and proposed recommendations for future actions is sent out for review two weeks prior to the meeting and the key findings are presented and discussed at the meeting.

A Dam Safety Advisory Team consisting of experienced senior technical staff, generally independent from the particular evaluation, provides advice on the technical aspects of the report. An outcome of the meeting is a decision that risks indicate either an increasing or decreasing justification to take additional actions. These actions could include: (1) no action (continue to operate the facility in a normal matter), (2) conduct additional explorations and studies to better understand the risks (by reducing uncertainties or improving confidence in the risk estimates), or (3) move into a corrective actions study to develop alternatives to lower the risks.

In addition to identifying additional actions, a consensus is reached on the DSPR for the dam, which is used for scheduling and prioritizing the actions. Throughout this risk assessment or decision-making process, a focus is on the estimated risk values and the strength of the dam safety case.

Qualitative Methods

Where preliminary risks or perhaps a screening of potential failure modes is needed, and there is limited available time or budget for a more detailed evaluation of risk, it may be appropriate to use a "qualitative" assignment of risks. Potential cases where qualitative evaluations may be desirable might include:

- Non-dam structures, such as canal embankments, tunnels, etc. where risk assessment principles can be applied to the decision making without the time, cost, and data/analysis requirements associated with a full blown quantitative risk analysis.
- Portfolio assessments where the goal is prioritization of risk reduction studies and actions via a cost effective and expedited evaluation.
- Sensitive cases that involve the public to a high degree whereby those involved (including reviewers) are more likely to understand qualitative assessments than full blown numerical analyses, and/or where calculation of fatality numbers is likely to be controversial or overblown by the media.
- A cost effective add-on to conventional Potential Failure Modes Analyses (PFMA) to better understand the risk involved in each potential failure mode as well as overall risk; a qualitative risk assessment can be conducted while the PFMA Core Team is already convened.

In these cases, a "risk matrix" can be set up to evaluate the results, with likelihood of failure on the vertical axis and consequences on the horizontal axis (similar to the f-N diagram). Typically, at least four or five categories are defined for each axis, as three categories don't provide enough resolution when it comes to evaluating the risks. The category descriptions need to be set up ahead of time and possibly tailored to the project being analyzed. For the likelihood of failure, possible categories might include Very High, High, Moderate, Low, and Remote. Each category would have a verbal descriptor and possibly a general range of expected likelihood. For example, a "High" classification might be used to represent a case where a fundamental condition or defect is known to exist, indirect evidence suggests it is plausible, and key evidence is weighted more heavily toward likely than unlikely; and/or a flood or earthquake with a return period between 1,000 and 10,000 years would likely trigger the potential failure mode. This suggests that the annual probability of failure is somewhat higher than the overall historical failure rate of about 1/10,000. Similar category descriptions are established for consequences with the level or severity of life loss or damage described in qualitative terms, but generally corresponding to order of magnitude ranges. Such a risk matrix is presented in Figure 4. The dashed and dotted lines shown in Figure 4 correspond roughly to the risk guidelines when the categories are defined in this manner (Scott, 2011).

Each failure mode to be considered can then be evaluated and portrayed in this type of matrix. For a portfolio ranking, a number of different failure modes for different dams can be portrayed, providing an indication of which dams may pose the higher risks.

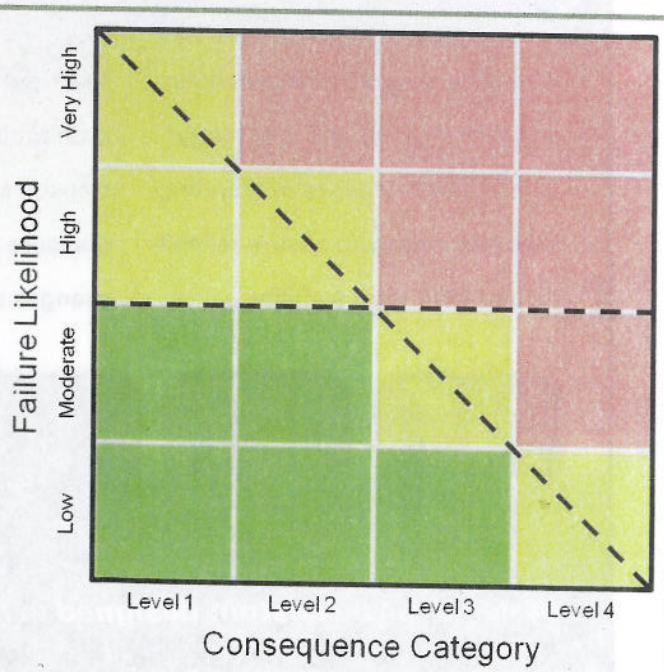

Figure 4. Qualitative Risk Matrix

FAILURE LIKELIHOOD	CONSEQUENCES OF FAILURE			
	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
VERY HIGH				
HIGH			Dam #2, PFM #3 (P)	
MODERATE		Dam #2, PFM #1 (M) Dam #2, PFM #4 (G) Dam #3, PFM #6 (P)	Dam #6, PFM #3 (G)	

Figure 5. Results of Qualitative Risk Assessment for a Portfolio of Dams

An example portrayal of failure modes at multiple dams using this qualitative approach is shown on Figure 5. The letter in parentheses represents the confidence in the category placement (G=good, P=poor, M=moderate), which aids in establishing follow-on actions. Results such as those shown in Figure 5 can aid in prioritizing the next step. If one or more potential failure modes plot in a red cell, it indicates the estimated risk likely exceeds the risk guidelines. If the confidence is poor, collecting additional information and perhaps quantifying the risks would be appropriate. If high risks are indicated with a confidence rating of good, a quantitative estimate would be appropriate before implementing risk reduction actions directly. If one or more potential failure modes plot in the yellow cells, the risks are estimated to be "borderline" with respect to the guidelines and additional work is probably warranted. Although potential failure modes plotting in the green cells typically indicate low risks, some judgment is needed to decide whether additional action is appropriate for these potential failure modes. If several failure modes fall in these cells near the yellow cells, or if they are rated with poor confidence, additional quantitative risk analysis may be appropriate to sum the risks and improve the confidence.

Conclusions

Risk analysis processes have proven to be very worthwhile for evaluating dam safety issues. A number of benefits result from a risk-informed approach to dam safety, including:

- Evaluating dams by considering both likelihood of failure and expected life loss helps identify recommended actions at facilities that have either or both a relatively high probability of failure or will result in significant life loss in the event of failure.
- By evaluating failure modes and thinking in depth about how a structure might fail, a team or individual analyst gains an increased understanding of a dam's strengths and weaknesses.
- The use of probabilistic loadings shows that not all dams have to be fixed for extreme loads.
- Creating event trees for dam safety deficiencies or failure mechanisms not readily evaluated by safety factors (such as an internal erosion failure mode) provides a rational approach to determining the threat posed by such mechanisms.
- Using risk estimates in conjunction with engineering judgment is required to build the dam safety case and assign a priority rating, which helps promote a solid interpretation of a dam's condition and provides a basis for determining any required actions.

- Using risk enables an organization to prioritize an inventory of dams based on relative risks, thus providing a logical means of prioritizing required dam safety actions and corresponding expenditures.

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