CHAPTER A-4 SEMI-QUANTITATIVE RISK ANALYSIS

A-4.1 Key Concepts

While Potential Failure Mode Analysis (PFMA) is the process for identifying potential failure modes, Semi-Quantitative Risk Analysis (SQRA) is a process to evaluate their significance from a risk perspective. SQRA is a risk categorization system that assigns likelihood and consequence categories to potential failure modes based on existing data and available consequence estimates. Situations appropriate for SQRA include:

- Situations where it is desired to apply risk analysis principles to decision making without the time, cost, and data/analysis requirements associated with a full-blown quantitative risk analysis.
- Portfolio assessments where it is desired to get a quick evaluation of the risks so that risk-reduction studies and actions can be prioritized.
- As a high-level screening to determine which potential failure modes should be carried forward for quantitative analysis, which require additional actions to reduce uncertainty, and which require focus of regular inspections and monitoring activities in the interim.

SQRA utilizes a risk matrix approach to assess individual potential failure modes as well as the total risk for a project. The SQRA method described in this chapter provides a relevant risk categorization system that is a useful and quick means to prioritize dam and levee safety activities, especially to determine if higher level studies would be beneficial for specific potential failure modes.

A-4.2 Likelihood of Failure

One component or measure of risk is the annual probability of failure (APF). The likelihood of failure is an estimate of the APF based on the strength and weight of the evidence. Failure or breach is characterized by the sudden, rapid, and uncontrolled release of impounded water (FEMA 2004) with the potential for life loss and flood damages due to breach.

The following sections briefly describe the hydrologic (flood) and seismic (earthquake) hazards analysis needed to perform the SQRA and two approaches that can be used to assign failure likelihood categories depending on the circumstances of the risk assessment. In the first approach, a comparative analysis is performed in which a relative comparison is made to an anchoring APF. The second approach involves a more explicit estimation of the APF considering the critical loading to initiate a breach. Both are described in the following sections.

A-4.2.1 Hydrologic Hazards

Hydrologic hazard curves take the form of flood-frequency curves in which annual exceedance probability (AEP) is evaluated as a function of water level or flood inflows. Flow relationships may be used for some scour-related potential failure modes like dam spillway erosion or riverine erosion of a levee embankment. Curves should extend to the overtopping flood event likely to initiate breach. Seismic potential failure modes are a function of both the earthquake and the water level at the time of the earthquake. Since the water level associated with a reservoir or river can vary throughout the year, the probability of the coincident water level at the time of the earthquake can be assessed from a stage-duration relationship. See Chapter B-1 for more information on assessing hydrologic hazards.

A-4.2.2 Seismic Hazards

An estimate of the seismic hazard at a site is typically needed to assess the probability of earthquakes that are likely to lead to failure. A detailed probabilistic seismic hazard analysis (PSHA) is used if available for a site. If such a study is not available, screening-level curves such as those available from the USGS Earthquake Hazards Program website can be used (USGS 2018). Curves should extend to 1/10,000 to 1/50,000 AEP, with the more remote values needed for higher consequence projects. Curves representing horizontal peak ground acceleration (PGA) are typically considered. For some concrete and steel structures, curves corresponding to the spectral acceleration (SA) at the natural period of the structure may be more useful. See Chapter B-2 for more information on assessing seismic hazards.

Levee and canal embankments, or foundations of dams, levees and canals comprised of saturated loose cohesionless materials are particularly susceptible to liquefaction and significant damage during earthquakes but may not result in uncontrolled release of impounded water because of the low probability of an earthquake occurring during periods of high water. In addition, repairs, setback levee construction, or evacuation of the potential inundation area are likely to occur prior to a subsequent flood. For these reasons, earthquake loadings are not normally considered for intermittently loaded levees and canals. However, for levees and canals that are frequently loaded, earthquake loadings may need to be considered. For dams, the coincident probability of high pool levels and seismic loading may be low enough alone to rule out seismic potential failure modes as non-risk drivers.

A-4.2.3 Comparative Analysis Approach

Examination of historical dam failure rates indicates that dams have failed at a rate of approximately 1 in 10,000 per dam year of operation (for both concrete and embankment dams), depending on the failure mode and age of the structure: Douglas et al. (1998), Foster et al. (1998), Hatem (1985), Von Thun (1985), and Whitman (1984). In a comparative analysis, the failure likelihood is assessed relative to the historical failure rate. For example, if the key factors affecting the potential failure mode are weighted toward adverse (more likely), the annual failure likelihood is probably greater than 1/10,000. If weighted toward favorable (less likely), then the annual failure likelihood is probably less than 1/10,000. This approach requires less rigor and may be appropriate for potential failure modes where the likelihood of the loading is high (e.g., during normal operating conditions for dams) or hydrologic potential failure modes where a certain flood is very likely to cause failure, as well as making rapid assessments with appropriately facilitated teams. However, it is difficult to assess potential failure modes where there is not a well-defined flood trigger or threshold to initiate and progress to breach. The failure likelihood categories and descriptions in Table A-4-1 can be used for this approach for dams only. These descriptions have been associated with an order-of-magnitude range of APF.

For levees, the annual frequency of overtopping can form the basis for evaluating failure likelihood for prior-to-overtopping potential failure modes. For example, if the overtopping frequency is estimated at 1/200 AEP and a breach prior to overtopping is less likely to occur than overtopping, the annual failure likelihood of the potential failure mode can be assessed as one or more orders of magnitude less likely than overtopping depending upon the strength of the evidence. For overtopping with breach, the frequency for the depth at which breach is likely to occur can be used.

Since the failure likelihood categories and descriptions in Table A-4-1 are anchored to a historical failure rate for dams, they are not appropriate for canals and levees. However, the ranges of APF can still be used to categorize the failure likelihood, but more frequent order-of-magnitude ranges of APF will likely need to be considered. Historical failure rates for canals, and overtopping frequency for levees can help guide selection of an appropriate range.

Table A-4-1 Failure Likelihood Categories for Dams

Failure Likelihood Category	Annual Probability of Failure	Description
Remote	more remote (less frequent) than 1/1,000,000	Several events must occur concurrently or in series to cause failure, and most, if not all, have negligible likelihood such that the failure likelihood is negligible.
Low	between 1/100,000 and 1/1,000,000	The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to initiation.
Moderate	between 1/100,000 and 1/10,000	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward “less likely” than “more likely.”
High	between 1/10,000 and 1/1,000	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward “more likely” than “less likely.”
Very High	more frequent (greater) than 1/1,000	There is direct evidence or substantial indirect evidence to suggest it has initiated or is likely to occur in near future.

A-4.2.4 Critical Loading Approach

The likelihood of failure is a function of both the likelihood of the loading condition that could lead to failure and the likelihood of failure given the loading condition. For normal operating conditions, the likelihood of the loading is high. However, for floods or earthquakes, the likelihood of the loading could be small. Therefore, the failure likelihood estimate can be improved by considering the likelihood of the loading. This requires identifying the critical loading level for the potential failure mode under consideration. For seismic potential failure modes, the probability of the earthquake and the coincident water level must be considered. For larger hydrologic events, tailwater can significantly affect the critical loading level. For example, the maximum high pool for a dam may result in a lower differential hydraulic head for initiation of a potential failure mode, and breach at that reservoir level may result in lower life loss due to warning and evacuation for uncontrolled spillway releases prior to breach. In this case, a reservoir level at the top of active storage (i.e., the level of the uncontrolled spillway crest or near the top of the spillway gates for gated spillways) may be more critical for differential hydraulic head and result in higher life loss. If the AEP of the flood for the critical loading level (from a flood-frequency relationship) is very likely to cause failure, then the APF is essentially equal to the AEP of that flood. Therefore, the assessment of failure likelihood should start with the probability of the critical loading level and then be reduced based on the likelihood of the step-by-step events that progress to failure or breach to obtain an order-of-magnitude estimate of the APF. With this approach a more precise estimate of the range of APF can be made than the comparative analysis. However, estimating the critical loading level can be difficult, especially when the performance is not well understood for the full range of loading and there is not a well-defined trigger or threshold to initiate and progress to breach.

A-4.2.5 Intervention

The potential for intervention to reduce the likelihood of failure must be considered for all potential failure modes. For seismic potential failure modes, it is also important to discuss whether there is a plan to inspect the structure following an earthquake and conduct post-earthquake repairs prior to a subsequent flood. In some cases it may be appropriate to consider likelihood of failure for both with and without intervention scenarios to understand the potential benefits of intervention while at the same time not masking the potential seriousness of a dam or levee safety issue by relying solely intervention to reduce the estimated risk.

A-4.3 Consequences

The other component of risk is the magnitude of consequences should failure or breach occur. Breach consequences of dams, levees, and canals can take many forms including life loss, property damage and other economic losses, environmental damage, and socio-economic impacts (see Chapter C-3). For safety risk assessments, the focus is on the potential for life loss, considering that the broader socio-economic, environmental, and property damages are generally commensurate. However, significant hazard potential projects do not have life safety risk by definition (FEMA 2004), and some projects may require an assessment of economic risk in addition to life safety risk.

Two approaches can be used to assign consequence categories depending on the circumstances of the risk assessment. In the first approach, descriptions are used and associated with order-of-magnitude ranges. This approach may be appropriate where little to no consequence information is available. The consequence categories and descriptions in Table A-4-2 can be used. If no significant impacts to the population at risk other than temporary minor, non-life-threatening flooding of roads or lands adjacent to the river, then no consequence category should be assigned. In this case, the rationale should be documented, but those potential failure modes would be considered non-risk drivers since there is no life safety risk. The ranges of economic loss shown in the table are not intended to be equated to the life loss ranges to obtain a value for human life. They are strictly for use as a categorization tool when life loss is small or negligible, and economic damages need to be considered from a risk perspective.

The second approach uses available consequence information to estimate the order-of-magnitude range of average consequences for the critical loading for the potential failure mode under consideration. For both approaches, the consequences being estimated are "incremental" (i.e., due to dam or levee breach over and above those that occur with operations as expected) which is the difference between breach and non-breach consequences.

Table A-4-2 Consequence Categories

Level	Life Loss	Economic Loss
1	Average life loss is less than 1. Although life-threatening flooding occurs, direct loss of life is unlikely due to severity or location of the flooding or effective warning and evacuation.	Average economic loss is less than $10 million. Limited property and/or environmental damage is likely.
2	Average life loss is in the range of 1 to 10. Some direct loss of life is likely, related primarily to difficulties in warning and evacuating small population centers.	Average economic loss is in the range of $10 million to $100 million. Moderate property and/or environmental damage is likely.
3	Average life loss is in the range of 10 to 100. Large direct loss of life is likely, related primarily to difficulties in warning and evacuating small population centers or difficulties evacuating large population centers with significant warning time.	Average economic loss is in the range of $100 million to $1 billion. Significant property and/or environmental damage is likely.
4	Average life loss is in the range of 100 to 1,000. Extensive direct loss of life can be expected due to limited warning for large population centers and/or limited evacuation routes.	Average economic loss is in the range of $1 billion to $10 billion. Extensive property and/or environmental damage is likely.
5	Average life loss is greater than 1,000. Extremely high direct loss of life can be expected due to limited warning for very large population centers and/or limited evacuation routes.	Average economic loss is greater than $10 billion. Extremely high property and/or environmental damage is likely.

A-4.4 Confidence

An essential part of SQRA is to document the confidence in the estimate to inform the potential need to take action or to reduce uncertainty. The confidence categories and descriptions in Table A-4-3 can be applied to both the failure likelihood and the consequences categories in this approach. The confidence and its potential impacts on the decision to take action to reduce risk or reduce sources of uncertainty are assessed. Lack of information is not low confidence in the decision. High uncertainty combined with low impact on the decision could result in a moderate or high confidence category because reducing the uncertainty will not change the decision. It is possible that a potential change in failure likelihood or consequences by itself could change the decision, or a potential change in both may be needed to change the decision. In the latter case, an overall confidence ranking would be appropriate and justified by the team in the documentation.

Table A-4-3 Confidence Categories for Failure Likelihood and Consequence

Confidence	Description
High	The team is confident in the risk characterization, and it is unlikely that additional information would change the order of magnitude of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty would change.
Moderate	The team is relatively confident in the risk characterization, but key additional information might possibly change the order of magnitude of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty may change.
Low	The team is not confident in the risk characterization, and it is entirely possible that additional information would change the order of magnitude of the assigned category to the point where the decision to take (or not take) action to reduce risk or reduce uncertainty could change.

A potential failure mode with low confidence, particularly if risk-reduction actions are indicated, would probably require additional investigations or analyses before taking risk-reduction action. However, if that potential failure mode has high confidence, it may be appropriate to go directly to interim risk-reduction actions or in some cases long-term risk reduction actions. When assigning confidence categories, the rationale must be documented, and the information that could be gathered to improve the estimate should be captured in the documentation, typically as a recommendation. It may be possible that even with low confidence, there may not be any additional information that could be collected to improve the confidence. In such cases, the rationale should be documented.

A-4.5 Portraying Risks

A risk matrix can be used to portray the likelihood of failure and consequences due to breach associated with the identified risk-driver (significant) potential failure modes. The general concept is illustrated in Figure A-4-1, where dam or levee risk increases as the plotting position moves up and to the right.

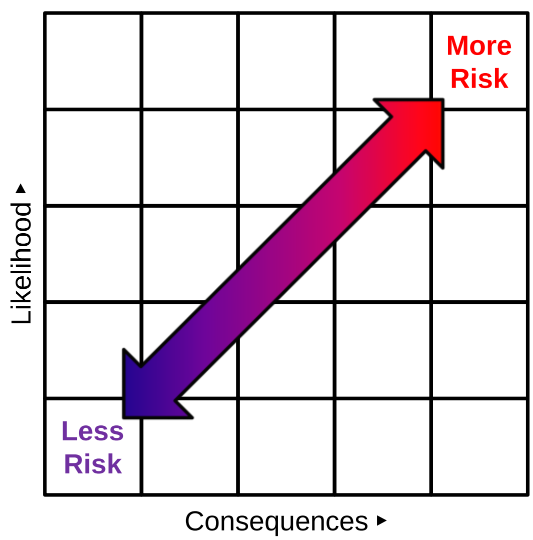

Figure A-4-1 General Risk Matrix Approach

A risk matrix using the general categories for failure likelihood and consequences described in the previous sections is shown in Figure A-4-2, with likelihood of failure on the vertical axis (using cell divisions corresponding to the failure likelihood categories) and the associated consequences due to breach on the horizontal axis (using cell divisions corresponding to the consequences categories). Cells of the risk matrix correspond to order-of-magnitude divisions on the f-N diagram (see Chapter A-9), and potential failure modes are plotted as boxes of the same size as the grid to represent order-of-magnitude estimates made by the team. Borderline estimate can be made (i.e., portrayed to the nearest half order of magnitude) provided the size of the box remains the same size as the grid.

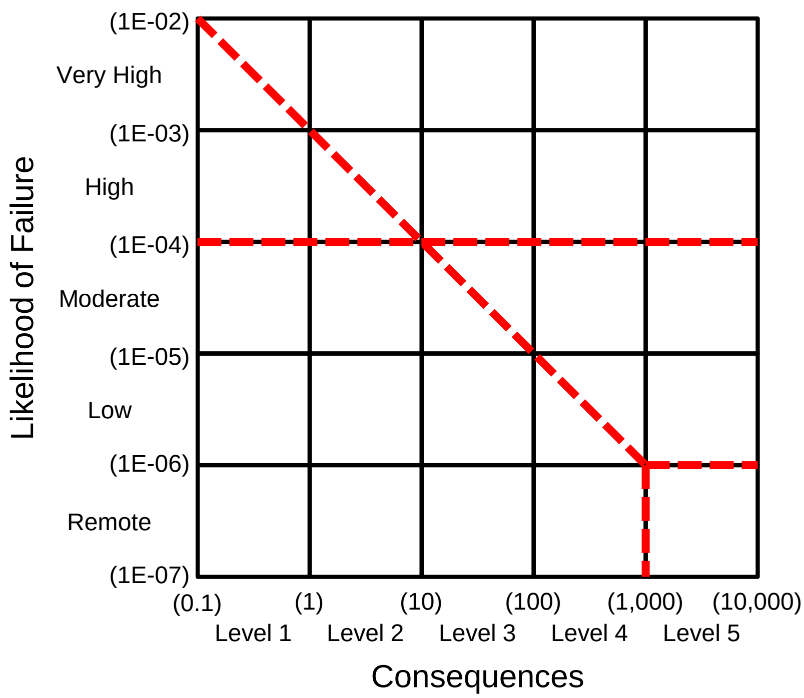

Figure A-4-2 Dam or Levee (Incremental) Risk Matrix

Societal life safety risk guidelines are represented in Figure A-4-2 by the diagonal dashed red line. The APF guideline for dams or individual risk guideline for dams and levees (assuming that the most exposed individual is exposed all of the time) is represented by the horizontal dashed red line. The dashed red line box at the lower right corner of the risk matrices corresponds to low probability-high consequence potential failure modes. Risk management is carefully considered for potential failure modes that plot in this region with APF less than 1/1,000,000 (i.e., remote failure likelihood) and estimated incremental life loss greater than 1,000 (Level 5). See Chapter

A-9 for additional information on governance and guidelines. There are usually no risk guidelines for economic risk. Therefore, dashed lines representing guidelines should not be displayed on risk matrices if portraying economic risk.

Although several potential failure modes may be identified by the team, only potential failure modes judged to be potential risk-drivers are fully evaluated (assigning failure likelihood and consequence categories) and plotted on the risk matrices. The potential failure modes that were excluded from further consideration (i.e., not plotted) because they were deemed non-credible or credible but non-risk-drivers (e.g., fundamental flaw does not exist, remote probability of occurrence, etc.) are documented along with the team's rationale, assumptions, and understanding so that a different team can review this information during the next scheduled periodic review, or sooner if an incident occurs, and understand what the original team was thinking and whether there are changed conditions, improved knowledge, or improved state of practice that would affect the risk assessment.

A-4.6 Estimating Risks

The results of the potential failure mode analysis (see Chapter A-3) can be used to place each potential failure mode in the appropriate failure likelihood and consequence category (i.e., risk category). This requires a clear and complete description of the potential failure modes and an evaluation of the adverse factors that make each potential failure mode "more likely" to occur as well as the favorable factors that make it "less likely" to occur. The rationale and key factors affecting the assigned failure likelihood category are documented. Similarly, the potential consequences due to breach are evaluated and assigned to the appropriate category, and the rationale for the assignment is documented. The confidence categories and rationale are assigned, and then each potential failure mode is plotted in the appropriate cell of the risk matrix. The risk is evaluated against the tolerable risk guidelines (see Chapter A-9), and the risk from all risk-driver potential failure modes should be added. Judgment is required to assign a total risk. In most cases, one or two potential failure modes will plot an order of magnitude above the rest, and they will control the total risk.

Advanced preparation is essential for a successful SQRA. Before conducting the PFMA, the multi-disciplined team must:

- Review all available background and performance data (including design, construction, geology, instrumentation, and other relevant information).
- Review available hydrologic hazard information.
- Review available seismic hazard information.
- Review available breach and non-breach inundation studies for various flood scenarios and their potential impacts downstream of dams and within the leveed area.

Then, the following steps are typically taken for each identified potential failure mode:

- Document the pertinent background and performance data.
- Fully describe the potential failure mode from initiation, through step-by-step development, to failure or breach (see Chapter A-3) so that the team has a common understanding of what is being estimated. It is also important to understand what the breach (uncontrolled release of impounded water) entails, as this has a direct bearing on the consequences.
- Develop the factors making the potential failure mode more likely and less likely to occur, including analysis results and associated load probabilities where applicable, and identify the key factors.
- Ask each team member to make their individual estimate of the likelihood of failure prior to further discussion, considering whether the evidence is weighted more toward more likely or less likely (or the loading likely to result in breach), and then discuss the results.
- Elicit failure likelihood from each team member, along with the reasoning behind their estimate. This typically encourages discussion among the team members. After the discussion has subsided, the facilitator summarizes what has been discussed, proposing a "consensus" failure likelihood (and the rationale for why it makes sense) and then asking if there are any objections. If objections are raised, additional discussion ensues, and the process is repeated. If a consensus cannot be reached, the range is captured along with the rationale for each estimate.
- Document the information for the estimated likelihood of failure and rationale, along with the confidence in the estimate and any additional information that could be gathered to improve the confidence, if applicable.

- Conduct a similar elicitation process for consequences. It is especially important to discuss differences between the likely breach flows associated with a potential failure mode and what was assumed in any breach inundation studies because the modeled breach parameters and outflow in the studies, and hence consequences, may not be appropriate for the potential failure mode under consideration.
- Plot the likelihood of failure and consequences for the potential failure mode on the risk matrix. It can be useful to list it on a Post-It Note and place it on a large blank risk matrix posted on the wall. Different colors can help distinguish different structures.

O'Leary (2018) provides additional details on the methodology to calculate and portray the total risk posed by a dam or levee beyond the basic risk matrix concepts discussed in this chapter, as well as the risk posed by an overtopping potential failure mode and the non-breach risk.

A-4.7 Non-Breach Risk

Dams and levees use a consistent approach for estimating non-breach risk. The AEP when the public would begin to experience flooding due to levee overtopping or dam spillway release and the AEP when life loss would start to occur are important to communicate flood risk to the public. For levees, the AEP for flooding is typically when the levee begins to overtop. For dams, the AEP for flooding is typically related to spillway releases. However, the annual probability of when life loss would start to occur depends on the specific situation but is typically less than the AEP for flooding. Failure to consider these larger, less frequent flood events results in an underestimation of the non-breach risk (O'Leary 2018). The likelihood of life loss or AEP when life loss begins to occur is plotted on the vertical axis of the non-breach risk matrix. For non-breach risks, the same consequence categories in Table A-4-2 can be used. Consequences associated with planned operational releases drive the non-breach consequence category for dams, whereas the consequences associated with an overtopping flood event without breach drive the non-breach consequence category for levees. In some cases, other sources of interior flooding of the leveed area may need to be considered in addition to overtopping flooding. Figure A-4-3 is an example of non-breach risk matrices where the vertical axis represents order-of-magnitude ranges of annual probability of life loss or economic loss due to non-breach flooding.

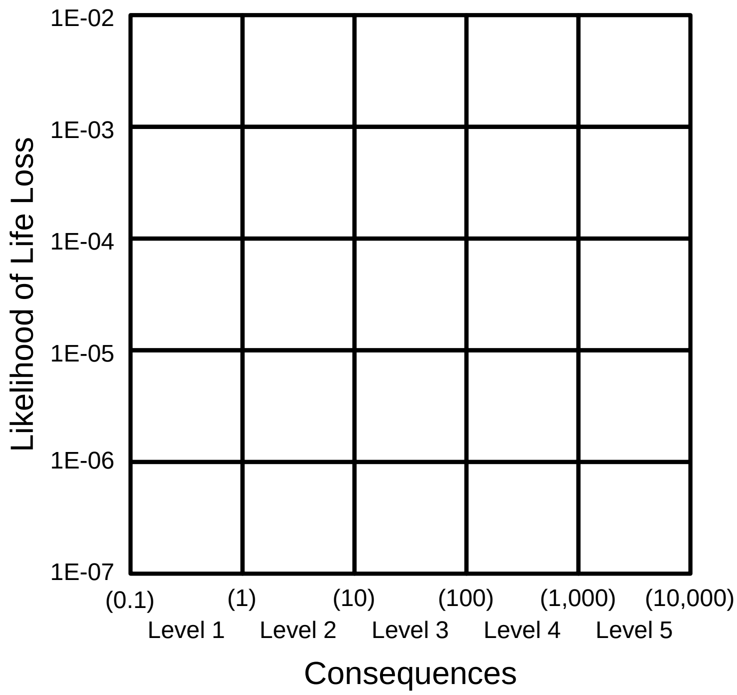

Figure A-4-3 Non-Breach Risk Matrix

A-4.8 Example

This example consists of a composite dam with a central gated spillway and embankment wing dams. The dam is approximately 6,400 feet long and 70 feet in height as shown in Figure A-4-4. The earth section of the dam is a homogeneous, compacted low permeability fill with an internal drainage system consisting of an inclined sand chimney and horizontal sand drain located downstream of the center line. The central concrete gravity structure consists of embankment wrap-around sections on each side and a central gated spillway with four gate bays. Flow is regulated by four Tainter gates, each 38 feet wide and 39.4 feet high.

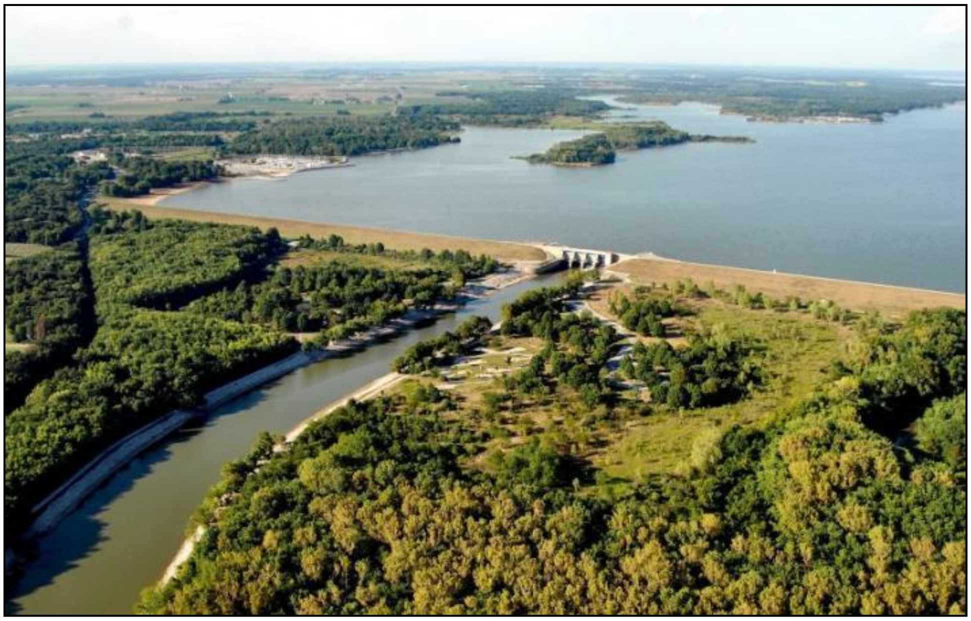

Figure A-4-4 Example Dam

The embankment's foundation consists of clays (CL and CH) overlying bedrock. This material is overlain by sands and silts, and in some areas a surficial layer of clay. Bedrock at the site consists of limestone and hard indurated shale. Joints in the limestone have been widened due to solutioning. The cutoff trench for the embankment was excavated to bedrock, which is shale in the lower sections and limestone on the abutments. The gravity and spillway sections are founded on shale. The excavation for the spillway section dips upstream at an angle of about 6 degrees. Piezometers indicate low pressures under the concrete structures.

The embankment materials consist of mostly lean clay (CL) with some high plasticity clays (CH) and a lesser amount of silt (ML). The embankment slopes are 3H:1V downstream and 4H:1V upstream.

Six towns that could be affected by a breach of the dam are located along the river downstream of the dam. One begins immediately downstream of the dam, and the last is about 80 miles downstream. Breach inundation mapping shows only the outskirts of the towns nearest the river would be flooded by breach inundation flows, with a population at risk of approximately 250.

An initial screening-level evaluation conducted 3 years prior to the SQRA suggested the potential failure modes of most concern involved the potential for arm buckling of the Tainter gates during flood operations (due to trunnion friction), internal erosion through the foundation or abutments, and embankment erosion due to wave overtopping during large floods since freeboard requirements are not met for the Probable Maximum Flood (PMF).

An evaluation of the potential for Tainter gate arm buckling due to moments induced by trunnion friction during flood operations resulted in a Moderate failure likelihood category. The bushings have become misaligned requiring redrilling and tapping for greasing, and original analyses show combined (axial and bending) stress ratios approaching unity for normal water loading and "cable load." However, the project maintenance staff has kept the trunnions greased. This factor tipped the evaluation to the "less likely" side. The confidence was rated as Low since the gates have not been analyzed with trunnion friction using modern methods and the long-term effectiveness of the trunnion greasing is uncertain. Since this potential failure mode is likely to result in the loss of only one gate, with mangled debris remaining in the opening to throttle flow, it is likely this uncontrolled release of the reservoir would not exceed the downstream the channel capacity (i.e., would remain within the banks). If there were any fishermen downstream, they could be caught by surprise and subjected to life-threatening flows, but it is likely they could get out of the way since the distance to safety is likely to be short. Therefore, a Level 1 consequence category was assigned with a High confidence rating.

Solutioned joints exist downstream of the cutoff trench, and a potential failure mode related to internal erosion of the foundation and embankment soils along these features could not be ruled out. There is no evidence to suggest it has occurred or is likely to occur. The cavity filling material was removed, and the voids backfilled with concrete at the cutoff trench contact, as shown in Figures A-4-5 and A-4-6. The cavities tightened with depth and the material in the cavities was found to be clay that required some effort to remove. The embankment soils have some plasticity and are not highly erodible. Therefore, the key evidence was weighted fairly heavily toward unlikely. However, since there are limited exposures and instruments (piezometers) with which to observe potential development of the failure mode and it was recognized there are considerable uncertainties with the geologic conditions downstream of the cutoff trench, a borderline failure likelihood category of Low to Moderate was assigned. Although the evidence was fairly compelling for the failure likelihood category, additional information about foundation pore pressures and geology downstream of the trench might show unexpected conditions in these areas. Therefore, a Moderate confidence level was assigned.

Figure A-4-5 Typical Limestone Foundation Joints

Figure A-4-6 Rock Foundation in Cutoff Trench after Dental Concrete Treatment

It is expected a breach under this failure scenario would take some time to develop due to the plasticity of the soils such that detection and evacuation would be likely. There is also a river gage at a downstream highway that may show increasing flows above the expected spillway discharge and trigger action. Only a small part of nearby communities would be inundated along with a few low lying farm houses. Some fatalities would be expected (i.e., less than 10). Since there isn't much difference between maximum spillway releases and dam breach inundation boundaries according to the inundation maps, it is doubtful additional information would reduce the uncertainty or change the consequence category. Therefore, a Level 2 consequence category was assigned with High confidence.

Using a reservoir stage-frequency relationship based on data from 1975 to present and available flood routings, the confidence limits for a pool reaching the crest of the embankments ranges from an AEP of 1/10,000 to much less than 1/100,000. Although freeboard requirements were not met for the PMF, an average AEP of less than 1/100,000 prior to overtopping led to a Low to

Remote failure likelihood category, since breach under minor overtopping would not be a certainty due to the plasticity of the embankment soils. The uncertainty associated with estimating frequencies based on a short period of record is not low. Therefore, the confidence rating was Moderate. Failure of the dam during an extreme event would potentially only harm those individuals not evacuated from a normal spillway release. The incremental population at risk (after evacuations for maximum spillway releases) would be about 60 individuals with a potential incremental life loss of 1 to 2 people. Therefore, a Level 2 consequences category was assigned. There is uncertainty as to where the dam would breach and how quickly the breach would develop. Additional information may change the uncertainty or consequence rating or it may not. Therefore, a Moderate confidence level was assigned.

The most critical potential failure mode identified relates to internal erosion through an area where closure was made in the embankment between Phase 1 and Phase 3 construction contracts, which was not identified by the initial evaluation. The embankment was constructed considerably differently between these two sections. The portion to the right of the closure section does not contain a chimney drain, has a thinner blanket drain (18 inches compared to 36 inches to the left), has a narrower cutoff trench bottom width (15 feet compared to 25 feet to the left), and the cutoff trench is offset further upstream. The left end of the Phase 1 embankment was exposed for up to 5 years before closure was made. There is no evidence to suggest special treatment or construction methods were or were not used at the embankment closure section. In addition, the trace of the interface is still slightly visible on aerial photography, as shown in Figure A-4-7, and some wet areas were observed on the downstream face in this area. There is more potential for a problematic defect near the top of the dam due in part due to the fact the embankment gets narrower and the stresses that would tend to close up a defect are lower. Therefore, the estimated failure likelihood category was considered High under normal high pool levels. A Low confidence level was assigned mainly since there is no compelling evidence to suggest the wet areas are the result of seepage through the interface between the Phase 1 and Phase 3 embankments. Key additional information could very well change the assigned category. A Level 2 consequence category was assigned with High confidence since some minor life loss might be expected due to a slug of unexpected water inundating portions of the downstream communities.

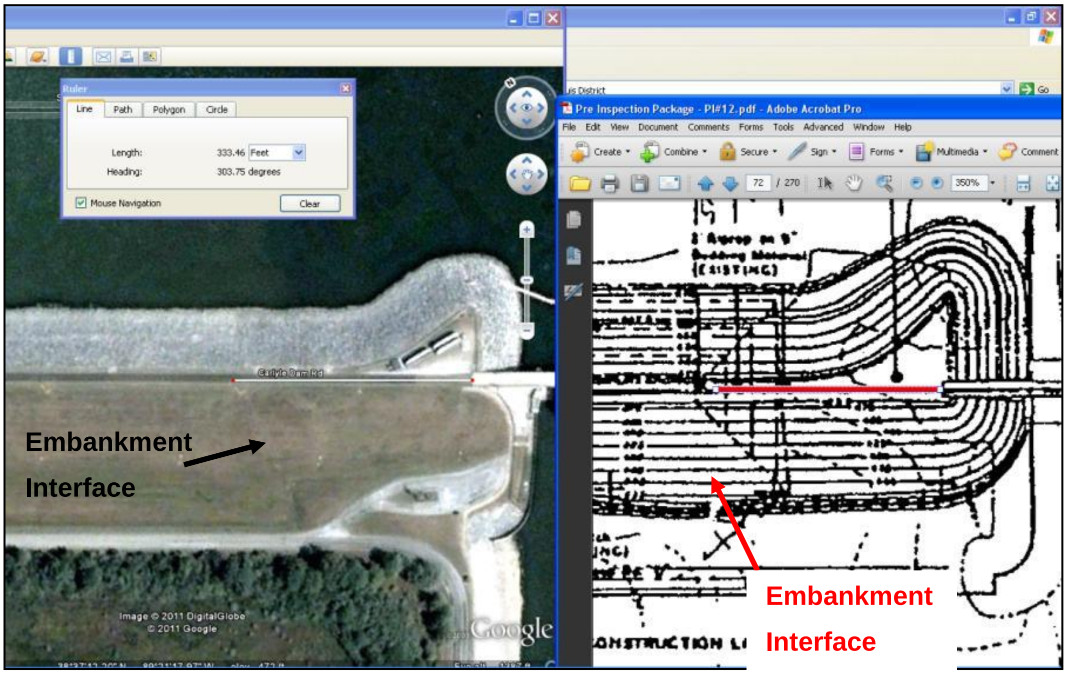

Figure A-4-7 Area of Phase 1 and Phase 3 Embankment Interface

Other potential failure modes were evaluated in a similar manner. The risk matrix shown in Figure A-4-8 only portrays the potential failure modes thought to control the incremental risk prior to the semi-quantitative evaluation (in green) as well as the potential failure mode that actually seems to control the incremental risk after this evaluation (in orange). As a result of this exercise, additional monitoring and exploration is planned for the embankment interface area, stemming from the high estimated incremental risk but low confidence in that assessment. In addition, due to the Low confidence rating on the Tainter gate evaluation, additional analyses of the gates are planned to verify the failure likelihood categories.

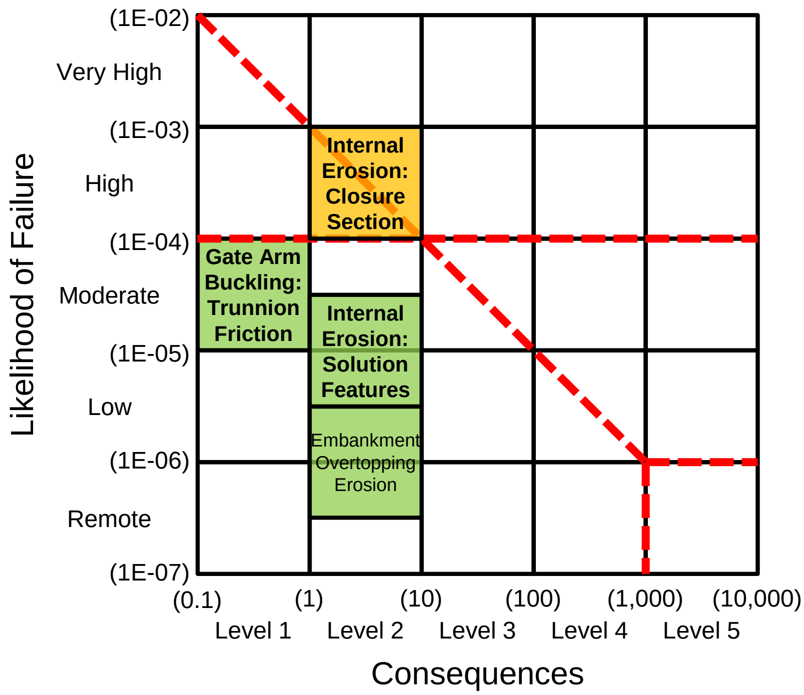

Figure A-4-8 Risk Matrix Solution for Example

A-4.9 Exercise

Take one of the potential failure modes developed for Evans Creek Dam or Cobb Creek Levee in an earlier exercise (see Chapter A-3) and place it into the appropriate risk category in the risk matrix shown in Figure A-4-1 or Figure A-4-2. Justify your result.

A-4.10 References

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