

# RECLAMATION

*Managing Water in the West*

**Interim**

## **Dam Safety Public Protection Guidelines – Examples of Use**

**Examples of How to Use Risk to Support Dam Safety Decisions**



**U.S. Department of the Interior  
Bureau of Reclamation  
Dam Safety Office  
Denver, Colorado**

**August 2011**

## **Mission Statements**

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

**Interim**

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# Introduction

## Risk Management

This document is intended to be used in conjunction with the Reclamation’s 2011 revision to the *Dam Safety Public Protection Guidelines*. The purpose of this document is to give some examples of how risk analysis results are used to support risk management decisions. Figure 1 shows the general input to risk management. The terms in Figure 1 are defined in the *Dam Safety Public Protection Guidelines* and are not repeated here. Table 1 is Reclamation’s Dam Safety Priority Rating (DSPR) chart, which is a key tool for risk management prioritization, and which will be discussed further in this document.



Figure 1. Dam Safety Risk Management Components

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Table 1. Bureau of Reclamation Dam Safety Priority Rating (DSPR)

Dam Safety Priority Rating	Characteristics and Prioritization Considerations	Potential Actions
<p><b>1 – IMMEDIATE PRIORITY</b> 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.</p>	<p><b>TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY IS EXTREMELY HIGH WITH HIGH CONFIDENCE</b> To assign this category consider if:</p> <ol style="list-style-type: none"> <li>1. There is direct evidence that failure is in progress and the dam is almost certain to fail if action is not taken quickly.</li> <li>2. Both the failure probability and the annualized life loss are extremely high.</li> <li>3. The annualized life loss or failure probability is driven by a single failure mode.</li> <li>4. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions.</li> </ol>	<p>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.</p>
<p><b>2 – URGENT PRIORITY</b> 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.</p>	<p><b>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</b> To assign this category, as well as prioritize dams within this category, consider if:</p> <ol style="list-style-type: none"> <li>5. Both the failure probability and the annualized life loss are very high to extreme.</li> <li>6. The annualized life loss or failure probability is driven by a single failure mode.</li> <li>7. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions.</li> <li>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.</li> <li>9. Risk reduction or confirmation is relatively easy and inexpensive.</li> </ol>	<p>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.</p>
<p><b>3 – MODERATE TO HIGH PRIORITY</b> 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.</p>	<p><b>MODERATE TO HIGH TOTAL ANNUALIZED LIFE LOSS OR TOTAL FAILURE PROBABILITY WITH AT LEAST MODERATE CONFIDENCE</b> To assign this category, as well as prioritize dams within this category, consider if:</p> <ol style="list-style-type: none"> <li>10. Both the failure probability and the annualized life loss are moderate to high.</li> <li>11. The annualized life loss or failure probability is driven by a single failure mode.</li> <li>12. The annualized life loss or failure probability is driven by potential failure modes manifesting during normal operating conditions.</li> <li>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.</li> <li>14. Risk reduction or confirmation is relatively easy and inexpensive.</li> </ol>	<p>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.</p>
<p><b>4 – LOW TO MODERATE PRIORITY</b> Potential failure mode(s) appear to indicate a potential concern, but do not indicate a pressing need for action.</p>	<p><b>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”</b> To assign this category, as well as prioritize dams within this category, consider if:</p> <ol style="list-style-type: none"> <li>15. The failure probability and annualized life loss are near guidelines</li> <li>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)</li> </ol>	<p>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.</p>
<p><b>5 – LOW PRIORITY</b> Potential failure mode(s) at the facility do not appear to present significant risks, and there are no apparent dam safety deficiencies.</p>	<p><b>LOW TOTAL ANNUALIZED LIFE LOSS AND TOTAL FAILURE PROBABILITY WITH MODERATE TO HIGH CONFIDENCE</b> The annualized life loss and failure probability are estimated to be low and are unlikely to change with additional investigations or study.</p>	<p>Continue routine dam safety risk management activities, normal operation, and maintenance.</p>

## Intended Use

The ultimate goal of a risk-informed dam safety decision is to determine whether additional actions are needed at a dam, and to establish the relative priority of those actions. Assigning each dam to a DSPR category and establishing other information that can be used to prioritize activities are means of achieving this goal. To help establish priorities, guide appropriate actions, and provide a consistent terminology, the DSPR table provides guidance to address potential dam safety issues at Reclamation dams. Reclamation dams are classified in a DSPR category based on their annualized failure probability and annualized life loss, as well as other pertinent factors. The classification of a dam is dynamic over time, changing as project characteristics are modified or more refined information becomes available affecting the load probability, failure probability, or consequences of failure.

The DSPR table (Table 1) presents different levels and priorities of actions that are commensurate with the individual conditions affecting the safety of Reclamation dams. Priorities range from “immediate” based on recognition of an urgent situation, to “low,” involving routine dam safety activities and continued normal operations. The DSPR table is used in conjunction with the risk guidelines to evaluate structures and guide and prioritize potential actions. The DSPR table also proposes factors that can help prioritize dams within a given DSPR category. This document will provide additional details regarding how to assess risks and assign DSPR categories for Reclamation dams.

## Using Risk Analysis Results to Assess Risks

The basic equation for risk calculation is shown below. When the consequences are expressed in terms of fatalities, which is typically the case for dam safety evaluations, then the risk is also referred to as Annualized Life Loss. The product of the loading probability and the probability of failure given the loading is referred to as Annualized Failure Probability, when the loading is expressed as an annual probability. The probability of failure given the loading is referred to as a conditional failure probability since it is conditional upon the loading.

$$p(\text{loading}) \times p(\text{fail} | \text{loading}) \times \text{Consequences} = \text{Risk}$$

## Calculating and Assessing Annualized Failure Probability and Annualized Life Loss

### *Calculating Annualized Life Loss f-N Pairs and Total Risk*

Risks are typically plotted on what is referred to as the f-N chart. This chart features estimated annualized failure probability on the vertical axis and expected number of fatalities on the horizontal axis, both expressed as log scales. The annualized failure probability and fatalities associated with a single potential failure mode is referred to as an f-N pair. The method typically used by Reclamation for calculating annualized life loss uses so-called f-N pairs and compares those f-N pairs and the total risk to the risk guidelines. The Public Protection Guidelines (presented in a separate document) provide guideline (threshold) values for which there is increasing justification to take action for both annualized failure probability and annualized life loss. If the risks associated with any given f-N pair is in the area of increasing justification to take action, then the total risk will also be in this region. However, the total risk may also exceed the guideline values even when none of the individual f-N pairs exceed the values by themselves.

### **Calculating the Annualized Failure Probability**

Potential failure modes are identified based on a thorough review of a dam's background information and current condition, and identifying vulnerabilities and possible ways in which the dam or one of its components could fail and release life-threatening flows. The identified potential failure modes are typically screened and low risk modes dismissed so that only the annualized failure probability for the significant modes are quantified. The potential failure modes are described thoroughly from initiation, through step-by-step progression, to uncontrolled release of the reservoir. This typically allows the significant potential failure modes to be broken down into a series of steps or states of nature that can be represented on an event tree. The annual load probability is typically included at the beginning of the tree. The probability for each subsequent event on an event tree can then be estimated. The annual failure probability is calculated by summing all individual event tree end-branches that result in uncontrolled reservoir release for a particular failure mode, including all load ranges. The result of this summation is the term Annualized Failure Probability. Because ranges of likelihood are typically estimated for each branch in an event tree, the final result should be a range of probabilities. A simplified calculation is shown in Table 2. See Reclamation's Dam Safety Risk Analysis Best Practices Training Manual [1] for additional details on performing a failure mode analysis, qualitative screening methods, and estimating failure probabilities.

### **Calculating the Consequences**

The life loss consequences are unique to each end branch of an event tree that leads to life-threatening uncontrolled release of the reservoir. The consequences should also have a range of estimates. The Best Practices manual [1] provides detailed information for estimating consequences.

**Table 2. f-N Calculations for a Given Potential Failure Mode**

End Branch	Annualized Failure Probability			Life Loss			Annualized Life Loss		
	Low	Best	High	Low	Best	High	Low	Best	High
End Branch 1	1.0E-3	2.2E-3	3.0E-2	3	34	50	3.0E-3	7.5E-2	1.5E+00
End Branch 2	8.0E-6	1.1E-5	7.0E-5	50	225	400	4.0E-4	2.5E-3	2.8E-02
End Branch 3	5.0E-4	7.5E-4	1.0E-3	3	34	50	1.5E-3	2.6E-2	5.0E-02
End Branch 4	3.2E-7	3.2E-6	3.2E-5	50	225	400	1.6E-5	7.2E-4	1.3E-02
<b>Total</b>	1.5E-3	3.0E-3	3.1E-2	3	33	52	4.9E-3	1.0E-1	1.6E+00

**Calculating f-N Pairs**

To generate f-N pairs which are used to compare against risk guidelines, annualized life loss values must also be calculated for each end branch that leads to failure. **Note: abbreviating annualized life loss in Reclamation documents is discouraged. It gives the impression that we are taking a very serious consequence rather lightly. Abbreviations tend to detract from the seriousness of dam safety issues.** The annualized life loss is calculated by multiplying the annualized failure probability by the life loss at each end branch. For multiple branch event trees, the annualized life loss values are then summed for all end branches, including all load ranges, associated with a potential failure mode. Two numbers result from this operation – the total annualized failure probability and the total annualized life loss for each significant potential failure mode.

To plot the f-N point on the risk chart, the total annualized life loss is divided by the total annualized failure probability to obtain a weighted average fatality estimate for each failure mode. The term “best estimate” is sometimes used because the statistical terms “expected” and “mean” are not always selected and may not be applicable. The best estimate can reflect the statistical mean of a distribution, median, mode, or an estimate based on judgment. In any case, the basis for the estimate should be documented.

When plotting individual potential failure mode risk estimates, only the best estimate value is plotted on the f-N chart without any uncertainty portrayed. When plotting the total risk estimate for the dam, uncertainty related to both the annualized failure probability and the annualized life loss is portrayed. Uncertainty in the total annualized failure probability is represented by a vertical line through the best estimate. Uncertainty in the total annualized life loss is represented by a diagonal line through the best estimate.

In Table 2, the low annualized failure probability was multiplied by the low life loss to calculate the low annualized life loss, and so on. Then each column was summed. The total life loss values were then calculated by dividing the

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annualized life loss by the annualized failure probability. It should be noted that this results in the largest possible range in annualized life loss for each branch. It may also be appropriate to use the best estimate of life loss for low and high failure probabilities and vice versa to see what effect this has on the range of annualized life loss. Also note that *the way in which the low, best, and high life loss values are reported in a table can result in confusion if the three values are also used to define a triangular distribution in an event tree calculation.* For example, if the total life loss values were treated as a triangular distribution in an event tree, the mean value of that distribution would be 29, as opposed to the 33 presented in the table as the best estimate value. Although this difference may seem to be insignificant, it can cause confusion when people select numbers out of a table to put into reports that don't match other numbers in the team reports. Therefore, care is needed to understand how the numbers were used in the risk analysis when reporting them and listing them in a table. *It is suggested that the mean estimate presented in any table correspond to the statistical mean used in the analysis and vice versa. If an estimate other than the mean is used, it should be clearly explained.*

Note that the range of total expected life loss does not encompass the entire range of all the end branch consequences. The weighted average generally tends to use consequences that are associated with the failure path with the highest probability of failure. This can be an important factor and should be examined carefully and noted for decision-makers, particularly when the differences in the total weighted consequences compared to some individual failure modes are substantial.

### **DSPR Possibilities**

The position of the total risk estimate on the f-N chart does not solely dictate the DSPR category. As described elsewhere in this document and in the Public Protection Guidelines, the total risk estimate is a consideration in the rating, but other potential factors include the strength of the dam safety case, the confidence in the risk estimates, the number of potential failure modes that drive the total risk, whether or not the risk is driven by a static potential failure mode or an unusual loading condition, and whether additional actions to reduce risk or better define risk could be accomplished with relatively simple or inexpensive measures. Examples are provided in Figures 1 through 5 that illustrate some possible total risk estimates for each of the DSPR categories. The examples are not intended to define upper and lower plotting positions that would apply for a DSPR category, but are intended to show a sample of possibilities that may be appropriate if a sufficient case can be made for the rating. The examples are also brief snapshots of the dams and do not fully describe potential failure modes, discuss specifically the level of confidence in the risk estimates or build an adequate dam safety case. The justification for the DSPR category must be included in the Decision Document/Technical Report of Findings. The following summaries describe the simple base justification for the DSPR ratings of the dams depicted in Figures 1 through 5. The base justifications are very brief and a more detailed case would be required for the Decision Document/Technical Report of Findings.

**DSPR 1 Possibilities (Figure 2)**

*Dam 1* – For this embankment dam, the total risk is driven by a static internal erosion potential failure mode that is in progress. The evidence for this is rapidly increasing seepage flows at the toe of the dam which are cloudy, indicating transport of embankment materials.

*Dam 2* – For this embankment dam, the total risk is driven by a hydrologic dam overtopping potential failure mode, which has increased substantially due to deflected end walls on the spillway crest structure which has severely limited the spillway gate openings. This has decreased the threshold flood to the 100-year event.

**DSPR 2 Possibilities (Figure 3)**

*Dam 1* – For this embankment dam, the total risk is driven by a hydrologic dam overtopping potential failure mode. The threshold flood is about the 1000-year flood and varies somewhat with the starting reservoir water surface elevation.

*Dam 2* – For this embankment dam, the total risk is driven by an internal erosion failure mode. Seepage has been increasing gradually at the downstream toe of the dam, but the seepage has been clear to date. A minor depression on the downstream face of the dam was recently documented in the area where the internal erosion is suspected.

*Dam 3* – For this concrete dam, the total risk is driven by a static potential failure mode that involves sliding of a wedge within the rock foundation. The stability of the wedge is marginal under current conditions, and is expected to get worse due to a reduction in foundation drain efficiency over time.

*Dam 4* – For this embankment dam, the total risk is driven by a seismic potential failure mode, related to liquefaction of the alluvial foundation. The reservoir is typically kept full, which limits the available freeboard on the dam.

**DSPR 3 Possibilities (Figure 4)**

*Dam 1* – For this embankment dam, the total risk is driven by a hydrologic dam overtopping potential failure mode. The threshold flood is about the 5000-year flood.

*Dam 2* – For this embankment dam, the total risk is driven by a static internal erosion failure mode. The potential for initiation of internal erosion is estimated to be high due to likely defects in the embankment.

*Dam 3* – For this concrete gravity dam, the total risk is driven by three seismic potential failure modes – sliding of a foundation wedge, sliding along a lift line coinciding with a change in the section geometry and buckling failure of the spillway radial gates. The individual risk for each of the three potential failure modes is about the same.

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**Dam 4** – For this concrete dam, the total risk is driven by a hydrologic potential failure mode, related to overtopping of the dam leading to erosion and undermining of the dam foundation.

### **DSPR 4 Possibilities (Figure 5)**

**Dam 1** – For this embankment dam, the total risk is driven by a hydrologic dam overtopping potential failure mode. The threshold flood is about the 40,000-year flood, based on a CR level flood frequency analysis.

**Dam 2** – For this embankment dam, the total risk is driven by three seismic potential failure modes, involving liquefaction of the dam foundation leading to dam overtopping, seismic cracking of the upper portion of the dam, and failure of the spillway gates. The risks for the three key potential failure modes are comparable. The seismic potential failure modes related to liquefaction are based on a very limited exploration program and indications are that loose foundation material zones are very limited in extent.

**Dam 3** – For this embankment dam, the total risk is driven by a seismic potential failure mode, related to failure of the gated spillway crest structure walls. This could lead to failure of the end spillway gates or there is a lesser chance that the walls could separate from the adjacent embankment material on the right side of the structure, creating a seepage path that could lead to erosion and breach of the embankment.

**Dam 4** – For this concrete gravity dam, the total risk is driven by two potential failure modes, related to overtopping of the dam leading to erosion and undermining of the dam foundation and seismic sliding of the dam along an unbonded lift line. The individual risks for the two key potential failure modes are comparable. Current loss of life estimates are based on a 20-year old inundation study and it is anticipated that a revised study would significantly increase the loss of life estimates.

**Dam 5** – For this embankment dam, the total risk is driven by two static internal erosion potential failure modes and a hydrologic dam overtopping potential failure mode. The dam has yet to fill to the top of active conservation pool in its twenty year history and there is the potential that loading of untested portions of the embankment could initiate the internal erosion mechanisms.

**Dam 6** – For this concrete gravity dam, the total risk is driven by a seismic potential failure mode related to sliding of a foundation wedge. This failure mode, while posing the greatest risk of any of the potential failure modes, by itself would be in an area of decreasing justification to take action to reduce risk. A potential wedge in the right abutment of the dam was analyzed but the block was identified based on joints identified in a limited set of photos from the site. The orientation and continuity of the joints obtained from a field investigation would likely reduce the probability that a removable block could form in the foundation.



**DSPR 5 Possibilities (Figure 6)**

**Dam 1** – For this embankment dam, the total risk is driven by a hydrologic dam overtopping potential failure mode. The threshold flood is about the 100,000-year flood. The CR level risk analysis assumed that the dam would breach once the threshold flood was exceeded, but the thick large rockfill shell forming the downstream face of the dam and the limited durations of overtopping indicate that this is a conservative assumption.

**Dam 2** – For this embankment dam, the total risk is driven by a four potential failure modes – one related to static internal erosion, two related to liquefaction of the dam foundation (leading to either dam overtopping or cracking of the upper portion of the dam), and one related to overtopping during a large flood. The individual risks for the four potential failure modes identified above are relatively equal.

**Dam 3** – For this embankment dam, the total risk is driven by a hydrologic dam overtopping potential failure mode. In the CR level risk estimate it was assumed that there was a 50 percent chance that the spillway would become 100 percent plugged due to debris. Senior reviewers agreed that there was great uncertainty with this assumption, but thought it was conservative. There has been debris in the reservoir but for the smaller floods that have occurred to date, the debris has been flushed through the spillway without creating any obstruction.

**Dam 4** – For this concrete dam, the total risk is driven by a seismic potential failure mode, related to movement of a wedge within the rock foundation of the dam. The estimate for this potential failure mode was based on a site investigation which relied on photogrammetry to define joint sets that would likely exist in the dam foundation. The conclusion of the joint analysis was that removable blocks would be unlikely to form.

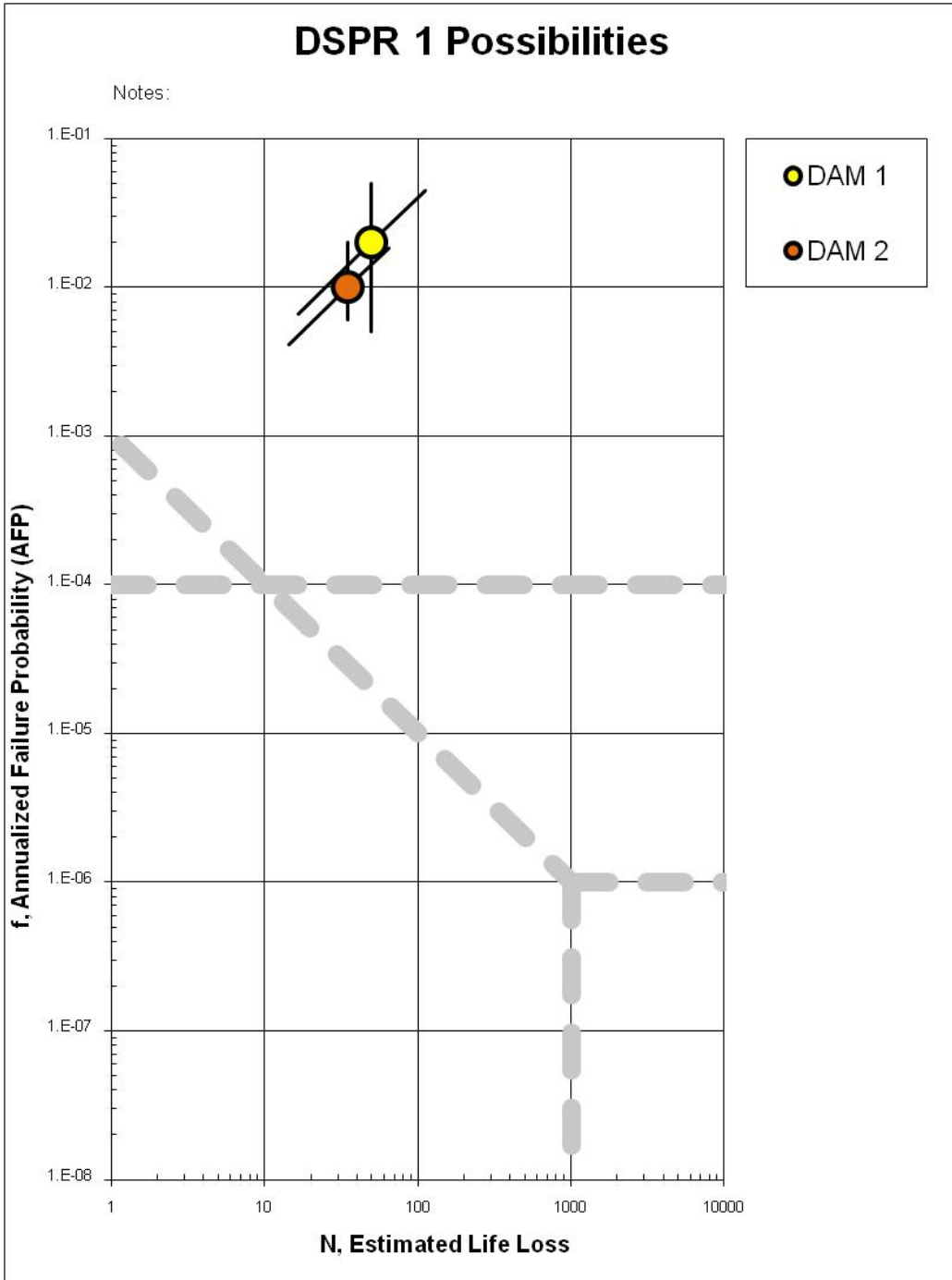


Figure 2. Potential DSPR 1 Dams

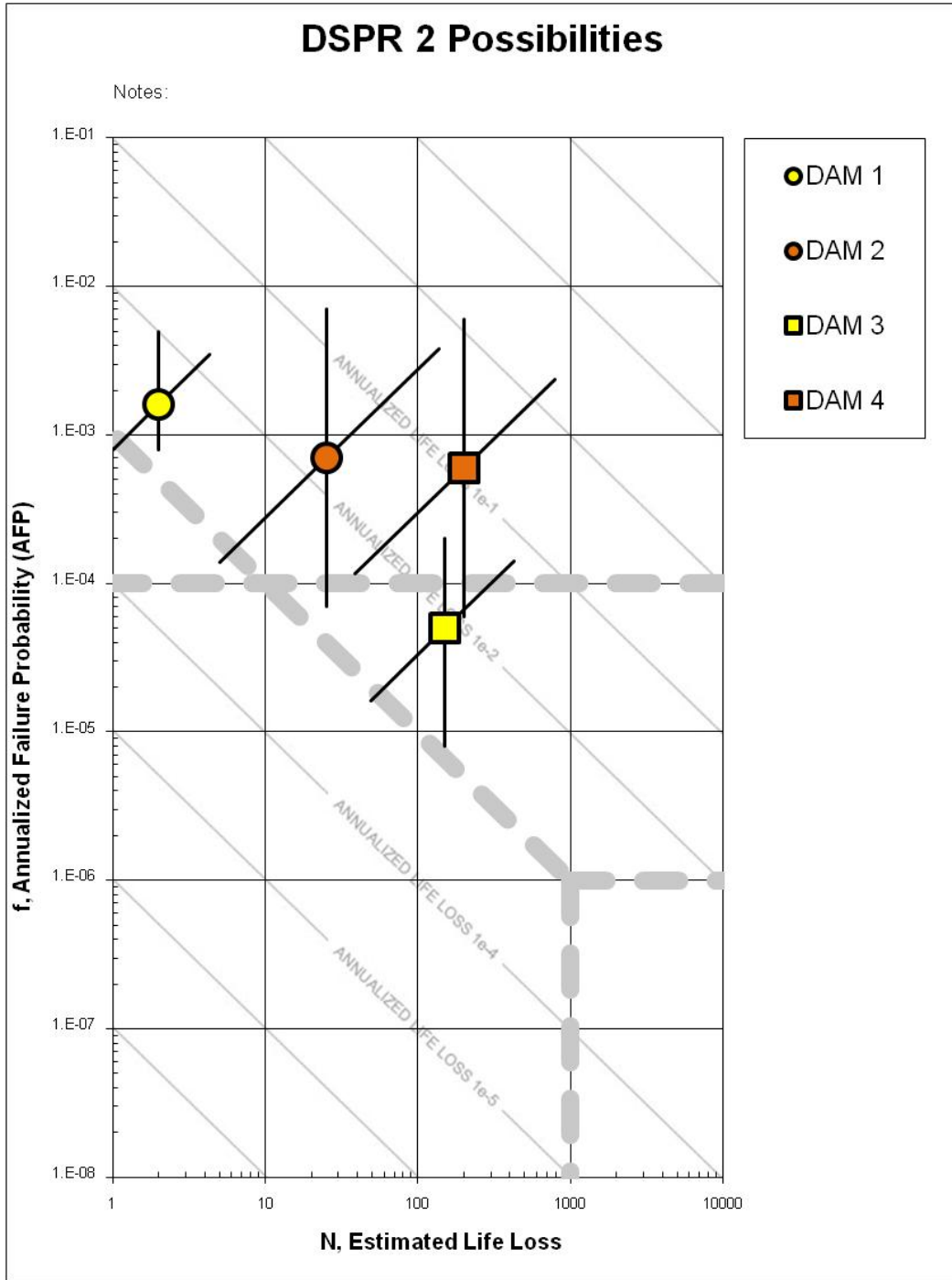


Figure 3. Potential DSPR 2 Dams

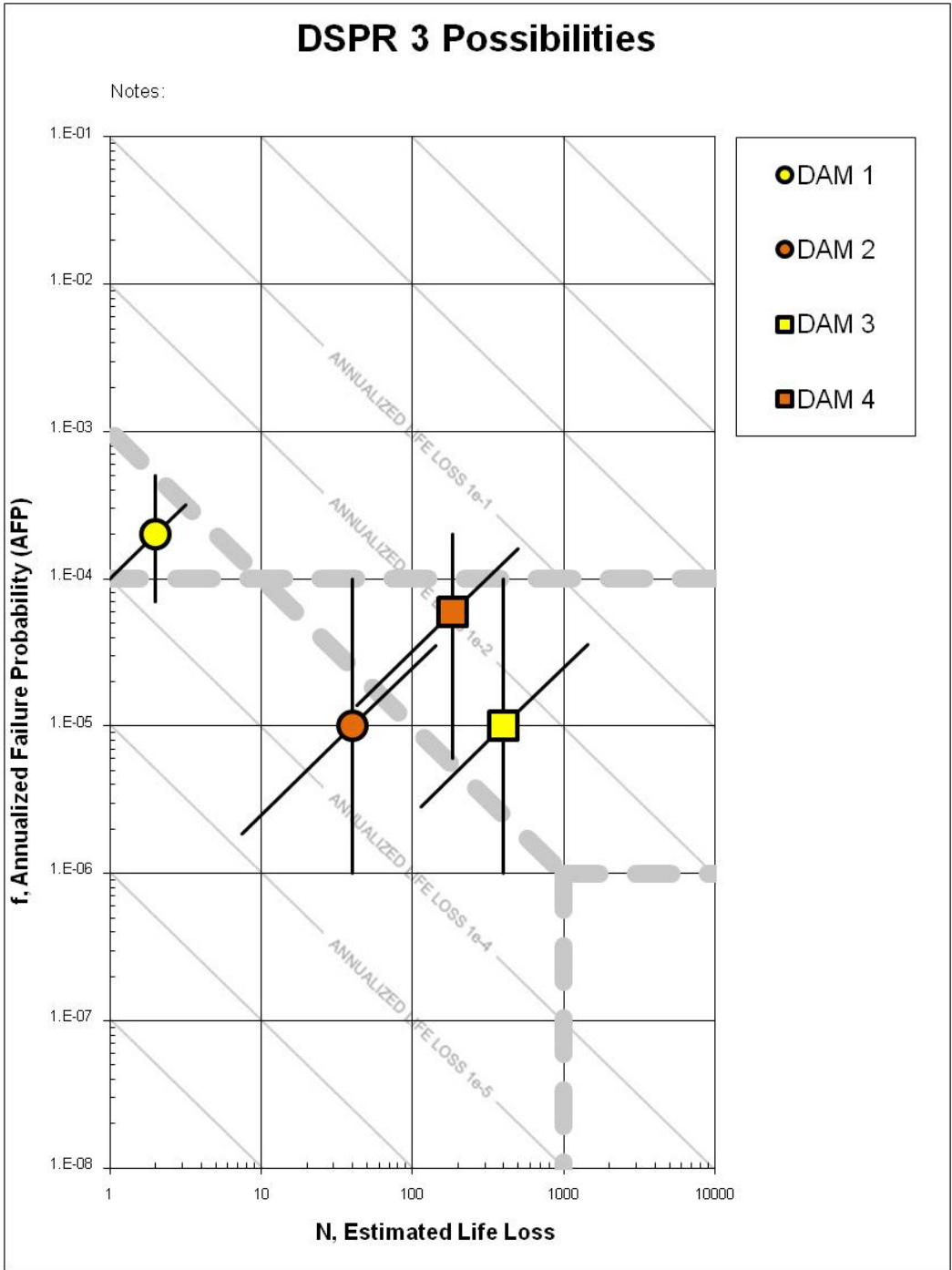


Figure 4. Potential DSPR 3 Dams

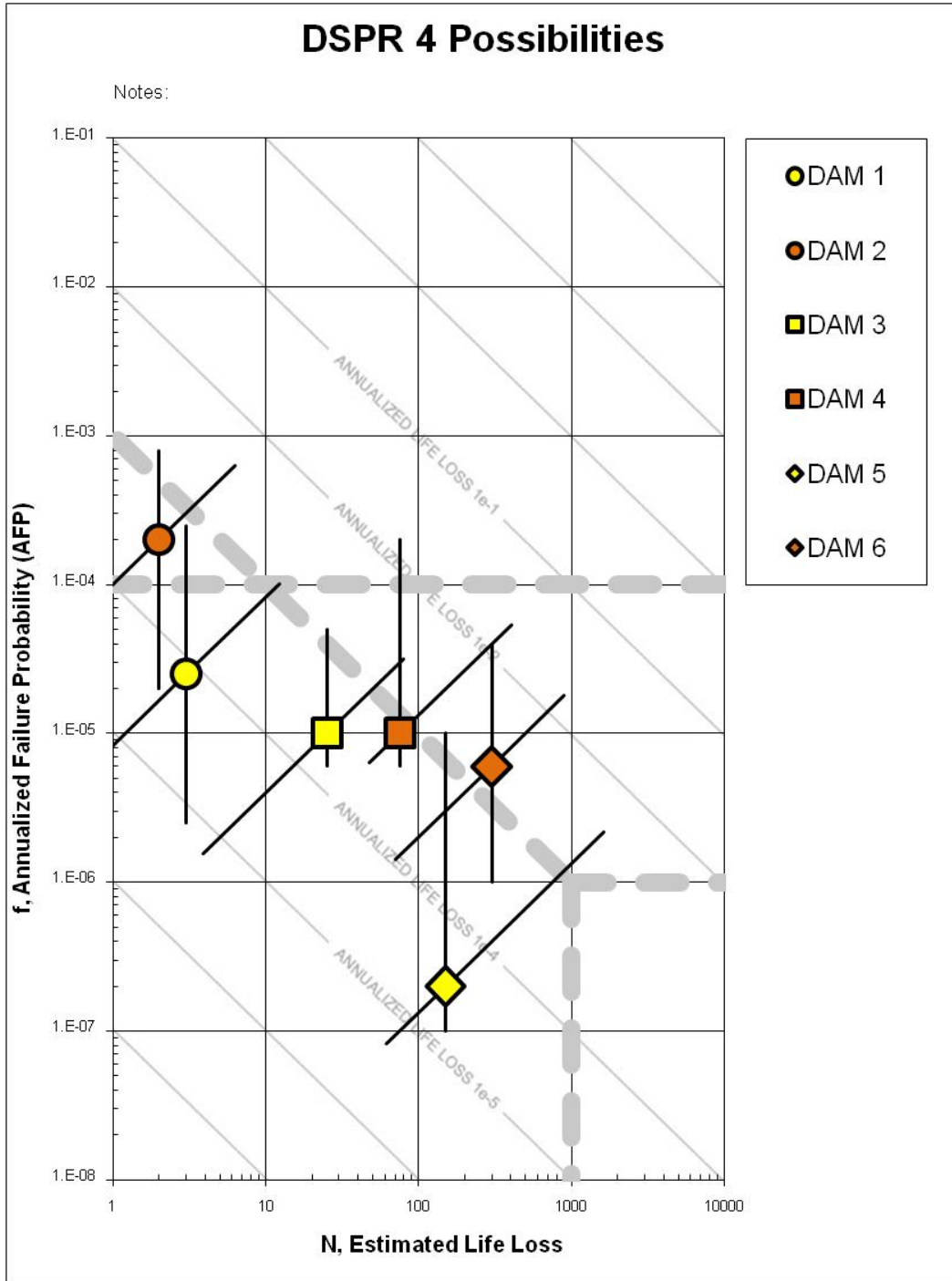


Figure 5. Potential DSPR 4 Dams

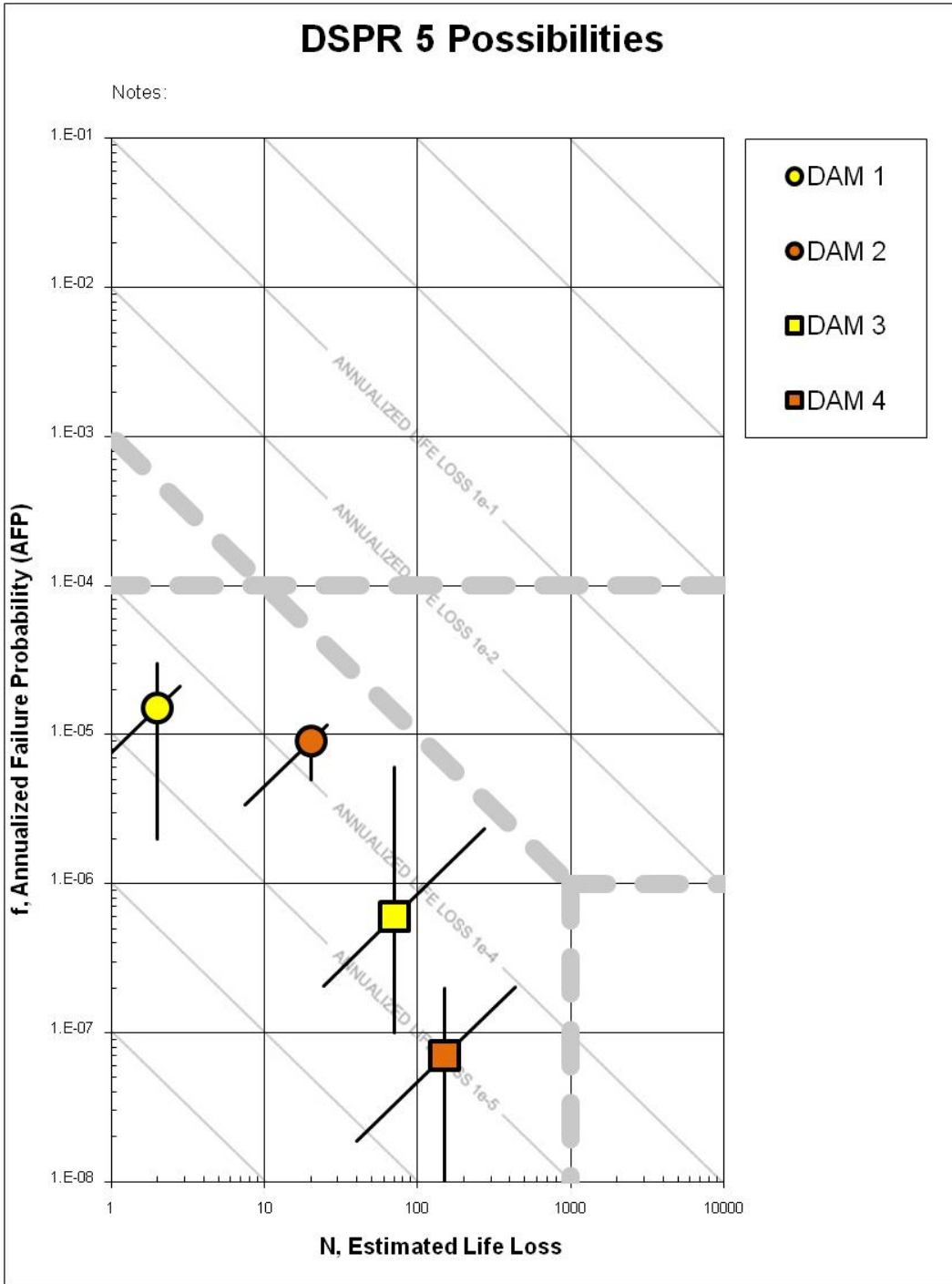


Figure 6. Potential DSPR 5 Dams

## Examples

The following sections give several examples of how the Public Protection Guidelines are typically used to support decisions within Reclamation. In reality, situations surrounding decisions can be complicated, and no template exists to cover every situation. However, there are techniques and strategies that use information commonly available from risk analyses to assist with decision-making.

Each example contains at least six sections; potential failure mode identification, failure mode risk estimates, failure mode risk charts, the findings and dam safety case, safety of dams recommendations, and the DSPR category. The first two would be from the risk analysis, whereas the last three are the actual risk assessment. The risk chart bridges between risk analysis and risk assessment.

### **Potential Failure Modes**

This section of each example either lists the failure modes considered or gives a brief overview of potential failure modes that are carried through the example. **In a risk analysis report, these potential failure modes should be described in greater detail from initiation, through step-by-step progression, to ultimate breach, likely with a figure or some photos to illustrate the envisioned failure process.** The compelling arguments that support the conclusion that a potential failure mode is more likely or less likely to develop would also be included. For simplicity, these detailed descriptions have not been included for the examples in this document. Each example was adapted from actual risk analysis reports.

### **Potential Failure Mode Risk Estimates**

This section of each example gives a listing of the potential failure modes, their associated probability of failure, and their associated consequences. Each example has already been adjusted for common-cause effects and assumes that the risks were calculated following procedures outlined in the Best Practices manual [1].

### **Risk Charts**

This section of each example displays the Annualized Failure Probability and Life Loss on the f-N chart.

### **Findings and Building the “Case” for Dam Safety Decisions**

Findings from an analysis of dam safety risks should include a summary of the risks posed by the facility, and discuss recommended future actions. Such findings should be supported by a logical set of factors that justify or “build the case” for the findings and recommendations. The dam safety “case” and the identification

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of risk management options are recognized as essential elements in Reclamation's prioritization efforts to ensure public protection is realized in the most efficient way possible. They represent understanding of existing conditions and predicted future behavior stated as objectively as possible. The “case” is intended to present rationale, in a formal and methodical manner to decision-makers so that they can take responsible action (or to justify no action). The case is a logical set of arguments used to advocate or justify a position that either additional safety-related action is justified, or that no additional safety-related action is justified. The case also contains components that can be used to prioritize actions.

***In practice, the case to support a decision should be clear and provide sufficient justification for actions (or no action). The write-up can be quite detailed, although it need not be lengthy.*** For the examples in this document, the case is simplified to the key arguments used to support a category or decision. The Best Practices manual [1] contains more detailed information about the case and how it's constructed.

### ***Safety of Dams (SOD) Recommendations***

Based on the estimated risks and dam safety case, there may be a need for SOD recommendations or perhaps SOD-related O&M recommendations. This section of each example lists the proposed recommendations that resulted from the dam safety study.

### ***DSPR Category***

For each example, this section discusses the arguments and supporting information used to categorize a structure using the DSPR table.

Note that there is a distinction between the findings/building the case discussions and the DSPR discussions, although there is some overlap. The findings/building the case discussion should concentrate on the summary findings of the potential risks and the technical factors that serve to justify the conclusions on risks posed and required future actions (if any). The DSPR assignment and discussion should consider additional factors such as the confidence in the risk estimates and findings, the criticality of the risks (urgent ongoing failure modes, high risks, potential/unverified failure modes, etc.), potential actions to consider, and the relative priority of recommended actions.

### ***Example 1 – DSPR 2 Facility With High Seismic Risks***

This example features a dam with high seismic risks justifying a DSPR 2 rating. The latest risks were estimated using a team risk analysis during Issue Evaluation studies. Significant data were obtained and high-level analyses performed to evaluate dam and spillway seismic response and provide a basis for risk estimates.



### **Description of Facility**

The facility in this example consists of an embankment dam and associated appurtenant structures. The dam has an approximate height above streambed of 125 feet and features a plastic clay central core flanked by transition materials and shells composed of silty sand; there is no engineered filter system. The embankment is founded on soft silts and clays approximately 30 feet in thickness. Two foundation trenches were excavated through the overburden to rock, to help ensure stability. However, significant overburden still remains within the footprint of the dam. The outlet works consists of a tunnel through the left abutment. The spillway, also located on the left abutment, features a crest structure with two radial gates and counterforted side walls approximately 25 feet high; a chute approximately 500 feet in length; and a conventional stilling basin. The entire spillway is founded on bedrock.

### **Dam Safety Issues and Type of Study**

This example dam is located in a highly seismic area, subject to some of the most severe earthquake loadings within our inventory of dams. Past CR studies have concluded that estimated risks posed by static and hydrologic failure modes indicate decreasing justification to reduce or better define these risks. However, seismic risks are a potential concern. Detailed Issue Evaluation studies including explorations, laboratory testing, and detailed engineering analyses have been conducted; and a team Issue Evaluation-level risk analysis was performed.

### **Potential Failure Modes Evaluated**

After screening out a number of other seismic failure modes judged to present significantly less risk, four failure modes were evaluated in detail by the Issue Evaluation risk team.

- PFM 1 – Dam overtopping resulting from seismic-induced deformations that exceed available freeboard (with or without strength loss in the foundation soils)
- PFM 2 – Internal erosion resulting from cracking in the embankment due to slope failures or Newmark-type displacements (with or without strength loss in the foundation soils)
- PFM 3 – Failure of spillway wall due to seismic loading
- PFM 4 – Failure of spillway pier due to seismic loading

### **Risk Estimates**

Risks were estimated by the team using typical Issue Evaluation-level event trees, group discussions of probability distributions, and Monte Carlo simulations. In addition, sensitivity analyses were run to determine the variance in estimated risks if key inputs (earthquake loadings, strength loss assumptions, etc.) were varied.

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The estimated risks are tabulated in Table 3 and plotted on Figure 7.

As can be seen, the highest seismic risk comes from dam overtopping, while the spillway wall failure and internal erosion failure modes also pose high risks. Only the pier failure has estimated risks that are below guidelines. The total risk plotted on the f-N plot is obviously largely influenced by the failure mode of dam overtopping.

**Table 3. Summary of Example 1 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Life Loss			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Dam overtopping resulting from seismic-induced deformations that exceed available freeboard	6.0E-05	6.0E-04	1.5E-03	10	140	200	8.4E-02
Internal erosion resulting from cracking in the embankment due to slope failures or Newmark-type displacements	2.0E-05	1.0E-04	6.0E-04	10	70	100	7.0E-03
Failure of spillway wall due to seismic loading	3.1E-05	3.1E-04	3.1E-03	10	55	100	1.7E-02
Failure of spillway pier due to seismic loading	6.6E-05	6.6E-05	6.6E-05	0	1	2	6.6E-05
<b>Subtotal</b>		<b>1.1E-03</b>					<b>1.1E-01</b>
<b>Total Annualized Failure Probability</b>	<b>1.1E-03</b>		<b>Total Annualized Life Loss</b>			<b>1.1E-01</b>	

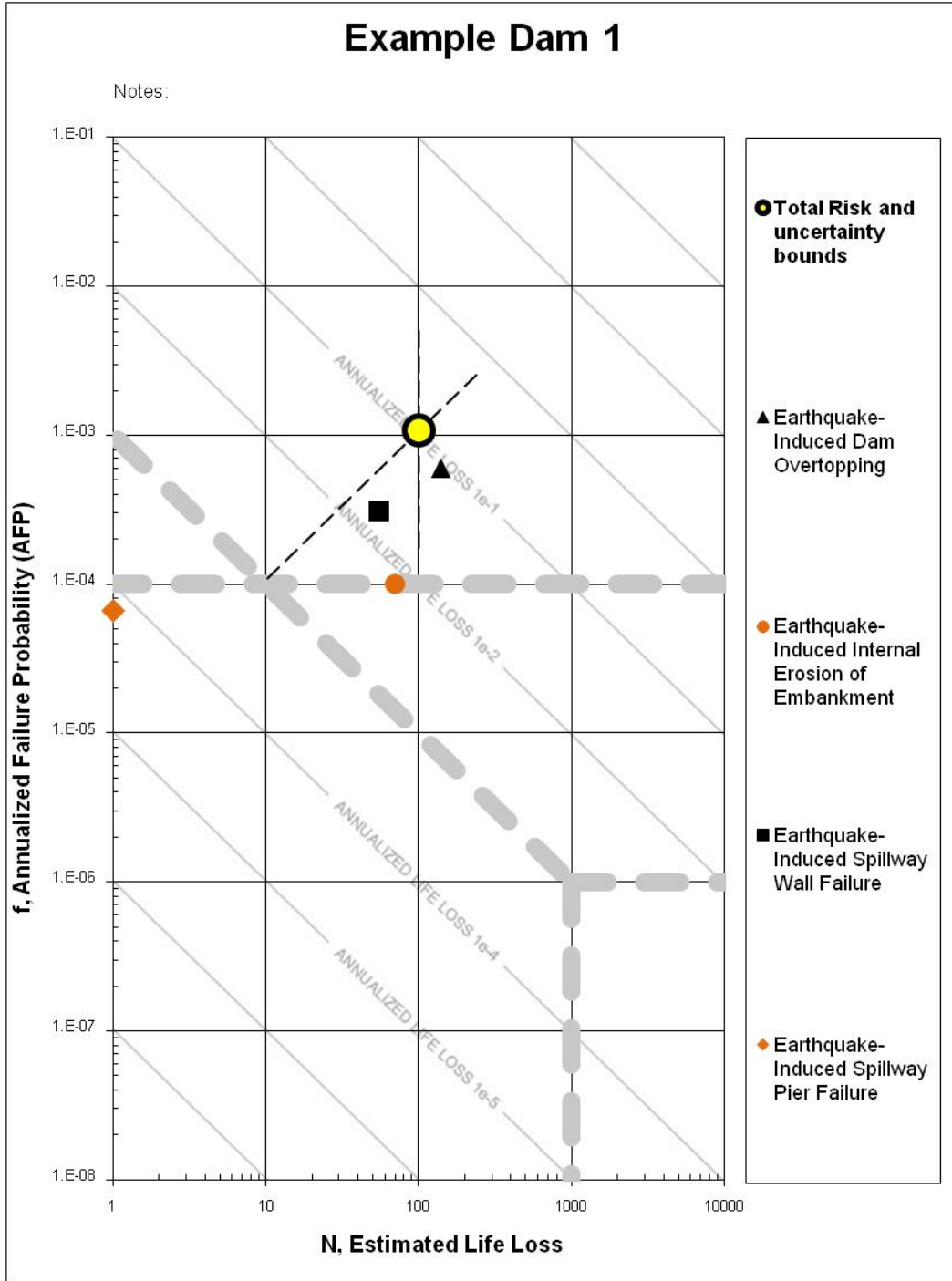


Figure 7. Risk Chart for Example 1

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**Findings and Dam Safety Case**

The following findings were presented in the Issue Evaluation documents:

The estimated mean risks associated with earthquake-induced dam overtopping, earthquake-induced internal erosion of the dam, and seismic failure of a spillway wall indicate increasing justification to reduce risks. The uncertainty with regard to these estimated risks does not warrant additional efforts prior to moving to the Corrective Action Phase. The primary factors associated with the need for risk reduction include:

- The seismic hazard at the site is very high, involving long duration, very strong motion earthquakes with relatively frequent return periods.
- Loose soils are present in the right side of the dam foundation; triggering analyses that suggest liquefaction is possible or even likely in these soils. In addition, low strength fine-grained soils comprise much of the foundation in the foundation; triggering analyses that suggest strength loss is possible or even likely in these soils as well.
- Engineering analyses and numerical modeling indicates that the embankment dam will experience severe deformations during the earthquake and likely fail due to overtopping or internal erosion.
- Engineering analyses and numerical modeling indicates that the spillway walls will be greatly overstressed during earthquake loading and likely fail.
- The pool is normally fairly high, and there are not large amounts of normal or median freeboard (that might make dam failure less likely).
- The downstream floodplain contains nearly 5,000 people who would be subject to flooding from a dam failure, including a PAR of a few hundred consisting of lumber mill workers less than a half mile downstream from the dam. Significant life loss is likely.

The estimated mean risks of a seismic failure of a spillway pier indicate decreasing justification to reduce risks. The uncertainty with regard to these estimated risks does not warrant additional efforts. The primary factors associated with the need for risk reduction include:

- Concrete cracking is not expected for the 1,000- to 5,000-year load range, and shear failure is considered to be virtually impossible for events up to the 10,000-year event.
- Even with rupturing of steel or a shear failure, the pier is expected to remain stable kinematically.

- Estimated loss of life for a pier failure is low since failure would not affect the spillway walls and discharges would be limited to the capacity of the spillway.

From past studies, the estimated mean risks associated with static and hydrologic failure modes indicate decreasing justification to reduce risk at this time. The uncertainty with regard to these estimated risks does not warrant additional study. Key factors that lead to this conclusion are:

- Although the embankment experienced considerable settlement during construction, there are no apparent signs of any cracking and observed seepage is minor and consistent.
- The clayey nature of the embankment and foundation soils make it less likely that erosion will initiate or continue to progress.
- Although the zone 2 and zone 3 contain considerable fines and may sustain a crack, they do meet particle retention filter criteria for the zone 1 core, and thus may serve as adequate filters or crack stoppers.
- New seepage areas, and indications of changing seepage conditions, should be readily apparent and detected by the damtender, providing time to take actions to remediate any developing internal erosion problem.
- The dam can safely pass the Probable Maximum Flood, and any storm capable of raising the normal high pool several feet above the previous historic high will have an infrequent return period.

### **Safety of Dams Recommendations**

Since static and hydrologic risks appeared to present decreasing justification for reducing risks, there were no SOD recommendations for those types of issues. However, given the high estimated risks and soundness of the dam safety case for potential failures of the embankment and spillway under earthquake loading, the following SOD recommendation was made in the Issue Evaluation:

**20xx-SOD-A** Initiate a Corrective Action Study to evaluate potential alternatives to mitigate the high risks of seismic failure modes of the embankment and spillway.

### **DSPR Category**

The Dam Safety Priority Rating (DSPR) system provides a means for Reclamation to establish the urgency of risk management activities and the relative priority of these actions within the overall inventory of dams. Based on the evaluations conducted during Issue Evaluation studies, this example dam is judged to have a DSPR 2 (Urgent Priority) rating. Justifications for this category include:

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- Both the annualized failure probability and the annualized life loss are very high (one to two orders of magnitude above guidelines)
- The high total risk does not result from a summation of many failure modes, but rather is primarily driven by two failure modes (seismic overtopping and spillway wall failure)
- Unlike many earthquakes, the subduction zone earthquake near this site can generate very large earthquakes with quite frequent return periods; a large portion of the risk occurs during earthquake loadings with return periods on the order of 1,000 years
- Monte Carlo simulations show that the median and mean risks are reasonably similar; risks are not driven by a small cloud of outlying points and there is a significant degree of confidence in the risk estimates
- Sensitivity analyses have shown that more favorable estimates of earthquake loadings, available strengths, and amount of embankment deformation do not appreciably lower the risk; thus there is confidence that additional studies would not alter the conclusion that risks are high

This DSPR 2 category suggests that a high priority should be given to developing potential corrective actions to reduce risk at this dam.

Note that there appears to be little justification to classify this example as a DSPR 1, since a failure is not in progress, and in fact will take an unusual loading condition such as an earthquake. A DSPR 3 category also does not appear appropriate given the very high risks and the sensitivity studies that provide a significant degree of confidence in the risk estimates.

### ***Example 2 – DSPR 5 Recently Modified Dam***

This example features a dam that has undergone modifications and now features most of the design details dictated by the latest state of practice in dam design. A CR report has established a DSPR 5 rating for the facility.

#### **Description of Facility**

This example facility is comprised of an off-stream reservoir impounded by three embankment dams (Dam #1, Dam #2, and Dam #3). Dam #1 is located on an arm of the reservoir that features inclined, steeply dipping foundation units that include karstic limestone and gypsum beds. Solutioning in geologic past had led to some degree of openness in parts of the foundation rock and a preponderance of breccia and infilled solution features. However, seepage had been relatively minor and constant throughout the early part of the operational history. (As discussed below, seepage behavior changed after 40 years of operation.) The other two embankments were located such that the karstic beds were well below the base of the dams and provided no real threat of seepage or erosion issues.

All three dams are zoned embankments with a conventional wide, central core of plastic clay flanked by shells of coarse-grained gravel and cobbles or rockfill. None were designed with internal filter systems. Cutoff trenches went to bedrock beneath the cores of the dams, but significant overburden was left within the footprints beneath the upstream and downstream shells. The structural heights of the dams ranged from 140 to 220 feet.

Two outlet works are located at the facility. One is a cut-and-cover conduit located within Dam #1, while the second is a tunnel located through the abutment of Dam #2. No operational issues have been noted with either structure. Because the reservoir is off-stream, no spillway was provided. The facility can store the Probable Maximum Flood (PMF).

The reservoir sits directly above a city. In fact, homes are located within a quarter mile of Dam #3. Thus, the population at risk (PAR) is quite high for this facility, and potential life loss in the event of a dam failure is a key concern.

### **Dam Safety Issues and Type of Study**

Dam #1 experienced increasing seepage, increasing foundation piezometric pressures, and sinkholes in the late 1990s (after more than 40 years of limited, consistent seepage). There was concern that infillings may have been washed out of some the karstic foundation units. Issue Evaluation studies and risk analyses concluded that this dam posed the highest (although uncertain) risks at the facility. The risk of seepage flows in the karstic foundation causing internal erosion at the base of the embankment and the potential for sinkholes and crest loss provided justification for pursuing risk reduction actions. In addition, due to the high PAR, lack of internal filters, and presence of potentially liquefiable soils beneath the dams; it was concluded that all the embankment dams at the facility posed static and seismic risks that justified corrective actions. Consequently all three embankments were modified in the early 2000s to remove the downstream shells and overburden beneath the shells, construct two-stage chimney and horizontal filters and drains to safely intercept and control any foundation seepage, and add a downstream berm and buttress (to provide improved seismic stability as well as a wider crest). In addition, an upstream blanket and extensive drainage system was constructed at Dam #1.

Subsequent end-of-construction risk analyses and successful reservoir re-filling demonstrated that the risks had been reduced to well below guideline levels. The latest evaluation of the facility has been a CR, performed by a Senior Engineer not familiar with the site and providing a fresh and independent assessment of the structure.

### **Potential Failure Modes Evaluated**

Since the example dams had recently been modified, there were few failure modes judged to be plausible. After screening out a number of other failure

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modes, three failure modes were evaluated in detail during the CR, all associated with the past seepage issues in the karstic foundation below Dam #1.

- PFM 1 – Internal erosion of embankment materials at the foundation contact at Dam #1
- PFM 2 – Internal erosion of foundation materials in a karstic channel at Dam #1
- PFM 3 – Internal erosion or overtopping due to collapse of an ancient karstic sinkhole feature at Dam #1

**Risk Estimates**

Risks were estimated in the CR using event trees and mean estimate probabilities for each node. As is typical for a CR, an order of magnitude range of uncertainty was assumed, and no Monte Carlo simulations were performed. The estimated risks are tabulated in Table 4 and plotted on Figure 8.

**Table 4. Summary of Example 2 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Life Loss			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Internal erosion of embankment materials at the foundation contact at Dam #1	1.2E-09	1.2E-08	1.2E-07	20	100	200	1.2E-06
Internal erosion of foundation materials in a karstic channel at Dam #1	7.9E-09	7.9E-08	7.9E-07	20	100	200	7.9E-06
Internal erosion or overtopping due to collapse of an ancient karstic sinkhole feature at Dam #1	2.0E-08	2.0E-07	2.0E-06	100	200	400	4.0E-05
<b>Subtotal</b>		<b>2.9E-07</b>					<b>4.9E-05</b>
<b>Total Annualized Failure Probability</b>	<b>2.9E-07</b>		<b>Total Annualized Life Loss</b>			<b>4.9E-05</b>	



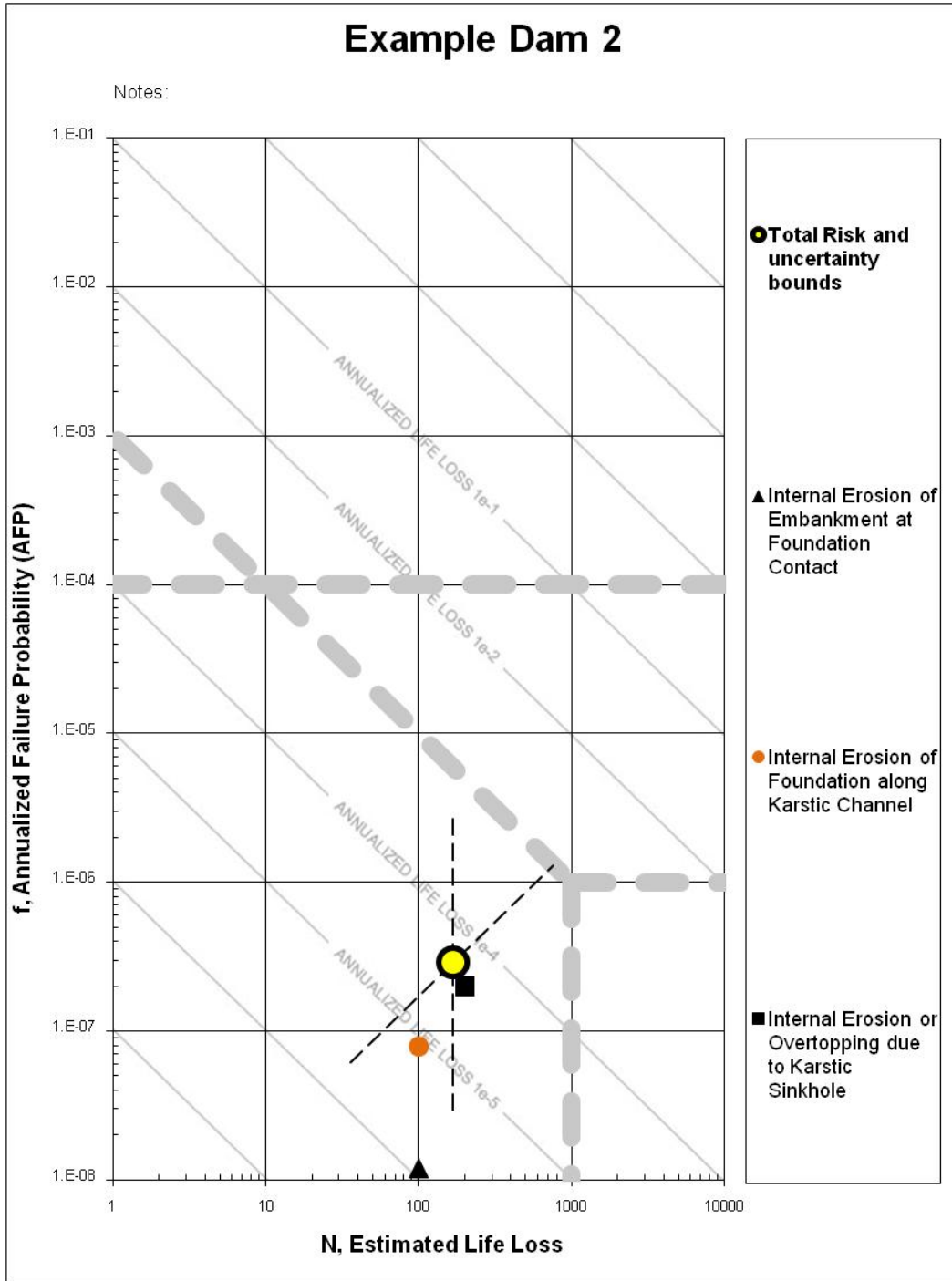


Figure 8. Risk Chart for Example 2

**Findings and Dam Safety Case**

As can be seen from the portrayal of risks, all the estimated annualized failure probability values and the estimated annualized life loss values are in the area suggesting decreasing justification for further actions to reduce risk. Based on the modification construction at these dams, the successful performance of the embankments based on instrumentation/surveillance during the past 7 years since the modification, and other factors considered during the CR evaluation, the very low annualized failure probabilities seem reasonable. These dams are now essentially state-of-the-practice, modern dams that have a low probability of failing and endangering downstream populations.

Because the dams can safely store and pass the PMF, and since the newly added stability berms are designed to prevent downstream slope failure in the extremely unlikely event of foundation liquefaction, the dams are not judged to be at any significant risk due to extreme loadings. Normal loadings appear to pose a slightly higher threat to the dam; however, estimated risk values are in the area of decreasing justification to take risk reduction actions. All three dams now have an engineered internal filter and drainage system to preclude internal erosion (piping); the embankment materials are plastic and well compacted; the facility shows steady, clear seepage flows; and observations of the exposed internal zones during construction of the modifications indicated no cracking and no signs of significant seepage. Bedrock pressures and seepage flows at Dam #1 have been dramatically reduced through the repair of a seepage entrance point (sinkhole) and the construction of an upstream blanket.

Although the consequences in terms of estimated life loss are significant in the event of dam failure, the low annual probabilities of failure have resulted in relatively low annualized life loss risks. All but one of the failure modes poses very low risk – several orders of magnitude below guideline values. The one exception is the sinkhole erosion failure mode at Dam #1. This failure mode has the highest risk (although still more than an order of magnitude below guidelines) primarily because of the relatively high life loss associated with a possible sudden and undetected failure. However, although the Issue Evaluation risk team estimated possible limited warning, there are reasons to believe that even this failure mode would be detected well in advance of dam failure. The extensive array of foundation piezometers located within the bedrock foundation and the extensometer in the left abutment area in the likely location of a karstic sinkhole feature should provide early indications that the groundwater regime is changing beneath the dam if erosion was in progress. In addition, it would be expected that downstream seepage monitoring locations would also show increasing trends. All monitoring activities should provide an indication of any future problems, which could result in an even lower estimated risk.

### **Safety of Dams Recommendations**

Given the low estimated risks and strong case that all dam safety deficiencies were addressed during the recent modifications, there were no SOD recommendations made for this facility in the CR.

### **DSPR Category**

The Dam Safety Priority Rating (DSPR) system provides a means for Reclamation to establish the urgency of risk management activities and the relative priority of these actions within our overall inventory of dams. Based on the evaluations conducted for this CR, this example facility is judged to have a DSPR 5 (Low Priority) rating. Justifications for this category include:

- Both the annualized failure probability and the annualized life loss are low (more than one to as much as three orders of magnitude below risk guidelines)
- The dams can safely store and pass the PMF
- The dams are not judged to be at any significant risk due to earthquake loadings, as the recent modification construction removed all overburden from beneath the downstream shells and the newly added stability berms are designed to prevent downstream slope failure
- All three dams now have an engineered internal filter and drainage system to preclude internal erosion; the embankment materials are plastic and well compacted; the facility shows steady, clear seepage flows; and observations of the exposed internal zones during construction of the modifications indicated no cracking and no signs of significant seepage
- In light of the thoroughness of the modification construction and the successful performance during reservoir re-filling, there are no signs of unsatisfactory performance and no reasons to expect unusual behavior in the future and there is confidence that the risks of failure are low
- There are no obvious additional studies that would improve the understanding of any potential dam safety risks

This DSPR 5 category suggests that this facility can continue with normal operations and that there is no need for any specific dam safety studies as long as the dams continue to perform as expected.

### ***Example 3 – DSPR 4 Embankment Dam***

In this example, a number of potential failure modes were estimated for an embankment dam as part of a Comprehensive Review. The annualized failure probability and annualized life loss are dominated by a single potential failure mode (Overtopping of the Dam During an Extreme Flood), but the total annualized

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failure probability and the total annualized life loss estimates indicate decreasing justification to take action.

### **Description of Facility**

The dam is a zoned embankment approximately 49 ft high with a crest length of 417 feet. The reservoir is drained to dead pool (invert of the intake structure) each year and begins filling in the fall. The reservoir is then allowed to store as much water as is available, which is usually below full pool. Since construction of the dam in 1959, the water level has reached an elevation of 3514.4 (full pool) a total of six times. In 1996 an unusually high reservoir elevation caused seepage to be exhibited on the downstream dam face. Similar seepage conditions had been noticed during previous high reservoir water levels. The 1996 seepage event ultimately led to modifications to the dam in 1999 that placed a filter trench, toe drain, and filtered berm at the downstream toe. Also, as part of the 1999 modification, the overflow sill in the upstream wall of the outlet works/spillway tower was cut lower by 3.4 feet to lower risk from failure during winter storm flood events.

### **Dam Safety Issues and Type of Study**

This example dam was evaluated as part of a CR. A number of potential failure modes were evaluated but the seismic and hydrologic potential failure modes were based on CR level hydrologic and seismic hazard studies. As a result of this, there is some uncertainty with these potential failure modes.

### **Potential Failure Modes Evaluated**

Seven potential failure modes were estimated for the embankment dam during the CR. There were four static potential failure modes, one hydrologic potential failure mode and two seismic potential failure modes. A description of each potential failure mode is provided below.

- PFM 1 – Internal Erosion of the Embankment - Seepage induced internal erosion of the core materials that would be transported to a downstream unfiltered exit point at the face of the dam.
- PFM 2 – Internal Erosion of the Embankment along the Outlet Works Conduit and into 12-inch pipe drain.
- PFM 3 – Internal Erosion through the foundation - Seepage induced internal erosion at the andesite/alluvium contact, or scour erosion of materials within the joints of the andesite, that would transport materials to a downstream unfiltered exit point.
- PFM 4 – Internal Erosion of the Embankment into the Foundation. Internal erosion initiates at the interface where the embankment was placed directly on loose, blocky debris not cleared during construction, or at the interface where the embankment was placed directly onto the alluvium.

- PFM 5 – Overtopping During Large Flood Event.
- PFM 6 – Embankment deformation induced by foundation liquefaction results in loss of the crest and dam failure by overtopping.
- PFM 7 – Seismic deformation causes cracking which leads to an internal erosion failure.

**Risk Estimates**

The risk estimates are summarized in Table 5 and Figure 9.

**Table 5. Summary of Example 3 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Loss of Life			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Internal Erosion Thru Embankment	5.0E-08	5.0E-07	5.0E-06	1	4	9	2.0E-06
Internal Erosion Along the Outlet Conduit	3.0E-08	3.0E-07	3.0E-06	1	4	9	1.2E-06
Internal Erosion Thru Foundation	2.0E-07	2.0E-06	2.0E-05	1	4	9	8.0E-06
Internal Erosion – Embankment Into Foundation	2.0E-08	2.0E-07	2.0E-06	1	4	9	8.0E-07
Dam Overtopping During Extreme Flood	2.0E-06	2.0E-05	2.0E-04	1	5	20	1.0E-04
Seismic OT Due to Foundation Liquefaction	7.0E-09	7.0E-08	7.0E-07	1	4	9	2.8E-07
Seismic Cracking of Embankment	2.0E-09	2.0E-08	2.0E-07	1	4	9	8.0E-08
TOTALS	2.3E-06	2.3E-05	2.3E-04	1	5	19	1.1E-04

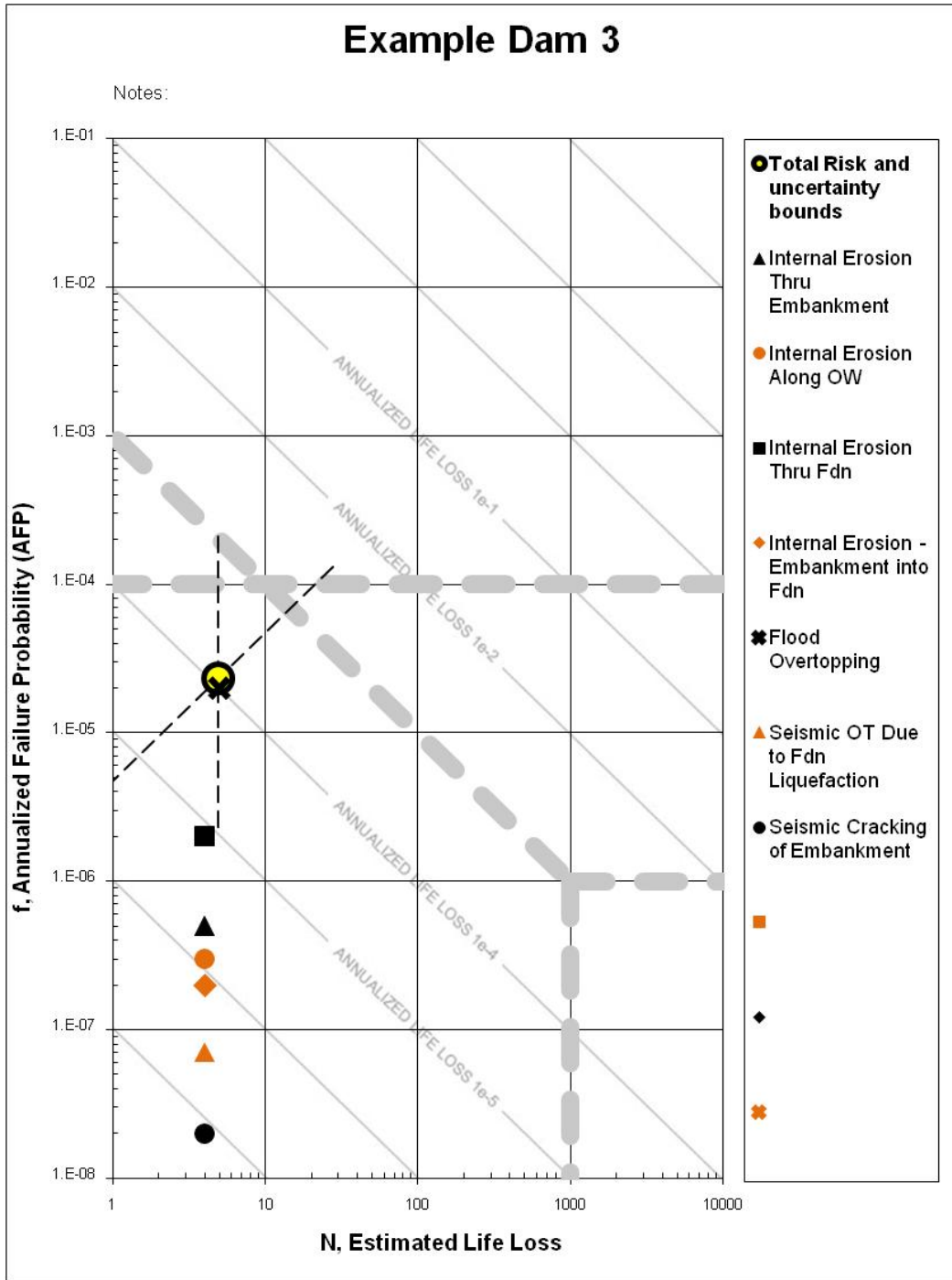


Figure 9. Risk Chart for Example 3

### Findings and Dam Safety Case

The claim is as follows: *“Both the total annualized failure probability and the annualized life loss indicate decreasing justification to take action to reduce risk. The dominant potential failure mode for this site is related to dam overtopping during an extreme flood event. Given the lower level of the CR flood frequency study and some potential issues related to flood operations, there is some uncertainty inherent in the risk estimates for the flood overtopping potential failure mode, but there are no obvious reasons to think that the risks are significantly higher than what has been estimated. Static internal erosion potential failure modes do not contribute significantly to the risks at this site, primarily due to the recent modifications. Seismic potential failure modes related to the embankment dam were estimated but have a very low annualized failure probability.”*

The failure mode associated with overtopping from a hydrologic event was examined, and failure was assumed to occur at the frequency of the threshold overtopping flood (about a 50,000-year event). The resulting annualized failure probability was 2.0E-5 and the resulting annualized life loss was 1.0E-4. The frequency of the threshold flood is based on a CR level hydrologic hazard analysis, which is a lower level study with some uncertainty. The spillway crest is an uncontrolled ogee structure that has two bays that are 50-feet wide (separated by a bridge pier that supports a highway bridge across the spillway crest structure). There are large trees in the upper portion of the drainage basin for the dam. Debris has not been reported as an issue during previous flood events, but there is some potential that debris could collect in the spillway bays and restrict flows, increasing the frequency of the threshold flood. Even with these uncertainties it is judged that the estimated risks are reasonable and there are no obvious reasons to think that the risks are significantly underestimated.

The risk associated with static internal erosion potential failure modes has effectively been mitigated by the 1999 modifications which included the toe, chimney, and foundation filters and drains. Prior to installation of the 1999 improvement, risk of static failure was estimated to be much higher. The potential failure mode with the highest probability of static failure is related to seepage through the foundation where internal erosion could occur below the foundation filter, through joints in the andesitic bedrock. The 1999 foundation filter was placed through the alluvium but not into the andesite; hence, seepage under the filter could take place. Internal erosion of the embankment into the foundation and through the foundation was estimated to be low, however, primarily because movement of materials into and through the jointed andesitic foundation is expected to be limited. While jointed, the andesite foundation joints are generally tight.

The annualized failure probability for seismic failure modes is considered remote given the information provided in the CR. The seismic loading is low as reflected

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by the estimated peak horizontal accelerations (0.2 g for the 10,000-year event and 0.4 g for the 50,000-year event). This failure mode would require liquefaction of the alluvial foundation materials and corrected SPT blow counts averaged 17, indicating liquefaction is unlikely. For the seismic cracking potential failure mode, the freeboard on the dam typically ranges from 20 to 30 feet for the 100-foot high embankment. It was concluded that it was unlikely that seismic cracks would extend deep enough to initiate seepage.

### **Safety of Dams Recommendations**

Given the low estimated risks and strong case that all dam safety deficiencies were very low and/or were addressed during past modifications, there were no SOD recommendations made for this facility in the CR.

### **DSPR Category**

For Example 3, the risk estimates appear to support a DSPR 4 (Low to Moderate Priority) rating. The total annualized failure probability and total annualized life loss estimates are driven by one potential failure mode which involves overtopping of the dam during an extreme flood. Both the total annual failure probability and the total annualized life loss estimates are within an order of magnitude of the guideline value for delineating between increasing and decreasing justification for taking action to reduce risk. Confidence is moderate due to the lower level of the hydrologic hazard study and the uncertainty as to whether debris could be a factor in restricting spillway releases. The level of the hydrologic hazard study creates uncertainty, but it is just as likely that the hydrologic hazard is overstated as it is understated. The issue of debris restricting flow through the spillway would only increase risk rather than reduce it. There is the potential for debris based on the presence of large trees in the upper portion of the drainage basin, but previous flood events have not involved any documented issues with debris at the spillway crest structure. Given the issues identified above, it is possible that refined studies and evaluations could increase the risk to the point where additional efforts to reduce risk are justified.

### ***Example 4 – DSPR 3 Concrete Arch with ALARP Considerations***

In this example, a single potential failure mode (Seismic Instability of the Right Abutment) dominates the annualized life loss and a single potential failure mode (Seismic Failure of the Left Abutment Spillway Gates) dominates the annualized failure probability. The total annualized failure probability estimate is borderline with respect to justification to take risk reduction actions. These estimates are a result of a brief Issue Evaluation study.

### **Description of Facility**

The dam is a variable-radius, thin-arch concrete structure with a crest length of 660 feet, a structural height of 305 feet, a hydraulic height of 266 feet, a top width of 8 feet, and a base width of 57 feet. The crest elevation is 1915.0 feet, and the dam crest is topped by 5-foot-high parapets on the upstream and downstream edges of the crest. There are three spillways at the dam - the left abutment



spillway with three radial gates, the right abutment spillway with six radial gates, and the right abutment tunnel spillway with a fixed-wheel gate.

### **Dam Safety Issues and Type of Study**

This example dam was evaluated as part of an Issue Evaluation which focused on potential failure modes related to movement of a foundation wedge in the right abutment of the dam. The Issue Evaluation was initiated by a CR, which indicated that risks due to failure of the foundation wedge provided increased justification to take action to reduce risk. The elevated risks were a result of a drainage system that was installed in 1998 becoming plugged and less effective over time. Two additional potential failure modes were estimated during the CR and were included in the overall portrayal of risk. These potential failure modes involved a structural failure of the arch during an earthquake and seismic failure of the left abutment spillway radial gates.

### **Potential Failure Modes Evaluated**

Four potential failure modes were evaluated for this Issue Evaluation. One static potential failure mode and three seismic potential failure modes were identified. A description of each potential failure mode is provided below.

- PFM 1 – Static Instability of Right Abutment. The existing foundation jointing forms three significant potential sliding wedges in the right abutment of the dam. Construction of the drainage adit and associated drainage features greatly reduced uplift pressures associated with seepage through the right abutment, resulting in improved stability of the wedges (post-drainage conditions). However, the effectiveness of the drainage system has been reduced based on decreased flow from the adit and increased water level readings at two permanent piezometers.
- PFM 2 – Seismic Instability of Right Abutment. This failure mode involves the same foundation wedges described in PFM 1. During an earthquake, movement of wedge No. 1 could result in increased uplift along joints which could further displace wedge No. 1 either during or after a seismic event, leading to loss of abutment support for the dam and subsequent failure and an uncontrolled release of the reservoir.
- PFM 3 – Seismic Cracking of Arch Dam. The mechanism involves the formation of potentially unstable blocks bounded by vertical contraction joints and horizontal lift joints that separate due to the excessive tensile stress in the upper 100 feet of the dam. Subsequent sliding/toppling of these blocks could occur as the earthquake continues, or during aftershocks.
- PFM 4 – Seismic Failure of the Left Abutment Spillway Radial Gates. During a major earthquake, loads transmitted from the reservoir overstress the spillway gate arms, leading to buckling of the gate arms and an uncontrolled release through the spillway gates.

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**Risk Estimates**

Risks were estimated by a team using typical Issue Evaluation event trees, group discussions and Monte Carlo simulations for PFM 1 and 2. Risk estimates for PFM 3 and 4 were adopted from the previous CR after a review by the Issue Evaluation risk analysis team. The risk estimates are summarized in Table 6 and Figure 10. This particular example is somewhat unique in that the total risk plotted on Figure 10 is a function of one failure mode (PFM 4) with a relatively high annualized failure probability and low life loss and a second failure mode (PFM 1) with a relatively low annualized failure probability but a high life loss. The resulting total risk plots between these two failure modes with a computed life loss not specifically related to either failure mode. In these cases, it becomes particularly important to look at the individual failure modes.

**Table 6. Summary of Example 4 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Loss of Life			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Static Instability – Right Abutment	2.8E-07	8.0E-07	5.7E-06	800	2000	3100	1.6E-03
Seismic Instability – Right Abutment	2.9E-09	5.9E-08	2.6E-07	800	2000	3100	1.2E-04
Seismic Cracking of Arch Dam	1.6E-08	1.6E-07	1.6E-06	800	2000	3100	3.2E-04
Seismic Failure of Left Abutment Spillway Radial Gates	4.0E-05	8.0E-05	1.2E-04	1	4	5	3.2E-04
<b>TOTALS</b>	<b>4.0E-05</b>	<b>8.1E-05</b>	<b>1.3E-04</b>	<b>7</b>	<b>30</b>	<b>195</b>	<b>2.4E-03</b>

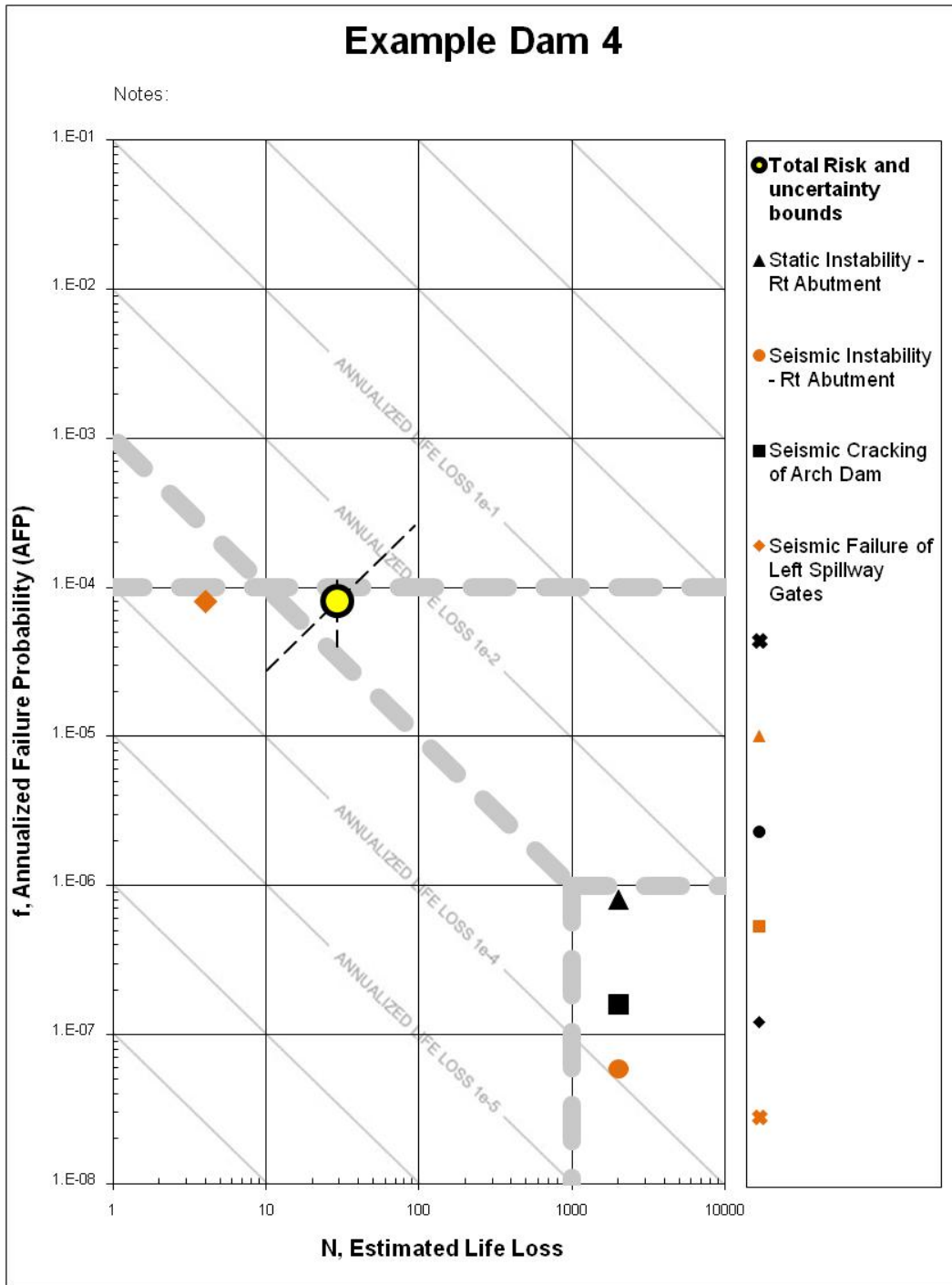


Figure 10. Risk Chart for Example 4

### Findings and Dam Safety Case

The claim is as follows: *“The total annualized life loss indicates increasing justification to take action to reduce risk and the total annualized failure probability is borderline in terms of justification to take additional action. The two measures are driven by different potential failure modes – total annualized life loss is driven by a static potential failure mode related to sliding of a foundation wedge in the right abutment. The total annualized failure probability is driven by a seismic potential failure mode related to failure of the left spillway radial gates. There is moderate confidence with the foundation stability failure mode. The confidence in the spillway gate potential failure mode is low. For all potential failure modes other than the spillway gate potential failure mode, the annualized failure probability estimates are very low, but life loss estimates exceed 1,000 people. For these potential failure modes ALARP considerations would apply. Alternatives for reducing risk would need to be identified and an evaluation made on the cost effectiveness of reducing risk for one or more of these potential failure modes.”*

There is moderate confidence associated with the potential failure modes involving static and seismic instability of a foundation wedge in the right abutment of the dam. The effectiveness of the right abutment drainage system installed in 1998 to address stability concerns has decreased. This is evidenced by the increased vegetation on the abutment, decreased flows through the deep drains, increased flows through the predrains, and increased piezometer readings. The current condition of the drainage system is thought to be approaching the pre-drain condition (prior to installing the drainage system - predrains, adit, and deep drains in 1998). Based on the results of the updated post-construction stability analyses using the NEWMARK analysis tool, Wedge 1, the upper-most wedge is the critical foundation wedge. The updated analyses indicate a static factor-of-safety of 1.36 for Wedge No. 1, assuming current uplift conditions.

The risk estimates were based on a current analysis, which included up to date uplift pressure measurements on the foundation block (although the instrumentation is limited and could not define the complete uplift pressure distribution on the block). The foundation block is clearly defined by joints that are exposed on the downstream portion of the right abutment. Continuity of joints is likely based on the joint exposures on the right abutment. The high risk for this potential failure mode (under static loading and to a lesser extent under seismic loading) is driven by the population at risk from a major metropolitan area downstream of the dam and loss of life estimates that range from 800 to 3,100 people. Even with some uncertainties it is judged that the estimated risks are reasonable and there are no obvious reasons to think that the risks are significantly underestimated.

The risk related to seismic cracking of the arch dam is also in an area where ALARP considerations would apply. The confidence in this risk estimate is moderate to high (the team was very confident that cracking would occur during large earthquakes; but less confident in their ability to predict a completed failure

surface due to the limited number of case histories). Since the annualized failure probability is very low and since this potential failure mode cannot be easily mitigated, no recommended actions are made at this time regarding seismic cracking of the dam.

The confidence in the seismic spillway gate potential failure mode is low. The estimates were based on a CR level evaluation. Since an analysis of the spillway gates for the seismic loading had not been performed, stresses in the gate arms were estimated by relating anticipated seismic loads on the gates to hydrostatic loads. This factoring of the gate loads was based on results from a number of radial gate seismic analyses for other dams, but the method provides only a rough approximation of the seismic loads and stresses in the gate arms.

### **Safety of Dams Recommendations**

Given the borderline annualized failure probability estimate associated with the seismic spillway gate potential failure mode and the ALARP considerations involving the potential foundation instability of wedges in the dam foundation, three safety of dams recommendations are made:

**20xx-SOD-A** Perform an analysis of the spillway gates using a 3D finite element model. The analysis should include both static and seismic loading conditions.

**20xx-SOD-B** Evaluate alternatives and develop costs for improving the stability of foundation wedges in the right abutment of the dam. The alternatives should consider stabilization measures for both static and seismic loading conditions.

**20xx-SOD-C** Conduct an updated team risk analysis to re-estimate the risks associated with recommendation 20xx-SOD-A and to estimate the risk reduction associated with the alternatives identified as part of recommendation 20xx-SOD-B. The risk reduction estimates and the construction costs associated with the alternatives will provide information that will be used to decide if additional actions should be pursued relative to the foundation stability potential failure modes.

### **DSPR Category**

For Example 4, there are two distinct considerations – one related to a potential failure mode that controls the total annualized failure probability but has relatively low consequences and one related to several potential failure modes with ALARP considerations (annualized failure probabilities are less than 1E-06 for three potential failure modes but all have loss of life estimates exceeding 1,000 people). The risk estimates appear to support a DSPR 3 (Moderate to High Priority) rating, but there are ALARP considerations relative to some of the future actions that might be taken. There is moderate confidence in the right abutment

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foundation instability potential failure modes (involving static and seismic loading cases; these potential failure modes have very high consequences and very low annualized failure probability estimates), but the risk estimates are based on detailed information and there is little room to improve the quality of these studies. The risks will also likely increase somewhat with time as foundation drains continue to plug, uplift pressures increase and the stability of the foundation wedge decreases. The spillway gate potential failure mode has low confidence and is borderline with respect to justification to take action to reduce risk, with relatively low consequences. It is likely that additional studies would reduce the uncertainty, potentially resulting in a lower estimate of risk. These studies would involve a finite element analysis of the spillway gates including seismic loads. In order to evaluate ALARP at this time, risk reduction alternatives for the potential failure modes relating to foundation stability would need to be developed and their cost effectiveness evaluated.

In terms of prioritization among other dams with a DSPR 3 rating, the risk is driven by a single potential failure mode under normal operating conditions. While the total annualized life loss for this dam indicates increasing justification to take action to reduce risk, the total annualized failure probability is borderline with respect to justification to take further action. It is likely that the fix to improve stability of foundation wedges would be expensive.

### ***Example 5 – DSPR 5 Modified Embankment Dam***

#### **Description of Facility**

The dam in this example consists of a 200-foot-high, 1,700-foot-long rockfill structure with a rolled earth core. The dam is comprised of a steep rolled earthfill central core with a transition zone of rock fragments, pit-run gravel, and quarry spalls fines, and flanked by an outer rockfill zone on both the upstream and downstream faces. The core and transitions are founded on bedrock, but the shells are founded on granular alluvial deposits. Modifications were completed in the 1950s and again in the 1990s to increase storage, address hydrologic deficiencies, and improve seismic stability. Release facilities at the dam include a service spillway, fuse plug auxiliary spillway and outlet works.

#### **Dam Safety Issues and Type of Study**

Prior to the 1990s modifications, this example dam was unable to safely pass the Probable Maximum Flood (PMF). Hydraulic deficiencies were corrected by raising the dam and constructing an auxiliary fuse plug spillway. Earthquake loading for the dam is dominated by a relatively large event occurring on a local fault only several hundred meters from the dam. However, this fault is very old and the probability of surface rupture is very low. Analyses of Standard Penetration Tests (SPTs) and cross-hole geophysical testing in foundation alluvium indicated potential for liquefaction of the alluvium and slope instability that could cause the dam crest to fall below the reservoir surface. In the 1990s, a 25-ft-high stability berm was constructed at the downstream toe of the dam to improve seismic stability. Since modifications to address hydrologic and seismic

deficiencies were completed in the 1990s, no significant dam safety issues have been identified in subsequent CRs. This evaluation of risks was performed for a CR by a Senior Engineer very familiar with the dam and its past issues.

**Potential Failure Modes Evaluated**

Several hydrologic and seismic potential failure modes were considered, but were judged to have very low risks. However, past modifications did not address static risks and some uncertainty remains with regard to possible cracks/defects in the embankment, adequacy of rock foundation treatment, and the ability of the transition zones to filter core material. Detailed risk estimates were evaluated in the CR for two static potential failure modes:

- Internal erosion of core material through the embankment
- Internal erosion of core material into the rock foundation

**Risk Estimates**

Risks were estimated by the Senior Engineer using a seven node event tree, slightly modified from the standard Best Practices [1] internal erosion event tree. Best estimate probabilities were assigned to each node; uncertainty was estimated but no Monte Carlo simulations were performed. The estimated risks are tabulated in Table 7 and plotted on Figure 11.

**Table 7. Summary of Example 5 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Life Loss			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Internal Erosion of core material through the embankment	6.0E-08	3.5E-06	2.3E-05	0	8	31	2.8E-05
Internal Erosion of core material into the foundation	6.0E-09	1.1E-07	6.0E-07	0	8	31	9.0E-07
<b>Total Annualized Failure Probability</b>	<b>3.6E-06</b>			<b>Total Annualized Life Loss</b>			<b>2.9E-05</b>

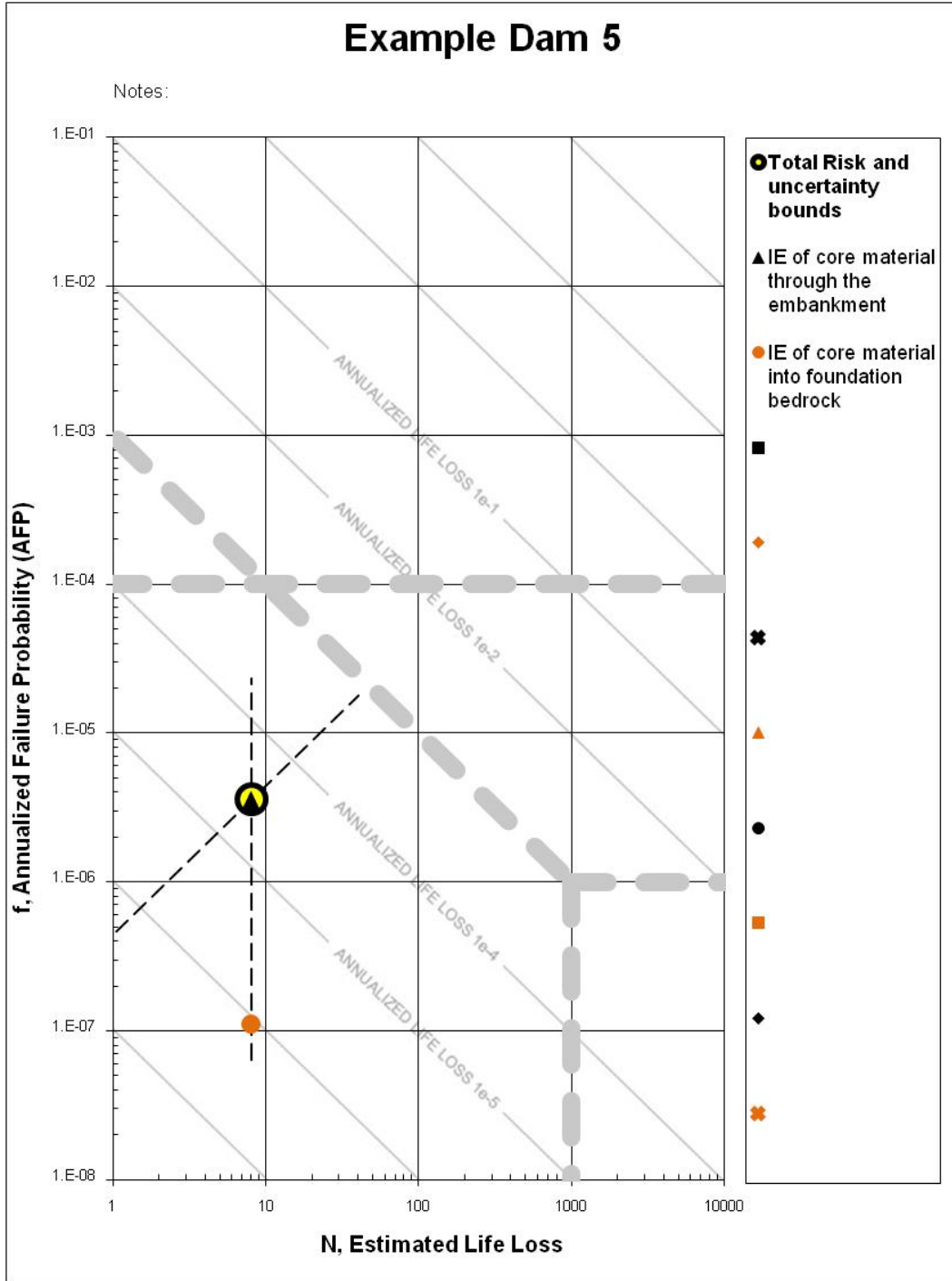


Figure 11. Risk Chart for Example 5



### Findings and Dam Safety Case

From the table and chart it is apparent that the annualized failure probability and annualized life loss estimates are in the area of decreasing justification to take action to reduce or better understand risks. Based on the modifications completed for this dam and the static risk factors considered for this CR, the low annualized failure probability seems reasonable. The primary static risk factors considered include:

- The source of the downstream transition zone material is river alluvium, and it is likely able to filter the core material; although, a detailed filter analysis has not been performed due to the lack of gradation information available on the transition material. Similarly, it is likely that the alluvial foundation materials would filter core material transported through fractures in the rock foundation.
- Longitudinal cracking has been observed and it is possible that settlement may have also caused transverse cracks that are not visible. However, there is no visible evidence of transverse cracking and there is no evidence of seepage through the embankment.
- The embankment core was well-constructed with a sheepsfoot roller and the probability of a continuous upstream to downstream defect in the core is low.
- The finer portions of the upstream granular transition zone might migrate into any crack that forms, effectively serving as a crack-stopper.
- The core foundation bedrock was not treated with dental concrete or slush grout, increasing the likelihood that core material could be transported into open joints; however, several defensive measures such as a grout cap and cutoff wall would tend to interrupt any upstream to downstream seepage path. Also, any eroded particles would need to travel long distances through open joints and fractures to daylight at an unfiltered exit in the rockfill or stability berm.
- The upstream rockfill shell zone materials are unlikely to be transported through a developing pipe, decreasing the probability that a pipe could form and breach the dam.

The risks from all flood-related potential failure modes were determined to be very low, and no quantitative risk analysis was performed. The facility was modified to pass the PMF so overtopping is not a credible failure mode. There is the possibility of an internal erosion failure mode developing in the upper, untested portion of the embankment that may have experienced some settlement-induced or desiccation cracking; however, the risks associated with this failure

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mode were judged to be very low because of the large (and infrequent) flood that would be required to make this failure mode a concern.

The risks from all seismic potential failure modes were determined to be very low, and no quantitative risk analysis was performed. Two seismic potential failure modes related to (1) cracking leading to internal erosion and (2) deformation resulting in overtopping, were considered because of the loose alluvial materials under the shells of the dam and the possibility of strong seismic shaking. However, there are many offsetting factors that would tend to lower the risks, including a downstream stability berm that limits deformation, an upstream transition zone that might serve as a crack stopper, a downstream transition zone that might filter core material, a minimum of 26 feet of freeboard, and a very low joint probability that a strong earthquake would occur when the reservoir is nearly full.

### **Safety of Dams Recommendations**

Given the low estimated risks and strong case that all dam safety deficiencies were very low and/or were addressed during past modifications, there were no SOD recommendations made for this facility in the CR.

### **DSPR Category**

The Dam Safety Priority Rating (DSPR) system provides a means for Reclamation to establish the urgency of risk management activities and the relative priority of these actions within our overall inventory of dams. Based on the evaluations conducted for this CR, this example dam is judged to have a DSPR 5 (Low Priority) rating. Key justifications for this category include:

- Dam safety modifications were completed in the 1990s to address hydrologic and seismic deficiencies. The current risks associated with hydrologic and seismic potential failure modes are considered remote and were not quantified in this CR.
- There is relatively high confidence that the hydrologic and seismic risks are very low. There is moderate confidence in the static risks, with the largest uncertainty associated with the ability of the downstream transition zone to filter the core.
- The total estimated annualized failure probability (only two failure modes were considered) is very low ( $4 \times 10^{-6}$ ) and the total annualized life loss is very low ( $3 \times 10^{-5}$ ); in the range of decreasing justification to take action to reduce or better understand risks.
- Although the zoned embankment was not designed with an engineered filter, the embankment was well-designed and constructed and the estimated risks for internal erosion failure modes are low. Primary factors that contribute to the low estimated internal erosion risks are the low estimated probability of a defect in the embankment, foundation treatment and grouting, upstream transition and rockfill zones that could serve as a

crack stopper or flow limiter, and the large gated spillway that could be used to quickly lower the reservoir if needed.

With such low risk estimates, it would be difficult to justify a DSPR 4 rating. Also, it would be difficult to build a case to justify taking action to better understand the risks since many aspects of the potential failure modes are reasonably understood.

### ***Example 6 – DSPR 3 Embankment with Internal Erosion Risks***

#### **Description of Facility**

The dam in this example is a homogeneous (clay, sand, and gravel) rolled earth embankment with a structural height of 110 feet built in the late 1930s. The dam has a very wide cross section with 3:1 and 2.5:1 slopes that transition to 5:1 and 10:1 slopes on the lower portions of the dam. There is a ‘rockfill’ buttress fill downstream that covers approximately the lower 20 percent of the dam. The dam was founded on river alluvium which consists mostly of transported glacial till materials. There is a spillway located on the left abutment that consists of a riprap-lined inlet channel, a concrete overflow crest structure, concrete chute and stilling basin, and a riprap-lined discharge channel to the river. The concrete crest structure and most of the concrete chute are founded on weathered sandstone that is un-cemented, or poorly cemented, at most locations. The dam is located 14 miles upstream from a population center of about 5,000 people.

#### **Dam Safety Issues and Type of Study**

The dam has performed satisfactorily since its completion in the late 1930s, despite some deficiencies such as a lack of engineered filters and several feet of embankment settlement due to consolidation of loose foundation soils. The settlement was so excessive that immediately after construction additional embankment material was added to restore the crest and camber. Settlement continued for approximately 50 years, then stabilized.

Past dam safety issues have focused on internal erosion through the weak spillway rock foundation, internal erosion through the embankment, and the potential for development of stagnation pressures that could lead to slab jacking and spillway failure during spillway releases. Ongoing freeze-thaw deterioration of the spillway slab causes spalling in the concrete and requires maintenance. In addition to the deterioration of the concrete, voids have been detected by ground-penetrating radar and coring investigations. Some erosion of the un-cemented sandstone under the slab has apparently taken place resulting in voids ranging from less than one inch to about four inches.

This evaluation of risks was performed for a CR by a Senior Engineer generally unfamiliar with past issues at the dam – providing a fresh perspective on the internal erosion and spillway issues.

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**Potential Failure Modes Evaluated**

Three static and one hydrologic potential failure modes were evaluated. Seismic potential failure modes were considered, but were judged to have very low risks due to the remote possibility of significant seismic loads and a minimum of 20 feet of freeboard. Detailed risk estimates were evaluated in the CR for the following potential failure modes:

- Internal erosion of the embankment initiating at potential cracks
- Internal erosion of weathered, un-cemented sandstone under the spillway slab
- Internal erosion of foundation soils under the embankment.
- Spillway flows leading to slab jacking, erosion, and breach of the spillway crest structure

**Risk Estimates**

Internal erosion risks were estimated by the Senior Engineer using a seven node event tree, slightly modified from the standard Best Practices [1] internal erosion event tree. Water surface profiles were developed and hydraulic jacking calculations were performed to evaluate the factor of safety against slab jacking. Spillway failure risks were estimated using the flood frequency and slab jacking calculation results. Best estimate probabilities were assigned to each node; uncertainty was estimated but no Monte Carlo simulations were performed. The estimated risks are tabulated in Table 8 and plotted on Figure 12.

**Table 8. Summary of Example 6 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Life Loss			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Static, internal erosion through embankment	8.7E-07	1.2E-05	1.9E-04	20	150	750	1.9E-03
Static, internal erosion through spillway foundation	1.3E-07	1.3E-06	1.3E-05	8	85	380	1.1E-04
Static, internal erosion through foundation	1.3E-07	2.0E-06	3.0E-05	20	150	750	3.1E-04
Hydrologic, spillway slab jacking	8.0E-09	1.2E-07	1.8E-06	1	2	35	2.4E-07
<b>Total Annualized Failure Probability</b>	<b>1.5E-05</b>			<b>Total Annualized Life Loss</b>			<b>2.3E-03</b>

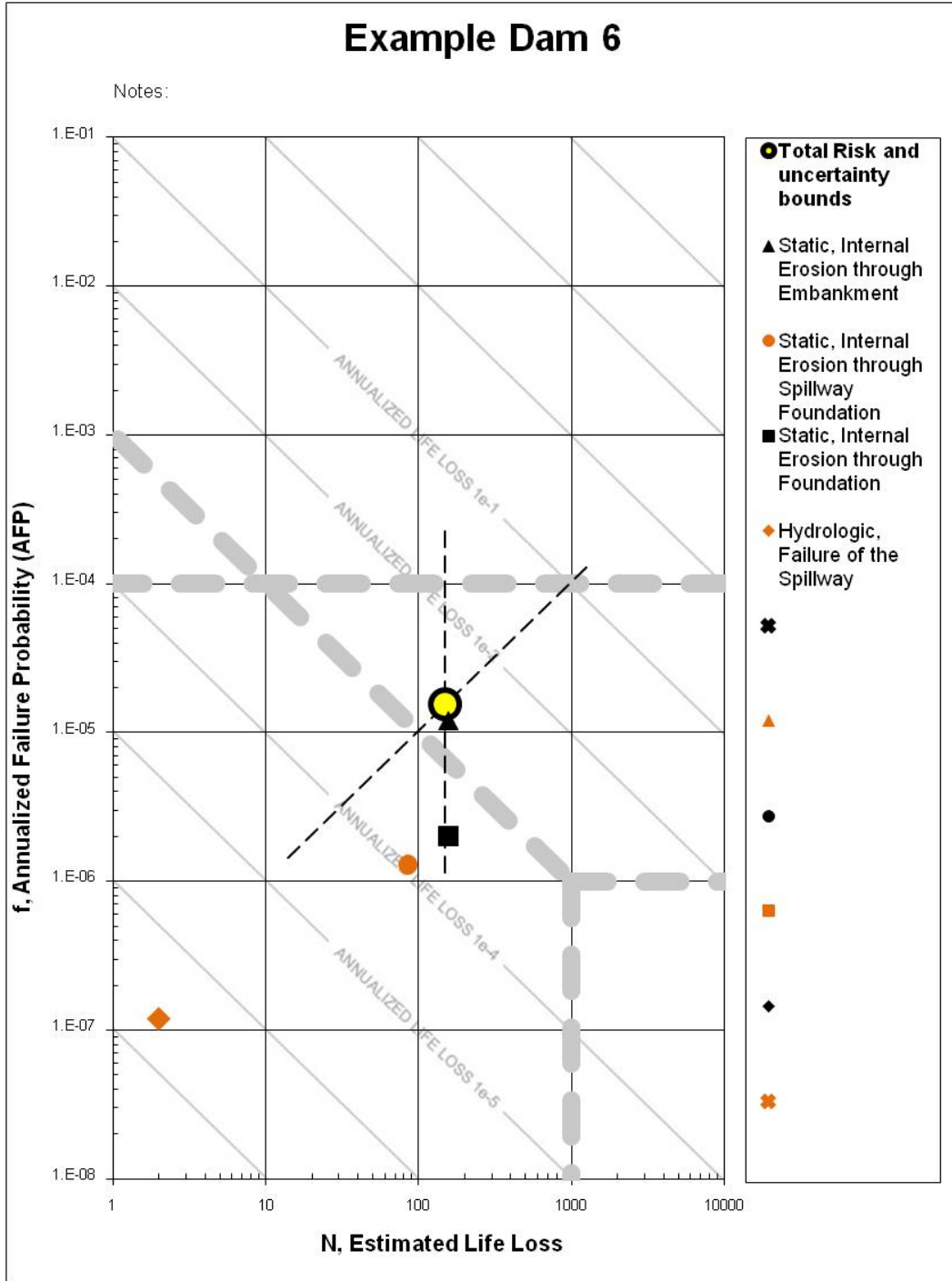


Figure 12. Risk Chart for Example 6

**Findings and Dam Safety Case**

Risks were evaluated for four potential failure modes; three under normal operating conditions and one hydrologic. The estimated risk for internal erosion through the embankment is in the area of increasing justification to take action to reduce or better understand risk; and the total risk for the dam is dominated by the risk of that potential failure mode. The total risk is judged to be moderate to high, with low confidence. Completion of an exploration program in the rockfill to assess filter compatibility would provide additional information to re-evaluate risks and could result in a reduction in risk to justify a lower DSPR category. Key factors that lead to this conclusion including descriptions of the more significant unknowns are described below.

The static risk of internal erosion through the embankment is estimated to be  $1.9 \times 10^{-3}$ . The dam is believed to be well constructed, but filters were not included in the design. Large foundation settlements occurred during and immediately after construction, indicating the possibility for cracking in the dam. There was also a winter shutdown at a relatively low elevation, leaving the embankment exposed to the weather over the winter. However, the dam was designed to be very wide, with 2.5:1 and 3.0:1 slopes on the upper part of the dam and 10:1 slopes on the bottom part. The primary uncertainties associated with the dam are (1) whether a defect (a crack or poor lift) exists, and the extent or size of such a defect, and (2) whether the downstream ‘rockfill’ zone would provide some filtering, perhaps allowing some continuation of piping (some erosion or excessive erosion) before choking off. Performance to date has been satisfactory and there have been no indications of adverse seepage conditions. A SOD recommendation was made to explore the ‘rockfill’ zone with a test pit exploration and laboratory testing program to address uncertainty regarding the existence of an unfiltered exit. If investigations reveal that the ‘rockfill’ zone has a substantial matrix of sandy material with no open voids between larger particles, the rockfill zone could provide some filtering capability and the risks could be reduced by a half or full order of magnitude.

There is significant uncertainty in the estimated loss of life associated with an internal erosion failure. Estimates range from about 20 (low – daytime) to 750 (high – nighttime). The primary PAR is located in a town located about 14 miles downstream of the unattended dam. Dated inundation mapping is available (~1984) but there are uncertainties associated with (1) the basis for the inundation (i.e. it’s unclear if the maps are for PMF overtopping) and (2) the warning time in the town. During the day, observations of rising water, effective communication and emergency response would contribute to longer warning times, a better understanding of the incident, and low fatality rates. However, there are less than 20 people upstream of the town who would be relied upon to provide warning to authorities in town should a breach occur at night. With a flood wave travel time of about 1.5 hours, and potentially only 15 minutes or less of warning, a higher fatality rate seems appropriate. There is significant uncertainty in these estimates that could be reduced with better inundation

mapping (i.e. for a failure under normal operating conditions) that includes flow depths and velocities. A high probability of failure caused by internal erosion through the embankment coupled with low confidence in the consequence estimate is the basis for making a recommendation to generate new inundation maps before the next CR. Consequences should be re-evaluated at that time using the new inundation maps.

The static risks for internal erosion through the spillway foundation and internal erosion through the embankment alluvial foundation are both judged to be low, in the area of decreasing justification to take action to reduce or better understand risk. The risk estimate for internal erosion through the embankment alluvial foundation is driven primarily by a low probability that internal erosion would initiate because of the very long seepage path and corresponding low gradient. The risk estimate for internal erosion through the spillway foundation is lower than the risk estimated in previous studies because additional spillway drawings were located that show details of the concrete cutoff wall upstream of the spillway. The cutoff wall is founded in shale bedrock and was designed to tie into the cutoff wall on the left abutment of the embankment. Based on the details on the drawings, it is apparent that the seepage path would be long and tortuous to bypass the cutoff wall. There is also a concern regarding the presence of voids under the spillway concrete that could be indicative of erosion of foundation material. A Ground Penetrating Radar study and two concrete coring investigations were completed since 2005. Results of those investigations indicate some small voids are present at some locations under the slab; although, the cause of the voids is unknown and the preferential seepage path is believed to be through the upper couple feet of sandstone overlying shale bedrock at about elevation 2530 rather than directly under the concrete slab. For these potential failure modes, risks are low and confidence is low to moderate.

The primary hydrologic failure mode of concern is related to failure of the spillway caused by stagnation pressure development and slab jacking. The estimated risk for this failure mode is low and the confidence in the estimate is moderate. Information from a Ground Penetrating Radar study and two concrete coring investigations was evaluated and previously unavailable spillway detail drawings were reviewed. The design drawings show that no water stops were included between the joints; however, other defensive design features (i.e. reinforcing across joints and keyed joints) were incorporated that would decrease the likelihood of slab jacking. Also, the factor of safety against slab jacking was computed for various floods. While spalling and deterioration of the concrete will probably continue to be an issue on the spillway, the investigations and analyses considered in this CR provide a moderate to high confidence level in the generally low risk estimates. However, if the spillway concrete is not repaired in a timely manner, the slab will continue to deteriorate at the joints and higher stagnation pressures could result in lower factors of safety for slab-jacking. O&M repairs should be made in a timely manner when deterioration is noticed on the slab.

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The potential for an increased risk of internal erosion through the embankment during a flood was also considered. The flood duration is not more than a few days and the reservoir is not likely to be at a high level for a long enough time to initiate erosion. While there may be cracks in the upper part of the embankment in which erosion could initiate, the embankment soils would resist erosion and the head on potential cracks was judged to be relatively low. Furthermore, there would be more ‘eyes on the dam’ during periods of high reservoir levels and any signs of adverse seepage could be addressed.

The risks from all seismic potential failure modes were determined to be very low, and no quantitative risk analysis was performed.

### **Safety of Dams Recommendations**

Since seismic and hydrologic risks appeared to present decreasing justification for reducing risks, there were no SOD recommendations for those types of issues. However, estimated static risks provide a justification to better define the risks. Given the uncertainty in the risk estimates, it is believed that additional exploration will provide additional understanding of the embankment materials and thus increase the confidence in the risk estimates. Thus, the following SOD recommendation was made in the CR:

**20xx-SOD-A** Perform test pit explorations, obtain samples, and perform lab testing in the rockfill section of the dam. Evaluate the filter compatibility of the rockfill with the embankment soils. After the studies are completed, reevaluate the static risk.

In addition, given the uncertainties in the consequences estimates, the following SOD-related O&M recommendation was made to enable a better estimate of life loss in future studies:

**20xx-2-A** Update inundation mapping prior to the next scheduled CR.

### **DSPR Category**

The Dam Safety Priority Rating (DSPR) system provides a means for Reclamation to establish the urgency of risk management activities and the relative priority of these actions within our overall inventory of dams. Based on the evaluations conducted for this CR, this example dam is judged to have a DSPR 3 (Moderate to High Priority) rating. Justifications for this category include:

- The risk is primarily due to the potential presence of embankment defects (cracks, poor lift) and lack of an engineered filter.
- High consequences due to little or no nighttime warning in town also impact the estimated risk.



- The high risk does not result from a summation of many failure modes, but rather is primarily driven by one failure mode (internal erosion through the embankment).
- The risk is not driven by an unusual loading event such as a remote flood or earthquake, but results from a static failure mode that could occur in any given year.

This DSPR 3 category suggests that priority should be given to completing the updated inundation mapping and the exploration program.

However, it is recognized that an argument could be made to support a DSPR 4 rating on the basis that risks might be overestimated and are likely to decrease if additional information is obtained. For example, the embankment internal erosion probability of failure might be overestimated due to the uncertainty associated with the downstream rockfill zone. Rockfill gradation testing is likely (but not guaranteed) to indicate that the rockfill is well-graded and could provide some filtering capability. Also, updated inundation mapping for a sunny-day failure condition would likely be used to support lower PAR and loss of life estimates. It is possible that the combined reduction in probability of failure and consequences could result in an order of magnitude reduction in total risk.

#### ***Example 7 – DSPR 4 Concrete Gravity Dam***

This example features a concrete gravity dam that has been in operation for over 60 years. A CR report has established a DSPR 4 rating for the facility.

#### **Description of Facility**

This example features a concrete gravity structure constructed in the late 1940s. The dam impounds a reservoir with an active conservation capacity of approximately 4,000 acre-feet, used for hydroelectric power generation. The dam has a structural height of 244 feet and a crest length of approximately 440 feet. The crest width is 24 feet and the base thickness is 193 feet. The upstream face is vertical from the crest to below the penstock intakes, then slopes down at 0.2H:1V to a 15-foot-radius curve that intersects the native rock. The downstream face slopes at 0.7H:1V. The foundation and abutments for the dam consist of solid granite but are broken into large massive sections by numerous fractures and seams.

An uncontrolled overflow spillway is located at the right abutment. The concrete ogee-shaped crest transitions to a 30-foot-diameter concrete-lined circular tunnel through granitic rock that discharges directly into the river. The design discharge capacity of the spillway is 50,000 ft<sup>3</sup>/s. There is no river outlet works system at this facility. All reservoir releases are made through the power penstocks and their respective hydraulic turbines.

**Dam Safety Issues and Type of Study**

This dam has performed very well under a limited range of loading conditions since completion of its construction in 1950. Overall, the dam and its appurtenant features appear to be in good condition and appear to be very well maintained. Historically, there have been no items or issues of concern identified that would result in modifications or limitations to the operation of the dam as currently documented in the SOP. However, the importance of foundation drainage is critical to ensure continued good performance, and there is some indication that the drains are losing some effectiveness over time. The drains were recently cleaned and some of the foundation drain holes were re-drilled in the last 20 years. The CR recommended that inspection criteria be established so that the extent of calcium carbonate and iron bacteria is limited to an amount that can be cleaned via power wash rather than costly re-drilling. The CR noted that foundation drains and formed dam drains provide key monitoring indicators for potential changed or previously undiscovered conditions at the dam that could significantly change the assessment of risk.

**Potential Failure Modes Evaluated**

The CR looked at potential failure modes that might occur during all loading conditions. A total of five failure modes were evaluated in detail during the CR, as listed below.

- PFM 1 – Static Dam Stability. This failure mode is potentially initiated by an undetected increase in uplift pressure during normal operating conditions along a (previously undetected) unbonded construction lift line near the base of the dam. Progressive increasing uplift pressures over time result in a reduction of net effective base pressures along the unbonded lift line. As uplift pressures continue to increase, initiation of sliding along the weak lift line occurs. Monolith sliding progresses, resulting in enough downstream movement to render the keyed monolith contraction joints less effective. Downstream movement progresses to the point where loss of reservoir water initiates and adjacent monoliths begin to twist and slide. Enough deflection of adjacent monoliths occurs and an uncontrolled release of the reservoir results.
- PFM 2 – Hydrologic Dam Stability. This is the same failure mechanism as PFM 1, except that the instability is triggered by an increase in reservoir loading due to an extreme flood.
- PFM 3 – Hydrologic Dam Overtopping. This failure mode is initiated by a significant hydrologic event in conjunction with debris clogging of the spillway tunnel. The potential for timber debris to clog and subsequently reduce the capacity of the spillway with a tunnel drop inlet configuration is considered a potential failure mode. As additional debris is trapped in the tunnel and hydraulic efficiency of the spillway is reduced, the reservoir water surface elevation increases to the point of overtopping the parapet wall, resulting in erosion of jointed foundation rock near the toe of the

dam. Erosion of the foundation rock progresses to the point where undercutting beneath the dam initiates and instability of the dam results. Enough monolith deflection occurs and an uncontrolled release of the reservoir results.

- PFM 4 – Hydrologic Spillway Erosion. In this failure mode, existing freeze-thaw damage of the tunnel concrete lining has created enough offsets to initiate cavitation during spillway operation. As a result, this failure mode would consist of progressive cavitation and removal of the spillway concrete tunnel lining under increasing spillway discharges. Once enough concrete has been removed, external pressure between the tunnel concrete lining and the surrounding rock could generate enough differential pressure to cause blowout of a significant portion of the tunnel lining concrete resulting in complete exposure of the surrounding rock. Increasingly turbulent flow then begins to remove surrounding rock and concrete material with progressive erosion that undermines the concrete monoliths and leads to a stability failure and uncontrolled release of the reservoir.
- PFM 5 – Seismic Dam Stability. This is the same failure mechanism as PFM 1, except that the instability is triggered by an earthquake.

**Risk Estimates**

Risks were estimated in the CR using event trees and mean estimate probabilities for each node. As is typical for a CR, best estimate probabilities were assigned to each node; uncertainty was estimated but no Monte Carlo simulations were performed. The estimated risks are tabulated in Table 9 and plotted on Figure 13.

**Table 9. Summary of Example 7 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Life Loss			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Static dam stability	1.7E-06	3.6E-06	5.6E-06	0	50	151	1.8E-04
Hydrologic dam stability	4.1E-08	8.2E-08	1.3E-07	1	10	27	8.2E-07
Hydrologic dam overtopping	4.7E-09	2.7E-08	6.5E-08	1	10	27	2.7E-07
Hydrologic spillway erosion	2.0E-07	5.7E-07	9.3E-07	1	10	27	5.7E-06
Seismic dam stability	5.0E-09	1.0E-08	2.0E-08	0	50	151	5.0E-07
<b>Subtotal</b>		<b>4.3E-06</b>					<b>1.9E-04</b>
<b>Total Annualized Failure Probability</b>	<b>4.3E-06</b>			<b>Total Annualized Life Loss</b>			<b>1.9E-04</b>

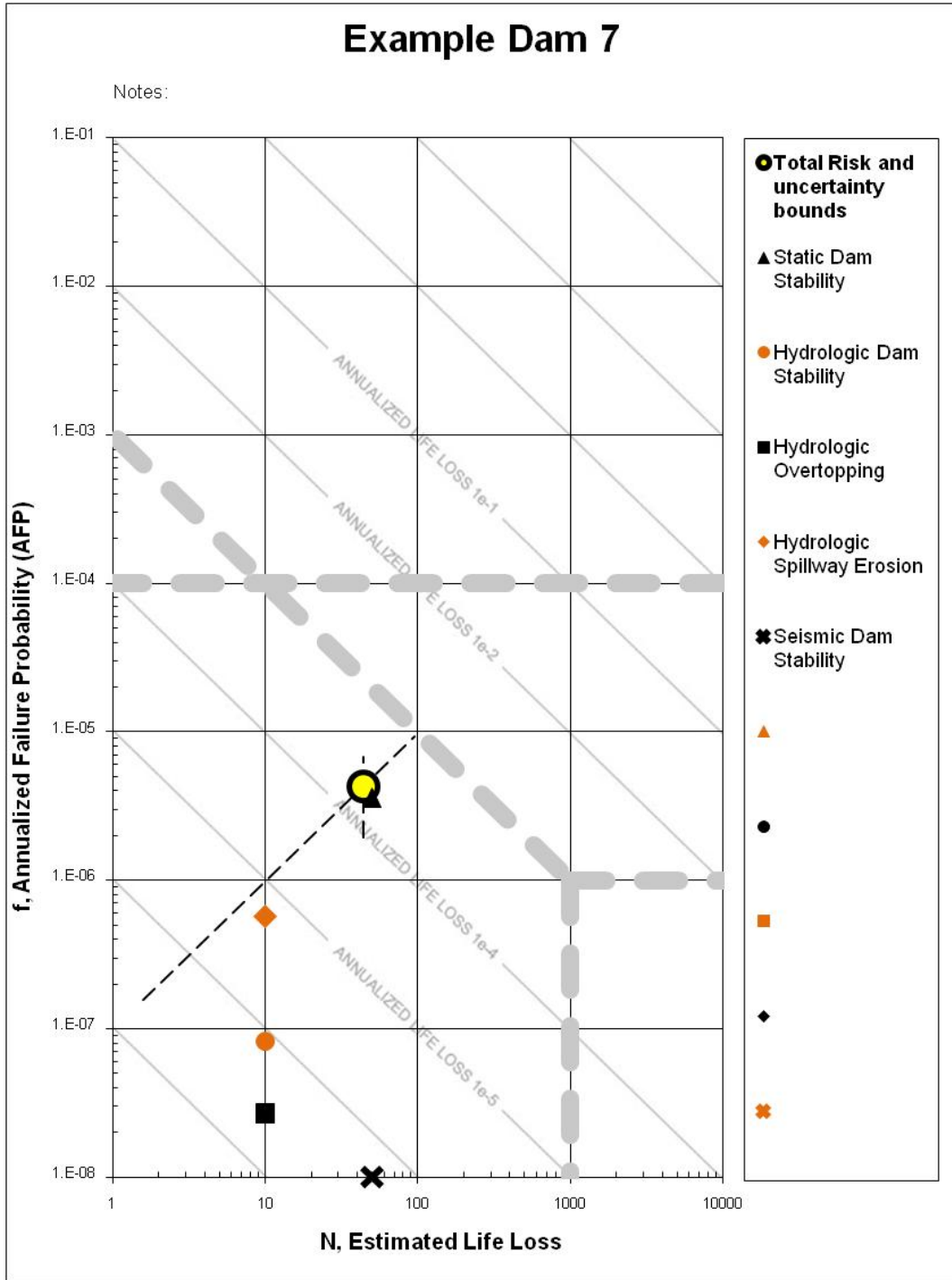


Figure 13. Risk Chart for Example 7

### Findings and Dam Safety Case

The estimated mean hydrologic and seismic annual failure probabilities for the example dam are well below the guideline values, indicating a decreasing justification for further actions to reduce risk. The key factors for this assessment include:

- The dam is a gravity dam that is in good condition with keyed contraction joints and is well keyed into the abutments and foundation rock of a narrow canyon.
- The consequences of dam failure are moderate.
- The dam does not overtop for flood events up to and including the 100,000,000-year flood event. Based on estimated maximum design log length of 50 feet and the horizontal opening length of the spillway crest of 106 feet, the debris accumulation potential along the spillway crest is low. Further, it would be very unlikely that any timber debris that passes over the crest of the spillway and gets wedged in the 30-foot-diameter spillway tunnel would be able to withstand the energy of discharge flows during a significant flood event. As a result, the assumption of a clogged spillway condition to the extent necessary to overtop the dam is highly unlikely.
- An erosion potential evaluation was completed as part of the CR in accordance with Reclamation's Best Practices [1] for dam safety risk analysis using stream-power erodibility index comparisons assuming overtopping of the dam were to occur. An estimated erodibility index range of 14 to 340 was computed for the surficial foundation rock with a mean estimate of 175. The estimated available stream power during an overtopping event is approximately 800 to 900 kW/m<sup>2</sup> for an average water jet fall onto the left abutment. As a result, the potential for initiation of surficial rock scour at the toe of the dam is high. However, the estimated erodibility index for the rock underlying the highly jointed surficial rock is likely significantly greater than that computed for the surficial rock. An erodibility index value of 10,000 was estimated for the underlying rock at the dam. This value could be as high as 35,000. As a result, the potential for significant erosion resulting in dam or foundation instability is very low.
- Erosion of the spillway tunnel concrete lining is likely to continue to be a maintenance problem and should be monitored and repaired, as necessary. Further, the likelihood of significant damage to occur to the tunnel lining during a low frequency flood event is high. Repairs will likely be costly when such an event occurs. However, the tunnel rock surrounding the tunnel lining is expected to be very erosion resistant at tunnel depth and, as a result, progressive removal of surrounding rock to the extent necessary to

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impact the dam or the foundation is expected to be very unlikely for the estimated 9 days of operation during a significant flood event.

- A previous Reclamation study concluded that there was no evidence to support the view that cavitation was the primary cause of the major damage observed in the spillway following the flood of record. A cavitation index ( $\sigma$ ) of 0.21 to 0.31 was computed in areas that sustained damage during the 1983 flood. As a result, it was concluded that the resulting damage to the spillway in 1983 was the result of freeze-thaw damage and any cavitation damage caused by freeze-thaw popouts are expected to be minor and not capable of damaging the spillway to the extent necessary to fail the dam.
- The peak horizontal ground acceleration for the 50,000-year earthquake is a modest 0.34g with stability analysis results indicating high factors of safety.

The static risk represents the highest risk to the dam due to the high probability of loading (1.0) associated with static failure modes compared to hydrologic and seismic failure modes. Although the risk of dam instability under normal operating conditions is considerably higher than under hydrologic or seismic loading, estimated risks are in the area indicating decreasing justification to take actions to reduce or better define risk. Key reasons for this finding include:

- The dam and appurtenant structures are considered well designed and constructed and have performed well since completion of construction over 50 years ago. The Technical Record of Design and Construction indicates that all dam lift lines were treated with grout prior to placement of the overlying lift suggesting that the lift lines throughout the structure should be adequately bonded.

Structural analysis results for all anticipated loading conditions based on existing static conditions and the hydrologic and seismic hazards presented herein and based on observed conditions at the dam suggest the structural integrity of the dam is adequate and requires no further evaluations at this time. Stability analysis results computed as part of the CR conservatively assume full uplift acting over the entire base of the dam and indicate high factors of safety. In addition, three-dimensional benefits associate with the site's narrow canyon and keyed contraction joints were conservatively neglected in the two-dimensional analyses. All of these factors suggest the dam has sufficient structural capacity to withstand all anticipated loading conditions.

**Safety of Dams Recommendations**

Given the relatively low estimated risks and strength of the dam safety case, there were no SOD recommendations made for this facility in this CR. However, in light of the concern that the annualized failure probability could rise in the future

if the drainage system loses effectiveness or is not maintained, the following SOD-related O&M recommendation was made:

- 20xx-2-A**      Establish a program to video inspect the foundation drains and formed drains consistent with the dam's CR cycle. Establish criteria for cleaning the drains as necessary based on the results of the video inspection and based on the performance trends of the monitoring data. Clean the drains with high pressure water jetting, as necessary, based on the inspection results. If drains are completely plugged with calcium carbonate deposits, drill the foundation drains to remove deposits at the time of cleaning. Document the drain inspection and cleaning program in the Standing Operating Procedures.

**DSPR Category**

The Dam Safety Priority Rating (DSPR) system provides a means for Reclamation to establish the urgency of risk management activities and the relative priority of these actions within our overall inventory of dams. Based on the evaluations conducted for this CR, this example facility is judged to have a DSPR 4 (Low to Moderate Priority) rating. Justifications for this category include:

- Both the annualized failure probability and the annualized life loss are in the area indicating decreasing justification for taking actions to reduce, or better define, the risk
- Given the satisfactory performance to date and analysis results, there is moderate to high confidence in the risk estimates; no further studies are deemed necessary
- However, the risks are driven by a single failure mode – dam instability during normal operations
- There is a possibility that the annualized failure probability might go up if the drainage system continues to lose effectiveness and/or is not maintained; conceivably this could raise the DSPR category
- In light of the issue, it is recommended that close attention be paid to the drain performance, and a recommendation is included to inspect and clean the system

This DSPR 4 category suggests that this facility can continue with normal operations, but that drain inspection and cleaning be considered an important periodic action required at this facility. The importance of the SOD-related O&M recommendation made during the CR for drain inspection and periodic cleaning is important to ensure that conditions do not worsen to the point that static stability

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could ultimately turn into a dam safety deficiency and a facility with a higher DSPR assignment.

A DSPR 5 category was not considered reasonable given the potential concern with a loss of drainage efficiency, as well as the point that the estimated risk associated with static stability under normal operations was not well below guideline values.

***Example 8 – DSPR 3 Dam with Borderline Risks***

In this example, a number of potential failure modes were estimated for an embankment dam as part of an Issue Evaluation. The annualized failure probability and annualized life loss both indicate increasing justification to take action to reduce dam safety risk, but both are driven by three relatively equal potential failure modes, one each from the static, hydrologic and seismic load categories. The three dominant potential failure modes by themselves indicate decreasing justification to take action.

**Description of Facility**

The dam impounds a reservoir containing 45,612 acre-feet of storage. The embankment dam has a crest length of 560 feet and crest width of 25.3 feet, at elevation 4430 equipped with an upstream parapet wall; a structural height of 135 feet; and a hydraulic height of 92 feet. The dam was constructed in 1961. Release facilities at the dam include two spillways. The North Spillway, located at the left dam abutment, consists of an inlet channel, a 50-by-50-foot Stoney gate, a relatively flat concrete-lined trapezoidal chute, and a discharge channel; there is no stilling basin. The discharge capacity of the North Spillway is approximately 50,000 ft<sup>3</sup>/s. The spillway is used to make normal operational releases from the reservoir. The South Spillway is located at the right abutment and consists of an uncontrolled ogee crest, a vertical shaft, and tunnel. The discharge capacity of the South Spillway is approximately 25,000 ft<sup>3</sup>/s.

**Dam Safety Issues and Type of Study**

This example dam was evaluated as part of an Issue Evaluation. A number of potential failure modes were evaluated but the seismic and hydrologic potential failure modes were based on detailed hydrologic and seismic hazard studies. The Issue Evaluation involved performing flood routings of frequency floods developed as part of the hydrologic study, and running water surface profiles for the North Spillway chute. The north spillway crest structure and chute walls were also evaluated for seismic loading from the updated seismic hazard study. Embankment samples were also obtained from locations along the south crest structure and chute walls of the North Spillway to evaluate filter compatibility between the Zone 1 and Zone 2 materials.

**Potential Failure Modes Evaluated**

Seven potential failure modes were estimated for the embankment dam during the Issue Evaluation. There were two static potential failure modes, three hydrologic



potential failure mode and two seismic potential failure modes. A summary of the potential failure modes is provided below.

- PFM 1 – Static Internal Erosion Along Foundation/Embankment Contact. Seepage induced internal erosion of the core materials that would be transported to a downstream unfiltered exit point at the face of the dam.
- PFM 2 – Static Internal Erosion of the Embankment along the North Spillway. This potential failure mode would occur if a flaw along the south wall already exists, high RWS elevations cause erosion to start, an unfiltered exit exists that causes a roof to form without the ability of self-healing, the upstream zone fails to limit the flows, intervention fails and ultimately the dam fails.
- PFM 3 – Hydrologic Internal Erosion of the Embankment along the North Spillway.
- PFM 4 – Hydrologic Dam Overtopping
- PFM 5 – Hydrologic – North Spillway Chute Wall Overtopping.
- PFM 6 – Seismic OT Plus Seepage Erosion Through Cracks Due to Foundation Liquefaction.
- PFM 7 – Seismic Internal Erosion of the Embankment along the North Spillway.

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**Risk Estimates**

The risk estimates are summarized in Table 10 and Figure 14.

**Table 10. Summary of Example 8 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Life Loss			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Static - Internal Erosion Along Foundation/ Embankment Contact	1.9E-06	9.1E-06	1.6E-05	8	16	45	1.5E-04
Static – Internal Erosion Along the North Spillway	3.0E-06	3.4E-05	2.0E-04	8	16	45	5.4E-04
Hydrologic – Internal Erosion Along the North Spillway	4.4E-09	1.3E-08	2.6E-08	9	12	14	1.5E-07
Hydrologic – Dam Overtopping	1.0E-05	3.4E-05	1.0E-04	9	12	14	4.0E-04
Hydrologic – North Spillway Chute Wall Overtopping	1.5E-08	2.0E-07	5.8E-07	8	12	15	2.3E-06
Seismic - OT Plus Seepage Erosion Thru Cracks Due to Foundation Liquefaction	3.1E-07	1.0E-06	1.0E-05	12	48	81	4.8E-05
Seismic – Piping Along the North Spillway	3.2E-06	2.2E-05	6.4E-05	8	16	45	3.5E-04
<b>TOTALS</b>	<b>1.8E-05</b>	<b>1.0E-04</b>	<b>3.9E-04</b>				<b>1.5E-03</b>

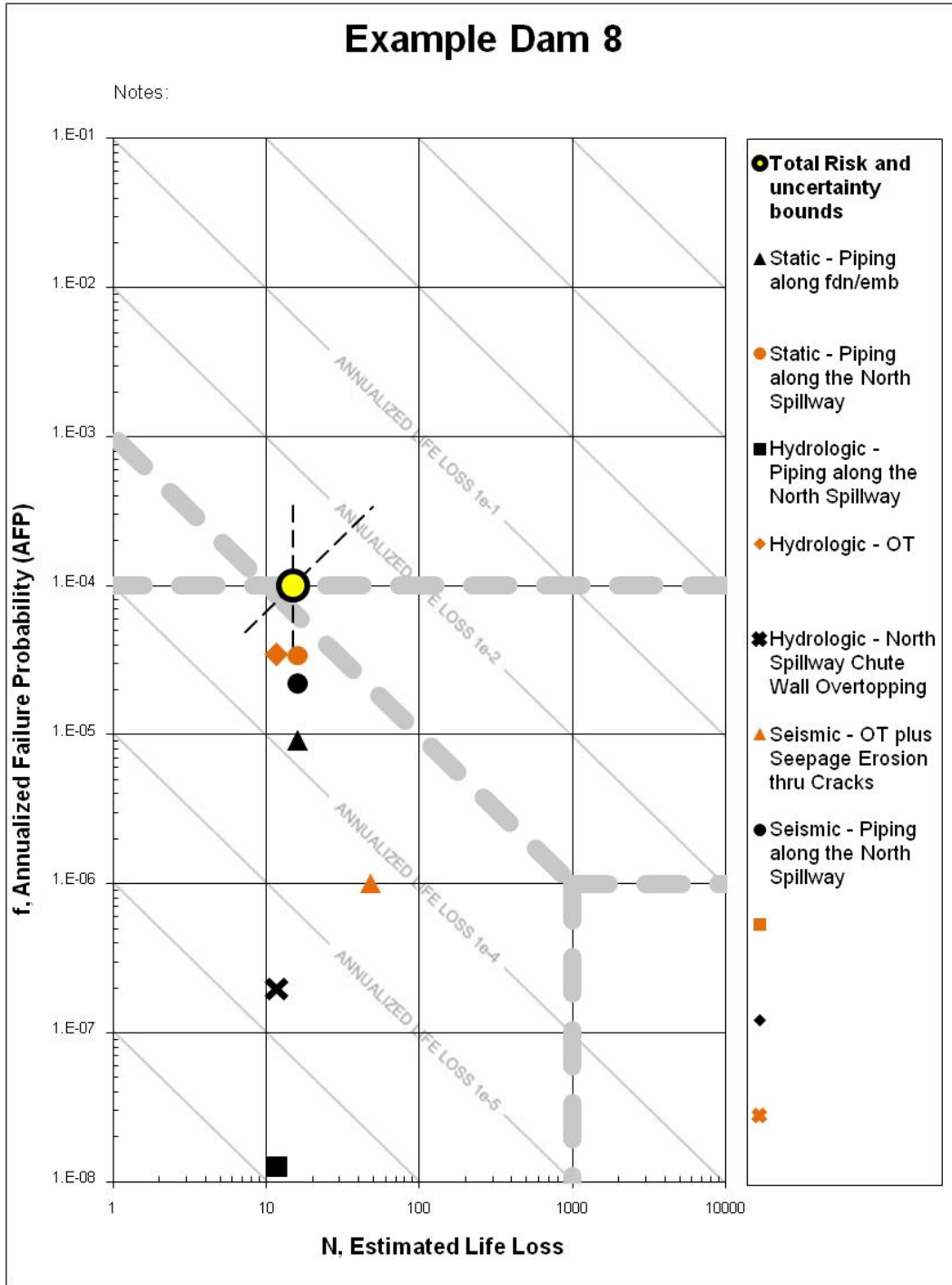


Figure 14. Risk Chart for Example 8

### Findings and Dam Safety Case

The claim is as follows: ***“Both the total annualized failure probability and the total annualized life loss indicate increasing justification to take action to reduce risk. There is no single dominant potential failure mode for this dam. The total annualized failure probability and the total annualized life loss was driven by the sum of three potential failure modes that are relatively equal in terms of estimated annual probability and of estimated consequences. The three key potential failure modes consist of a static, a hydrologic and a seismic potential failure mode and individually each would indicate decreasing justification to take action to reduce risk. Based on the level of study, the exploration program and the detailed analyses that were conducted, there is moderate to high confidence in the risk estimates and the finding is that additional action is warranted to explore actions to reduce the overall risk for this dam.”***

The potential failure mode associated with overtopping from a hydrologic event was evaluated by the Issue Evaluation risk analysis team. The threshold overtopping flood was estimated to be about a 20,000-year event). A fragility curve was developed by the team that related the depth of overtopping to a conditional failure probability for breach of the dam. The fragility curve considered the likely locations where erosion would initiate on the downstream face of the dam, the erosion resistance of the embankment materials and the duration of overtopping flows. Debris plugging of the spillways at this dam was not considered an issue, since there is an upstream dam with a substantial log boom. The resulting estimated annualized failure probability was  $3.4E-05$  and the estimated annualized life loss was  $4.0E-04$ . It is judged that the estimated risks are reasonable and there are no obvious reasons to think that the risks are significantly underestimated or overestimated.

The risk associated with static internal erosion potential failure mode along the south wall of the North Spillway was also estimated by the risk analysis team. The crest structure and chute walls of the North Spillway are vertical, so achieving good compaction against the walls would have been difficult during construction, but actual conditions along the spillway wall are unknown. Samples of the silty Zone 1 material and the downstream Zone 2 material were obtained and gradations determined for these two materials. It was concluded that the two materials are not filter compatible, thus creating the potential for movement of the erodible Zone 1 material into the Zone 2 material. The resulting estimated annualized failure probability was  $3.4E-05$  and the estimated annualized life loss was  $5.4E-04$ . There has been no significant seepage reported along at the downstream toe of the dam, adjacent to the south wall of the spillway. While there is some uncertainty regarding the actual conditions along the spillway wall, it is judged that the estimated risks are reasonable and there are no obvious reasons to think that the risks are significantly underestimated or overestimated.

The risk associated with seismic internal erosion potential failure mode along the south wall of the North Spillway was also estimated by the risk analysis team. A lot of the same considerations described above for the static internal erosion failure mode apply here. An additional consideration is possible deflections of the wall during an earthquake. A structural analysis of the wall was conducted and the results indicated that while the wall was unlikely to fail at any earthquake level, deflections of the top of the wall of up to 3-inches could occur for earthquakes exceeding the 5000-year level. This could create a seepage path that would initiate erosion of the embankment adjacent to the wall. The resulting estimated annualized failure probability was  $2.2E-05$  and the estimated annualized life loss was  $3.5E-04$ . While there is some uncertainty regarding the actual conditions along the spillway wall and the potential for a gap to form between the wall and the adjacent embankment during an earthquake, it is judged that the estimated risks are reasonable and there are no obvious reasons to think that the risks are significantly underestimated or overestimated.

### **Safety of Dams Recommendations**

The total risk is mostly generated from three potential failure modes – one involving overtopping of the embankment dam during a large flood and the other two involving internal erosion of the embankment at the interface of the embankment and the south wall of the North Spillway (under static and seismic conditions). Because of cost effectiveness considerations, a dam safety recommendation was not made to address reducing risk for the overtopping potential failure mode. A recommendation is made to address the potential failure modes related to internal erosion along the south wall of the North Spillway.

**20xx-SOD-A** Initiate a Corrective Action Alternatives Study to evaluate potential alternatives to mitigate the high risks related to potential failure modes involving internal erosion of the dam embankment along the south wall of the North Spillway.

### **DSPR Category**

For Example 8, the decision between a DSPR 3 and a DSPR 4 is difficult. The total annualized failure probability and total annualized life loss estimates both are borderline with respect to justification to take action to reduce risk. The total estimates in both cases are driven by potential failure modes from each of the three load categories. The individual annualized failure probability and annualized life loss estimates for the three key failure modes would indicate decreasing justification to take action to reduce risk. Confidence is moderate to high based on the level of the studies that were conducted. Two of the three potential failure modes are essentially the same failure mode (internal erosion of the embankment along the south wall of the North Spillway) but under different loading conditions. These potential failure modes may be relatively easy to address with a modification to the dam since the location is well defined and limited. The hydrologic overtopping potential mode would be difficult to address and would likely require a major structural modification to the dam and/or one of

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the spillways. Based on this, a recommendation is made to initiate a corrective action study to address the internal erosion potential failure modes along the south wall of the North Spillway. Given some of the above discussion, this would likely be a low priority DSPR 3 dam.

***Example 9 – DSPR 4 Very High Consequences and Low Probability of Failure (ALARP Considerations)***

**Description of Facility**

This example dam is a modern, well-designed and constructed zoned rockfill structure with a structural height of over 600 feet and a crest length of 1,600 feet. The embankment was constructed in an arc of 2,000-foot radius at the axis of the crest, convex side upstream. Dam construction occurred from the late 1960s through the 1970s. The upstream and downstream slopes of the dam are relatively steep; 1.5:1 near the crest and 2:1 for most of the slope. The dam consists of five main zones including a central inclined impervious core (zone 1), an intermediate transition zone (zone 2A) just downstream of the core, and wide upstream and downstream filter transition zones (zone 2). Rockfill shells flank the transition zones and constitute the bulk of the structure (zones 3, 4, and 5).

There are multiple outlet works facilities, including a hydroelectric powerplant. There is an unlined spillway in rock located approximately 1.5 miles from dam. The dam impounds a reservoir with a storage capacity of over 2 million acre-feet. It is located in an area of significant seismicity approximately 35 miles upstream from a major population center with a PAR over 300,000.

**Dam Safety Issues and Type of Study**

Because this dam was well-designed and constructed, there are few technical aspects of the dam that present any dam safety issues. Based on first-hand knowledge from those involved with design and construction of this dam, great care was taken throughout all phases of the project from design through foundation excavation and treatment, and embankment construction. A substantial amount of data is available from design and construction to evaluate the safety of the dam. Gradation data indicates the zone 2 filter downstream of the core does not meet current no-erosion filter criteria. The dam is operated to provide significant flood storage; however, the reservoir has never risen above the normal maximum water level and the upper 47 feet of the dam is untested. Failure of this high dam with a very large reservoir just upstream of a major population center would have disastrous results with flooding over 1600 square miles. Because of the significant PAR and the potential for very high loss of life, low estimates of probability of failure still result in high total risk values. This example demonstrates one approach that can be taken when risks are in the ALARP area of the risk chart.

This evaluation of risks was performed for a CR by a very experienced Senior Engineer. Information obtained from a concurrent Issue Evaluation study was also used by the Senior Engineer in the CR evaluations.

### **Potential Failure Modes Evaluated**

Many potential failure modes (over 20) were considered during the CR and the concurrent Issue Evaluation. All but three were ruled out because they were judged to contribute negligible risk to the total risk profile. This was largely due to the great care taken in the design and construction of the dam. The three potential failure modes that were evaluated in the CR are each related to internal erosion through the embankment:

- Static - Internal erosion of core material through the embankment
- Flood - Internal erosion of core material through transverse cracks in the upper, untested portion of the embankment
- Seismic shaking resulting in settlement and cracking, leading to internal erosion of core material through transverse cracks

### **Risk Estimates**

Internal erosion risks were estimated by the Senior Engineer using an eight node event tree, based on the standard Best Practices [1] internal erosion event tree. The risk analysis focused on two main issues; the probability that a defect exists where internal erosion could initiate, and the probability that zone 2 fails to filter either the zone 1 core or the zone 2A transition. For the static and flood conditions, the existing defect was judged to be related to transverse cracking through the core caused by settlement. For the seismic failure mode, shaking could cause settlement and cracking leading to internal erosion. Best estimate probabilities were assigned to each node; an order of magnitude uncertainty was assumed and no Monte Carlo simulations were performed. As indicated by the values in Table 11, the estimated probabilities of failure are very low – judged to be near the lower limit of what can be reasonably estimated. The large PAR results in a large potential loss of life. Overall, total risk and individual failure mode risks are in the area where ALARP considerations should be addressed, as shown on Figure 15.

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**Table 11. Summary of Example 9 Risk Estimates**

Potential Failure Mode	Annualized Failure Probability			Life Loss			Annualized Life Loss
	Low	Best	High	Low	Best	High	
Static - Internal erosion of core material (zone 1 or 2A) through the embankment	2.90E-08	2.90E-07	2.90E-06	1,000	7,000	15,000	2.0E-03
Flood - Internal erosion of core material through transverse cracks in the upper portion of the embankment	5.40E-09	5.40E-08	5.40E-07	700	1,200	1,900	6.5E-05
Seismic shaking resulting in settlement and cracking, leading to internal erosion of core material through transverse cracks	1.80E-09	1.80E-08	1.80E-07	4,500	9,500	18,000	1.7E-04
<b>Total Annualized Failure Probability</b>	<b>3.6E-07</b>			<b>Total Annualized Life Loss</b>			<b>2.3E-03</b>



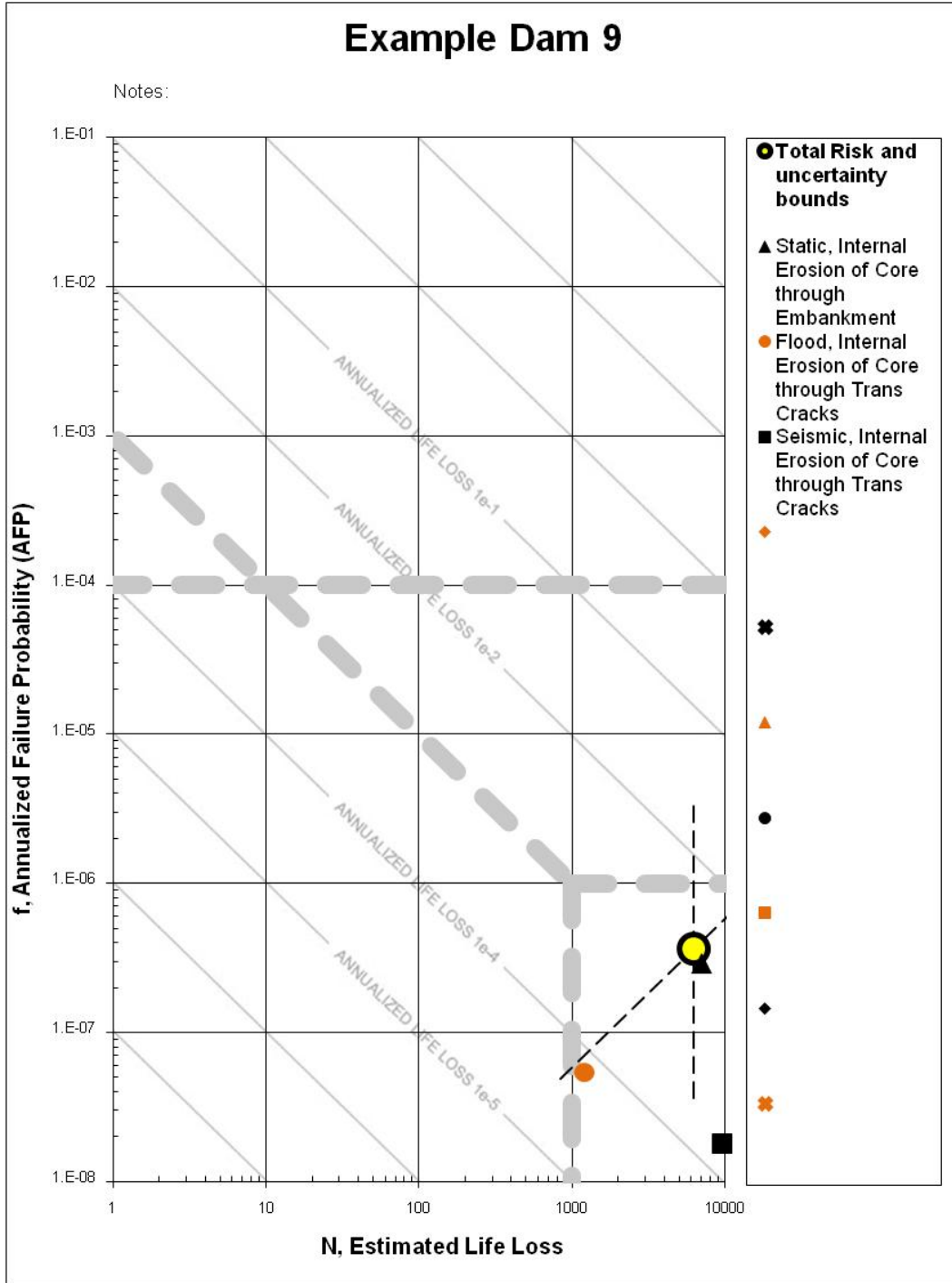


Figure 15. Risk Chart for Example 9

**Findings and Dam Safety Case**

Risks were evaluated for three potential failure modes related to internal erosion under three different loading scenarios. A detailed risk estimate was made for only one potential failure mode under static loading conditions. Most of the total risk (about 90%) is contributed by the static potential failure mode. This involves piping of the core material (zone 1 and/or zone 2A) through the zone 2 filter and out through the zone 4 rockfill shell and/or zone 3 rockfill drainage blanket. The primary factors that contributed to the low overall probability of failure for this potential failure mode are:

- The dam was well-designed and constructed. The probability of a flaw existing where internal erosion could initiate was judged to be low. The compacted core material has some plasticity and would be resistant to erosion. Although, it was recognized that the well-compacted core materials are more likely to sustain a roof and/or hold a vertical crack.
- The dam has only settled a total of about 1.5 feet, which is equal to the design camber. Considering the total height of the dam, this settlement is considered minor and significant cracking resulting from this settlement is unlikely.
- The dam has performed well with very little seepage being observed downstream.
- Dam design and construction was well-documented and the records were used extensively in the risk analysis – resulting in increased confidence in the risk estimates.
- The dam has been tested up to the normal maximum water level with no indications of cracking or unusual seepage.
- The upstream transition zone 2 might serve as a crack stopper if internal erosion did initiate.
- As part of the Issue Evaluation, a filter compatibility analysis was performed using a detailed event tree to better understand compatibility of the materials, resulting in a small probability that an unfiltered exit exists. The zone 2 filter does not meet modern “no erosion” filter criteria, and may be internally unstable (such that the finer fraction would erode through the coarser fraction, leading to poorer filter compatibility). The comprehensive records and gradation plots prepared during construction proved to be invaluable for this analysis. There is reasonable confidence that at most locations, most of the zone 2 materials will provide some degree of filtering for the core materials. However, despite all the effort during construction to prevent segregation and meet gradation requirements, there is still a remote possibility that incompatibility exists and continuing erosion could occur.

For flood conditions, a similar potential failure mode was evaluated because the dam would be in a “first filling” situation and there is some uncertainty regarding the probability of cracks or defects above the normal maximum water level. In addition to the factors considered for the static internal erosion failure mode, the very low probability of failure for this failure mode is driven largely by the very remote (>1 million year) flood event it would take to raise the reservoir to the point of inundating cracks and causing erosion. There are two benches in the foundation profile on the upper right abutment, and small cracks were observed in the crest roadway at this location. It seems fairly certain that there are some transverse cracks in the crest of the dam at this location. However, it is very unlikely they are open to any significant depth.

The seismic potential failure mode involves seismically-induced cracks extending below the reservoir due to differential settlement exacerbated by benches in the abutment profile, and subsequent seepage erosion through the cracks. Similar to the flood loading, the associated risks are very small. This is primarily due to the large freeboard (at least 47 feet and typically much more), the well compacted rockfill embankment founded on hard rock, and the very large and remote earthquake events that would be needed to drive cracks to these depths. It was estimated that there is roughly a 10 percent chance of initiating erosion through cracks for a 100,000-year earthquake.

For all three loading conditions, the PAR and estimated loss of life are significant, among the highest of any Reclamation dams. The estimated loss of life for a flood condition failure is lower than that estimated for static or seismic failures because of the additional ‘eyes on the dam’ and warning time associated with a monitoring during a hydrologic event. A seismic failure of the dam would represent the worst case loss of life scenario. A seismic event large enough to cause damage to the dam would also cause significant regional damage, making it more difficult to communicate and evacuate major population centers in the event of a dam failure, even though it might take 3 to 6 hours for a flood wave to arrive. Because of the large PAR, and uncertainty regarding the ability to safely evacuate so many people from such a large inundation area, there are significant unknowns in the loss of life estimates – but it is difficult to imagine a scenario where the loss of life could be much less than 1,000.

### **Safety of Dams Recommendations**

Since seismic and hydrologic risks appeared to present decreasing justification for reducing risks, there were no SOD recommendations for those types of issues. However, estimated static risks potentially provide a justification to better define the risks. However, the risks are primarily driven by the very high life loss associated with a failure of this high dam and extremely large reservoir. The estimated annualized failure probabilities for static failure modes are quite low. ALARP considerations suggest the dam is well designed, and appreciable improvements would not be practicable. For these reasons, the prudent risk

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management approach was judged to be continued careful attention to monitoring, surveillance, and emergency preparedness activities. Thus, one SOD recommendation and one SOD-related O&M recommendation were made to improve monitoring at the site:

- 20xx-SOD-A** Perform testing of the pneumatic and open standpipe piezometers and re-instate them to the extent possible as part of the ongoing monitoring program. If none of the piezometers can be re-instated, evaluate the need to install new piezometers in the lower portion of zone 2 to monitor water levels in this location. See the Structural Behavior section of the 2007 CFR report for additional details on which piezometers are potential candidates to be re-instated.
- 20xx-2-A** Update the Communication Directory in the Emergency Action Plan.

**DSPR Category and ALARP considerations**

The Dam Safety Priority Rating (DSPR) system provides a means for Reclamation to establish the urgency of risk management activities and the relative priority of these actions within our overall inventory of dams. Based on the evaluations conducted for this CR, this example dam is judged to have a DSPR 4 rating. In addition, the total risk is in the area where ALARP should be considered when making decisions regarding dam safety actions. Justifications supporting the DSPR category and ALARP categorization include:

- The estimated probabilities of failure are very low primarily due to the well-designed and constructed embankment.
- Consequences of a dam failure would be disastrous with significant loss of life and flooding over 1600 square miles.
- Total annualized life loss is high because of the potential for significant loss of life.
- Because the consequences of failure would be catastrophic, and very little could be done to mitigate the risks from a structural standpoint, careful risk management of potential failure modes is essential.

ALARP considerations apply when the AFP is less than  $10^{-6}$  and the estimated loss of life is greater than 1,000. For this example dam, the following factors were considered in the ALARP evaluation:

- The total annualized life loss is  $2.3 \times 10^{-3}$ , which is above the guideline value where there is usually increasing justification to reduce or better understand risks. The AFP and estimated loss of life for each failure mode are in the area where ALARP should be considered.

- Although no alternatives have been studied, it seems likely that risk reduction measures at this dam that involve modifying the dam would be extraordinarily costly because it is a high, zoned rockfill dam. Any modification to reduce risk would need to include construction of a “no erosion” filter zone downstream of the core zone, which would involve substantial excavation and re-construction of the entire downstream portion of the dam. Project benefits would be lost for several years during construction. Furthermore, it is possible that cracking could be introduced in the dam over time due to differential settlements between the original section and the modified downstream section. Because of the already low probabilities of failure, the amount of risk reduction achieved would likely be small (i.e. less than a magnitude of order) and the cost would be disproportionately excessive.
  
- Risk reduction measures that involve modifying the dam would not be cost effective to the overall dam safety program because the same funding could be used to significantly reduce risk on many other structures. To quantitatively evaluate cost effectiveness, very rough Risk Reduction Index (RRI) and Relative Risk Reduction Index (RRRI) values were estimated. High RRI and RRRI values indicate effective risk reduction measures, but it is important to note that values are relative within the portfolio. The estimated RRI and RRRI values for this example dam are about a magnitude of order lower than average RRI and RRRI values for a typical Reclamation dam modification, and are much lower than RRI and RRRI values for several recent Reclamation dam modifications. Therefore, it appears that the estimated risks are as-low-as-reasonably-practical and it is difficult to justify taking any action to reduce risk.

A DSPR 3 rating could be considered if there was less confidence in the risk estimates that would justify taking action to better understand risks. However, many aspects of the design and construction are well-documented and there is reasonable confidence in the factors considered in the probability of failure estimates. The primary uncertainty is whether a crack exists low enough in the dam that could lead to initiation of internal erosion. Because of the large PAR, there is also uncertainty regarding the ability to safely evacuate so many people from such a large inundation area. Despite this uncertainty, the potential loss of life would be significant (in the high hundreds, or thousands) even in the best case scenarios. Therefore, a detailed inundation and loss of life study is not likely to change the total risk picture or the need to consider ALARP. It is interesting to note that if the consequences were lower (i.e. much less than 1000), an argument for a DSPR 5 (Low Priority) rating could be made. There are probably DSPR 5 rated dams that were not designed and constructed as well as this dam. However, because of the significant consequences, the *Dam Safety Public Protection Guidelines* suggest this dam would not be rated better than a DSPR 4. This seems appropriate because with so many lives at risk, it might not be in the best interest of the public to rate this dam as Low Priority.

# Using Risks and Costs to Evaluate ALARP

## Definition of ALARP

The “as-low-as-reasonably-practicable” (ALARP) considerations provide a way to address efficiency aspects in both individual and societal risk guidelines. ALARP only has meaning in evaluating the justification for, or comparison of, risk reduction measures: it cannot be applied to an existing risk without considering the options to reduce that risk.

Determining that ALARP is satisfied is ultimately a matter of judgment. In making a judgment on whether risks are ALARP, the following factors should be taken into account (adapted from New South Wales Dam Safety Committee, 2006, [2]):

- The level of risk in relation to the risk guidelines;
- The disproportion between the sacrifice (money, time, trouble and effort) in implementing the risk reduction measures and the subsequent risk reduction achieved;
- The cost-effectiveness of the risk reduction measures;
- Any relevant recognized good practice; and
- Societal concerns as revealed by consultation with the community and other stakeholders.

ALARP considerations apply when societal risks are estimated in the range where the Annualized Failure Probability is less than  $10^{-6}$  and the estimated loss of life is greater than 1,000. They can also apply to other situations. For example, it may be possible to reduce risk to just below the guidelines for a given cost, but to get it comfortably below the guidelines (e.g. an order of magnitude) could require a substantial increase in cost. ALARP considerations could be used to decide whether that extra cost is justified.

## Calculating Risks and Costs to Evaluate ALARP

Making the case that risks are ALARP indicates that cost effective measures have been considered and further efforts to reduce risks are unreasonable. Although not the sole measure of ALARP, the most common method to determine ALARP is cost effectiveness. Technical teams present alternatives to decision-makers, who are charged with determining the appropriate balance of

costs and risks. Two indices are suggested for use in evaluating ALARP. Risk is defined as annualized life loss below.

***Risk Reduction Index (RRI)***

RRI is a relative measure of the effectiveness of risk reduction measures. It is the difference in annualized life loss between the before and after condition divided by the cost.

$$\text{RRI} = [\text{Risk}_{\text{before}} - \text{Risk}_{\text{after}}] * 1,000 / \text{Cost (M\$)}$$

***Relative Risk Reduction Index (RRRI)***

RRRI is another relative measure of the effectiveness of risk reduction measures. It is the quotient of annualized life loss between the before and after condition divided by the cost.

$$\text{RRRI} = [\text{Risk}_{\text{before}} / \text{Risk}_{\text{after}}] / \text{Cost (M\$)}$$

**Evaluating ALARP**

Higher RRI and RRRI values indicate more effective risk reduction measures. Values calculated for a specific project can be used to compare to RRI and RRRI for projects where previous modifications have been implemented to get a sense as to whether an inordinate amount of funds would need to be expended for the level of risk reduction that would be achieved.

It should be noted that evaluating ALARP considerations in the very low failure probability/very high consequences region may require a more qualitative approach. That's because estimating failure probabilities to the very low values in this region is difficult and uncertain. Teams must develop alternatives for discussion. Close coordination between the technical staff and decision-makers is required to establish whether ALARP considerations are satisfied.





## References

- [1] “Dam Safety Risk Analysis Best Practices Training Manual,” Bureau of Reclamation, Denver, Colorado (see Dam Safety Office internet page for latest version).
- [2] “New South Wales Government Dams Safety Committee 2006, Risk Management Policy Framework for Dam Safety,” New South Wales, Australia, August 22, 2006.

