A RISK-BASED RE-EVALUATION OF RESERVOIR OPERATING RESTRICTIONS TO REDUCE THE RISK OF FAILURE FROM EARTHQUAKE AND PIPING

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Abstract: In 2005 the Sacramento District of the US Army Corps of Engineers implemented an operating restriction to reduce the risk of an earthquake-induced failure of Success Dam, which could cause significant life loss and property damage. This paper describes an update of the 2004 risk-based evaluation of operating restrictions for Lake Success, which incorporated new information obtained by the District and enabled a re-evaluation of the level of the operating restriction and provided a basis for a possible modification of the restriction.

Keywords: Earthquake Failure Modes, Flood Failure Modes, Operating Restrictions, Piping Failure Modes, Risk Assessment, Tolerable Risk Guidelines

INTRODUCTION

Risk Assessment Objective

In 2005 the Sacramento District of the U.S. Army Corps of Engineers (USACE) implemented an operating restriction with a maximum target reservoir pool elevation of 620 feet (188.98 m) to reduce the risk of an Earthquake-induced failure of Success Dam that could cause significant life loss and property damage. The purpose of this study was "*to update the 2004 Risk-Based Evaluation of Operating Restrictions for Lake Success*" to incorporate new information obtained by the District. In addition, the scope of the failure modes that were considered in the 2004 Study (Bowles et al 2005) was expanded to include all "*significant and credible potential failure modes*" identified for Success Dam.

Project Description

Lake Success has been operated by the Sacramento District since completion of construction in 1961. The project comprises the dam, the Frazier Dike and a reservoir located on the Tule River about six miles (10 km) east of Porterville and 45 miles (72 km) north of Bakersfield, California (Figure 1). The reservoir captures runoff from a 391 square mile (1 013 km^2) mountainous watershed. It is part of a system of reservoirs that provide flood protection to the Tulare Lakebed and adjacent areas. It also provides irrigation water storage and recreation benefits.

Success Dam is a compacted earthfill embankment dam 145 feet (44.2 m) high, 3,404 feet (1 038 m) long and with a crest elevation of 691.5 feet (210.77 m) as shown on Figures 2 and 3. The dam has a central core of sandy clay and clay, and a pervious shell. The shell material is protected by a 12-foot (3.7 m) thick transition zone[1], which partially meets modern filter criteria between the core and the transition material and between the transition material and the pervious shell. However there is evidence from construction photographs that in the cutoff trench in the left abutment the transition material has "tapered out" and is not available to protect the core from the migration of fines into the terrace deposits. Modern filter criteria are not met between the core and the terrace deposit and this represents a flaw that could lead to a piping failure. There is a cutoff trench under the core that extends through the recent alluvium to either bedrock or in some cases to an older alluvium stratum. The recent alluvium was not excavated in the area beneath the pervious shell. Shear wave velocity measurements and standard penetration tests in the recent alluvium and the upstream and downstream embankment shoulders indicate that these materials are loose and could be subject to liquefaction during an earthquake.

There is a 12-foot diameter outlet works conduit founded on bedrock under the right side of the dam at the location shown on Figure 2. The outlet works is founded on bedrock. It has an upstream bulkhead gate as well as the gates at the location of the control tower. A free overflow spillway is located in the right abutment with a crest at the full pool elevation of 652.5 feet (198.88 m).

Frazier Dike is a containment dike located at the north end of Lake Success. The toe of the dike is at approximately the full pool level and the crest elevation of 691.5 feet (210.77 m) is the same as the

[1] Commonly referred to as a "filter zone."

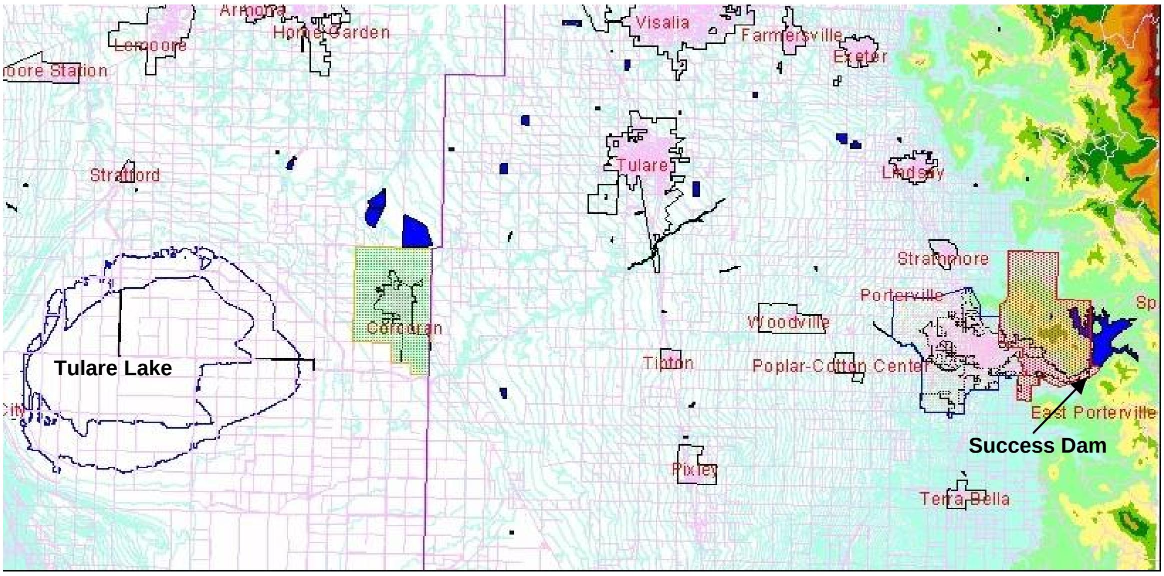

Figure 1. Map of Downstream Area

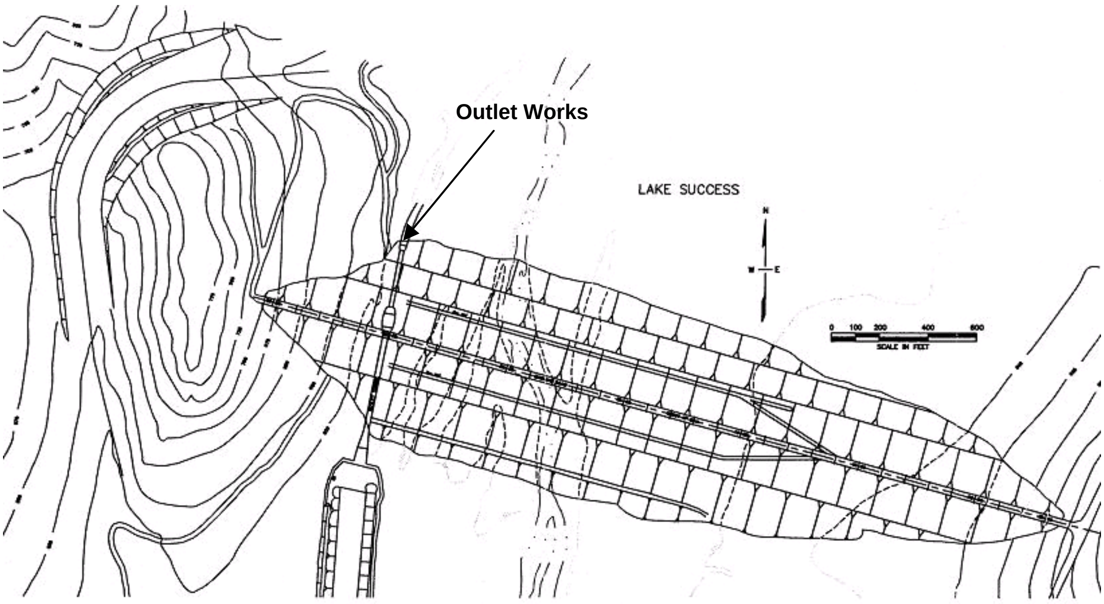

Figure 2. Plan View of Success Dam (Provided by the Sacramento District)

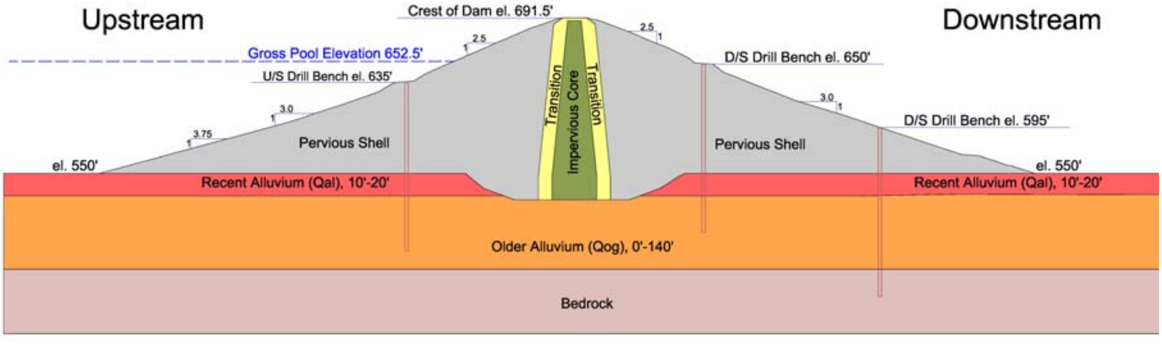

Figure 3. Typical Cross Section for Success Dam (Provided by the Sacramento District)

Main Dam. It is a compacted homogeneous embankment without slope protection except for a thick grass cover.

Concern about earthquake induced liquefaction in the recent alluvium foundation leading to significant crest settlement and horizontal movements for the Main Dam lead to the District's decision in 2004 to commission a risk assessment to explore the justification for an operating restriction until a permanent structural solution is completed (Bowles et al 2005).

POTENTIAL OPERATING RESTRICTIONS

The authorized (No Restriction) Flood Control Diagram (FCD) for Lake Success sets a maximum target pool elevation of 652.5 feet (198.88 m) in the summer. An operating restriction would reduce that maximum target pool elevation as shown in Figure 4. This would reduce the durations of high pool elevations and hence the probability and consequences for failure modes other than those associated with major floods. Five potential operating restrictions (ORs) were considered in the risk assessment and are referred to by a code, which includes their reduced maximum target pool elevation in feet, as follows: OR.640, OR.630, OR.620, OR.600 and OR.580.

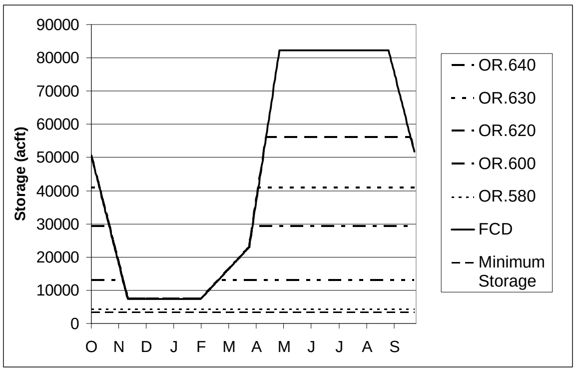

Figure 4. Original Flood Control Diagram and Potential Operating Restrictions

In the 2004 Study a daily reservoir simulation for the 44-year period of record was used to estimate modified stage-duration relationships for each potential operating restriction (Figure 4). The costs of the potential operating restrictions were based on their estimated economic impacts. The effects on seasonal patterns of reservoir releases and pool elevations were simulated and provided to water user's representatives to estimate the two types of economic impacts of the potential operating restrictions that are listed below:

- Agricultural losses associated with reductions in irrigation water (Table 1).
- Increased flood damages in an historic terminal lake, Tulare Lake (Figure 1), which is a highly productive agricultural area in Kings County (Table 2).

Net recreational losses, allowing for shifts to other lakes in the region, were estimated to be US$2.1 m for OR.630 and OR.640, and US$2.8 m for OR.580, OR.600 and OR.620, respectively.

RISK ASSESSMENT APPROACH

Earthquake Failure Modes

Three types of Earthquake liquefaction-induced failure modes were considered: a) vertical crest deformation and failure by above-core erosion (ACE) of the dam if the concomitant reservoir pool elevation is high enough; b) seepage erosion through cracks (SEC) resulting from disrupted filters and drains and transverse cracking induced by deformation; and c) embankment and tower deformation resulting in failure by piping into a rupture in the control tower - outlet works system, referred to as a tower-induced piping (TIP) failure. The ACE failure could lead to initiation of a breach of the dam immediately after the earthquake or, like the SEC and TIP failure modes, it could be delayed for some time after the earthquake in which case warning times can be longer than for an immediate ACE failure.

Vertical embankment deformation greater than one foot could damage the control tower resulting in a loss of the capability to operate the outlet works gates, and hence, a loss of reservoir control. Vertical embankment deformation greater than three feet (0.91 m) would be expected to damage the control tower beyond the point where regaining outlet works gates operation is feasible. The District estimates that it, if feasible, would take about three weeks to regain operation of the outlet gates, or to implement a controlled breach of the dam, if needed, in the event that the control tower damage is too great to regain outlet works operation capability. During this period the reservoir pool could rise. Therefore, the ACE, SEC and TIP liquefaction-induced failure modes were also considered to have the potential to occur in a delayed manner during a three-week period following the earthquake.

The Earthquake event tree in Figure 5 is slightly simplified from the full form that is used in the DAMRAE software. DAMRAE is software that has been developed at Utah State University for USACE as the risk analysis engine for their dam safety risk management program (Srivastava et al 2008 and 2009a).

The Earthquake event tree was applied separately to each of three Earthquake magnitudes to represent Earthquake loading over a range of peak ground accelerations (PGAs) and their associated annual exceedance probabilities (AEPs) for each magnitude range, as follows:

a) From 0.1 g to 0.65 g for the less than M 6.5.
b) From 0.1 g to 0.3 g for the M 6.5 - M 7.0.
c) From 0.05 g to 0.25 g for the greater than M 7.0.

Table 1. Estimated Economic Losses to Downstream Agricultural Interests (2004 US$)

Potential Operating Restriction	Representative Water Year					Average Annual Economic Losses ($/year)
	Very Dry	Dry	Below Average	Average	Wet	
	1976	1964	1985	1996	1980	
OR 640	$0	$0	$0	$940,660	$1,065,050	$401,142
OR 630	$0	$0	$635,810	$2,014,530	$2,152,920	$960,652
OR 620	$0	$0	$1,420,440	$2,836,050	$2,952,250	$1,441,748
OR 600	$878,220	$1,038,240	$2,590,700	$3,940,300	$3,797,220	$2,448,936

Table 2. Estimated Additional Flood Damages to Agricultural Lands in Tulare Lakebed (2004 US$)

Potential Operating Restriction	Representative Water Year					Average Annual Additional Flood Damages ($/year)
	Very Dry	Dry	Below Average	Average	Wet	
	1976	1964	1985	1996	1980	
OR 640	$0	$0	$0	$0	$3,100,000	$620,000
OR 630	$0	$0	$0	$0	$3,100,000	$620,000
OR 620	$0	$0	$0	$0	$3,200,000	$640,000
OR 600	$0	$0	$0	$0	$7,500,000	$1,500,000

The Earthquake magnitude range is specified in branch Level 1 in the event tree as labeled in Figure 5. The "fan-shaped" symbol in Level 2 of the event tree represents a continuous event branch group[2] comprising a set of 21 branches that cover each range of PGAs listed above, and their AEPs for the Earthquake magnitude specified in Level 1 based on the PGA versus AEP relationships derived from URS (2004) and shown in Figure 5a.

Level 3 in the Earthquake event tree is a continuous branch to represent the range of pool elevations at the time that an earthquake occurs and the fraction of time that each interval of pool elevations occurs. This type of loading is represented by the stage-duration relationships for each potential operating restriction that were obtained using the daily reservoir simulation. For the No Restriction alternative, the historical stage-duration relationship was used (see Figure 5b). For the risk model runs that considered potential operating restrictions, stage-duration relationships were estimated using a daily reservoir simulation model in the 2004 Study. Twenty-four, four-foot intervals of reservoir stage or pool elevation were considered between mid-point elevations of 567 feet (172.82 m) and 659 feet (200.86 m).

Level 4 is a state function branch in which vertical embankment deformation is interpolated from relationships (see Figure 5c) developed by the District using results from FLAC model runs for a range of Earthquake magnitudes, PGAs and reservoir pool elevations using the values of these three loading variables specified in Levels 1, 2 and 3, respectively. These are considered to be most likely (mode) estimates of the vertical deformation and uncertainty bounds were judgmentally estimated to calculate the conditional probability of Earthquake-induced above-core erosional failure (Level 5) based on the vertical deformation being sufficient for the top of the embankment core to fall below the pool elevation (Level 3) at the time of the earthquake as illustrated by the shaded area in the triangular probability distribution in Figure 5d and entered in the failure branch in Level 5 of the event tree.

Level 6 of the event tree is a failure branch that represents the occurrence of a SEC failure, a tower-induced piping (TIP) failure, or no failure. The system response probabilities (SRPs) for these failure modes are shown in Figure 5e and are conditioned on embankment vertical deformation (Level 4) and pool elevation (Level 3). They were estimated by expert judgment. These two failure modes are not mutually exclusive. They are classified as common-cause failure modes because they can occur simultaneously as the result of a "common cause"; that is, the earthquake-induced deformation of the embankment and the tower. To properly estimate the overall probability of failure and associated consequences, a common cause adjustment (Bowles et al 2001) was applied to the SRPs for these three failure modes in Level 6 using DeMorgan's rule (Ang and Tang 1984) based on an assumption that their occurrence is statistically independent.

The two branches in the upper part of Level 7 of the Earthquake event tree represent the events that the outlet works remains functional after the earthquake (the upper branch) or that it becomes non-functional (the lower branch) given that the dam has not failed immediately or soon after the earthquake. The latter outcome includes the possibility that reservoir control is recoverable for vertical embankment deformations less than three feet (0.91 m), or that it is not recoverable for larger deformations. The SRP for the outlet works becoming non-functional is estimated to be dependent on embankment vertical deformation

[2] The structure of the event tree diagram to the right of this continuous branch should be visualized as being repeated for all intervals of PGA or separate branches represented by the continuous branch. These branches are omitted from the event tree diagram to avoid a large and dense tree diagram that can be difficult to interpret. However, the entire event tree structure is computed in the DAMRAE software.

(Level 4) as presented in Figure 5i.

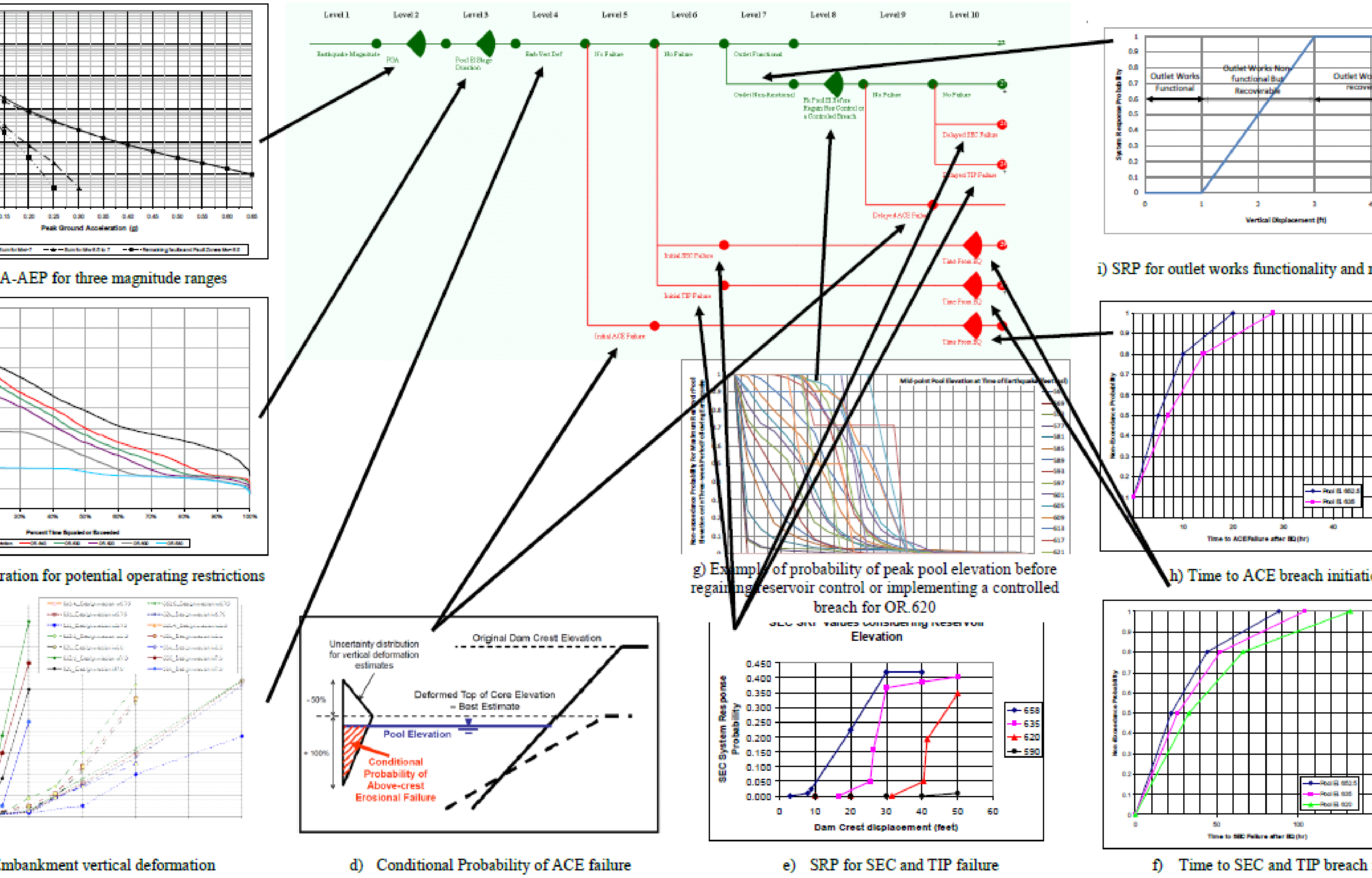

Figure 5. Earthquake Event Tree for Success Dam with Earthquake Loading, SRP and Other Relationships

The continuous event branch in Level 8 of the event tree covers a range of four-foot reservoir pool elevation intervals that the reservoir can attain during a three-week period following the earthquake as a result of the loss of reservoir control. Twenty-three four-foot intervals of reservoir stage or pool elevation were considered between Elevations 587 feet (178.92 m) and 671 feet (204.52 m), plus an open interval at Elevation 585 feet (178.31 m) and below. Each interval of reservoir pool elevation has an estimated probability of occurring based on the reservoir pool elevation at the time of the earthquake (Level 3). This relationship is represented as a probability transition matrix for each potential operating restriction alternative as illustrated graphically in Figure 5g for OR.620. These relationships were estimated using the daily reservoir simulation under the assumption of loss of reservoir control resulting in the outlet gate being jammed in its current position for a three-week period starting on any day of the period of record.

Levels 9 and 10 of the Earthquake event tree represent the delayed manifestations of the same initial failure modes that are represented in Levels 5 and 6, respectively, as initial failure modes. When considered as initial failure modes, their SRPs depend on the average of the pool elevation interval specified in Level 3. For the delayed failure case, their SRPs depend on the average of the pool elevation interval specified in Level 8. For the delayed failure modes, the SRPs applied in Levels 9 and 10 are calculated as the increase in the SRPs due to any rise in pool elevation between the time of the earthquake (Level 3) and three weeks later (Level 8). In the case that the reservoir pool remains at the same elevation or decreases, a value of zero is assigned to the SRPs.

The three continuous event branches in the three lowest failure branches of Level 10 of the Earthquake event tree represent the time from occurrence of the earthquake until an ACE, SEC or TIP breach initiates, which is defined as the start of the breach process in the dam break-inundation modeling. This branching was needed for calculation of warning times that are an important predictor of life loss. The estimated probability of various times to breach initiation conditioned on pool elevation (Level 3) are presented in Figure 5h for the ACE failure mode and in Figure 5f for the SEC and TIP failure modes.

No Earthquake failure modes were considered for Frazier Dike. Although the dike may be damaged in a major earthquake, little is known about its likely seismic performance, and the dike only retains water when the pool is above the current full pool level. The performance of the Frazier Dike under earthquake loading should be included in a Dam Safety Modification Study risk analysis.

Flood and Flood-internal Failure Modes

Flood failure modes (i.e. overtopping and wave erosion for the Main Dam and overtopping for Frazier Dike[3]) and Flood-internal failure modes (i.e. piping and slope instability for the Main Dam) were included in the event tree shown in Figure 6. The following six piping failure modes were considered: a) piping into terrace deposits in the left abutment; b) piping into rock in the right abutment; c) piping through the rock foundation; d) piping through the embankment; e) piping through the foundation in the old alluvium; and f) embankment piping along the outlet works.

Level 1 in the Flood event tree shown in Figure 6 is a continuous event branch representing 500 intervals of peak reservoir pool elevation and their corresponding annual probabilities of occurrence, obtained from the peak reservoir pool elevation - AEP relationships in Figure 6a for each potential operating restriction alternative. The high frequency part of these relationship were developed using results from the daily reservoir simulation for each potential operating restriction. Peak reservoir pool elevations considered in the event tree ranged from a failure threshold event with an AEP of about 1 in 1.2 up to events that exceed the AEP of 1 in 10,000 assigned to the PMF by two orders of magnitude of AEP consistent with new USACE guidance. The threshold event corresponds to an annual peak pool elevation of about 620 feet (188.98 m) for the No Restriction alternative and about 581 feet (177.09 m) for OR.580 (see Figure 6a).

Level 2 is a state function branch in which the peak overtopping depth is calculated by subtracting the dam crest elevation from the peak reservoir pool elevation (Level 1).

Level 3 is a failure mode branch that represents the ten Flood and Flood-internal failure modes. The conditional probability of occurrence of each failure mode is represented by their respective SRPs, which are conditioned on peak reservoir pool elevation (Level 1) or peak reservoir overtopping depth (Level 2). A common-cause adjustment was applied to all ten SRPs with "freezing" to fix the contributions to total probability of failure and failure consequences at the pool elevation where one SRP first becomes 1.0 (Srivastava et al 2009b). The SRPs for each of the piping failure modes (see Figure 6d) were estimated using guidance from the USACE Piping and Seepage

[3] Although failure of either the Frazier dike or the Main Dam would reduce the loading on the surviving structure, it was agreed with the District that the dike would not be considered in this risk analysis except for a Flood-induced overtopping failure mode. However, excluding piping-seepage and instability failure modes for Frazier Dike increases the estimated probability of failure for the Main Dam under Flood loading while decreasing the total estimated probability of failure for the Main Dam and Frazier Dike under Flood loading. It is recommended that all significant failure modes for Frazier Dike be included in a Dam Safety Modification Study risk assessment.

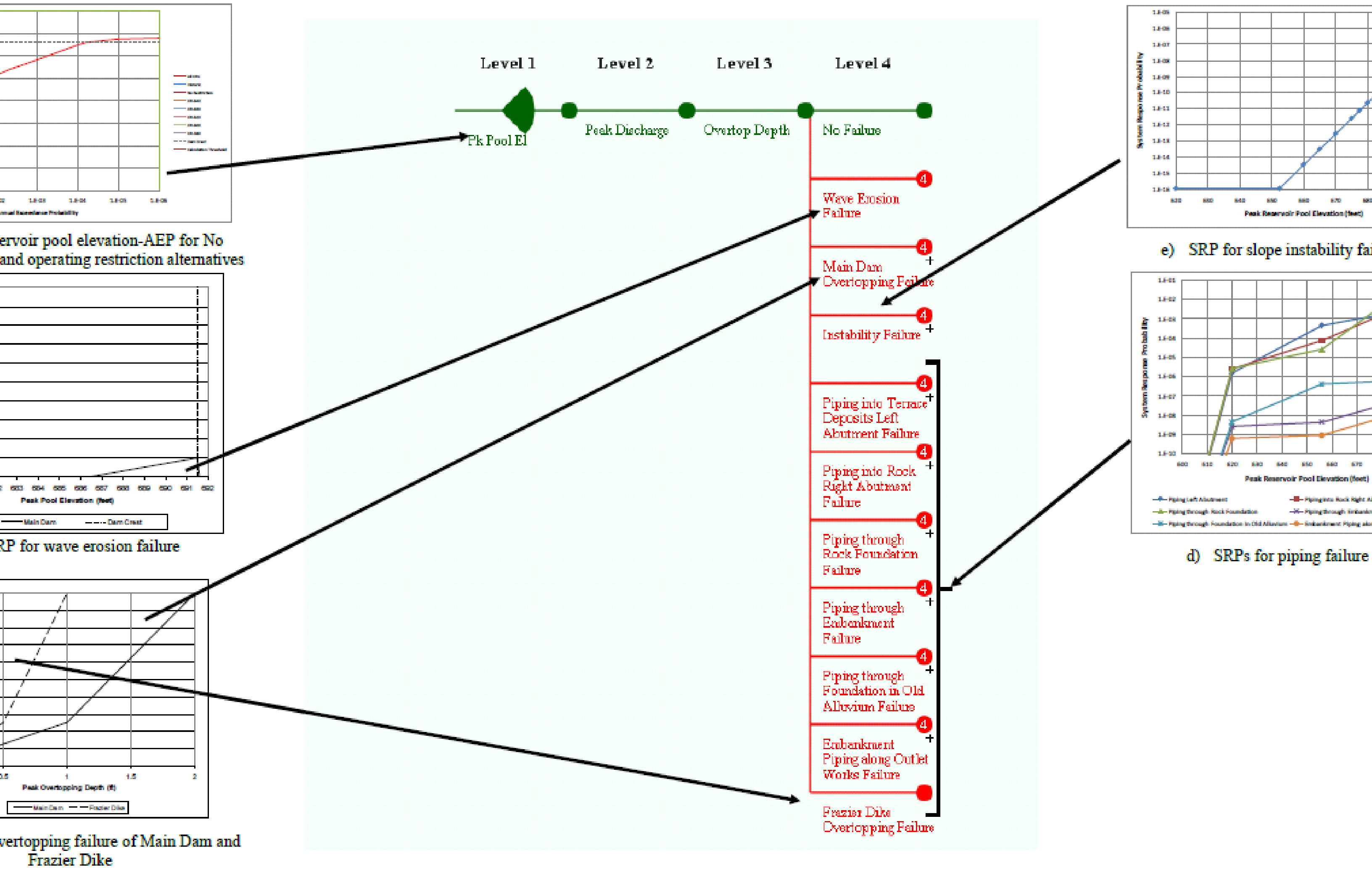

Figure 6. Flood and Flood-internal Event Tree for Success Dam with Flood Loading and SRP Relationships

Toolbox (USACE 2009b)[4] and for the instability failure mode (see Figure 6e) using a probabilistic slope stability analysis performed by the District using the SLOPE/W software. Overtopping and wave erosion SRPs (see Figures 6c and b, respectively) were estimated by expert judgment.

Consequences of Failure

The estimates of life loss and economic damages (in 2004 US$) from the 2004 Study were used in this Update Study and some new approximate estimates for Flood and Flood-internal failure modes for a wide range of reservoir pool elevations. All consequences estimates were based on the results from dam breach-inundation modeling and life loss was estimated using the Reclamation (Graham 1999) method with consideration given to the timing of the issuance of warnings, including the probability distribution of time from the occurrence of the earthquake until initiation of an ACE, SEC or TIP-induced breach as a function of pool elevation (see Figures 5h and f). No consequences were estimated for Frazier Dike failure.

The District plans to update consequences estimates using the HEC-FIA model (Needham et al 2010) based on 2D inundation modeling. Life-loss estimation in HEC-FIA uses a simplified version of the LIFESim model (Aboelata and Bowles 2005) developed for USACE by the Institute for Dam Safety Risk Management at Utah State University.

[4] The probabilities of the existence of a flaw for all piping failure modes were set equal to 1.0 in this risk assessment. This is inconsistent with the current USACE (2009b) toolbox procedure, which is to include the probability of a flaw in calculating system response probabilities (SRPs) for piping failure modes. If the flaw exists, including the probability of a flaw has the effect of reducing the estimated probability of a piping failure for a specific dam in a way that needs to be understood in using the resulting risk estimates. The underlying effect of using the probability of a flaw is to make the resulting SRP estimate a weighted average for the two cases of the flaw existing and not existing. These two cases represent the reality that the "state of nature" is that either flaw exists for a specific dam or it does not. They can be considered separately using probabilities of a flaw of 1.0 or 0, respectively, instead of combining them as a weighted average. These two cases can be run through the risk assessment calculations as upper and lower bound cases, respectively, to represent the range of uncertainty about the existence of the flaw, and to evaluate the effect of this source of uncertainty on the resulting decisions and tolerable risk evaluations. The weighted average SRP estimate can also be considered to be an average SRP estimate for many hypothetically similar dams with the same uncertainty about the existence of the flaw. While this averaging may have value for some types of portfolio decisions, it was judged to be an inappropriate way to address this type of uncertainty for the operating restriction risk assessment for Success Dam. Since the probabilities of flaws existing were close to 1.0 for all of the piping failure modes that significantly contributed to the risks for Success Dam, it was decided not to consider the lower bound case of the probability of a flaw equal to zero, and to use only the upper bound case of the probability of a flaw equal to 1.0. For this risk assessment this approach had a limited effect on the resulting risk estimates and the associated operating restriction decisions in comparison to using the procedure of including the probability of a flaw.

The Earthquake and Flood and Flood-internal event trees, shown in Figures 5 and 6, respectively, provide the structure for the risk model that is used to estimate the probability of failure for Success Dam. Economic and life-loss consequences were incorporated into the event tree risk model using consequences subtrees that were appended to each branch of the event trees but which are not shown in this paper. They comprise exposure (day and night) and consequences branches in the DAMRAE event tree risk models.

USACE Tolerable Risk Guidelines

The proposed USACE tolerable risk guidelines (USACE 2009a, Munger et al 2009) were applied to assess the significance of estimated risks for each operating restriction alternative. These guidelines include a two-part evaluation process. The first part compares total estimated risk for all failure modes against the following tolerable risk limit values for existing dams:

1) An Annual Probability of Failure (APF) of 1 in 10,000 /year as a measure of the performance of the dam (Figure 7);
2) An Individual Risk (IR) expressed as a probability of life loss for the identifiable person(s) most at risk of 1 in 10,000 /year as a measure of life-safety risk (Figure 8);
3) A Societal Risk (SR) expressed as a limit of tolerability on a cumulative probability distribution (F-N chart) of exceeding various magnitudes of (random) life loss as a measure of life-safety risk (Figure 9); and
4) An Annualized Life Loss (ALL) of 0.001 lives/year as the average magnitude of life loss from the probability distribution of life loss in 3) as a measure of life-safety risk (Figure 7).

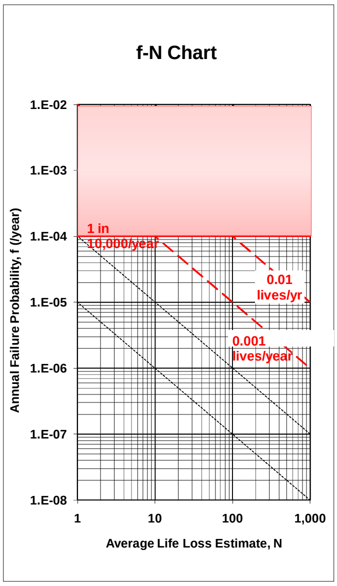

Figure 7. f-N Chart USACE APF and ALL Tolerable Risk Limit Guidelines

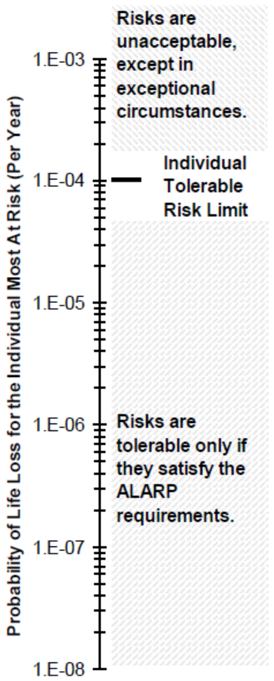

Figure 8. USACE Individual Risk Guideline for Existing Dams

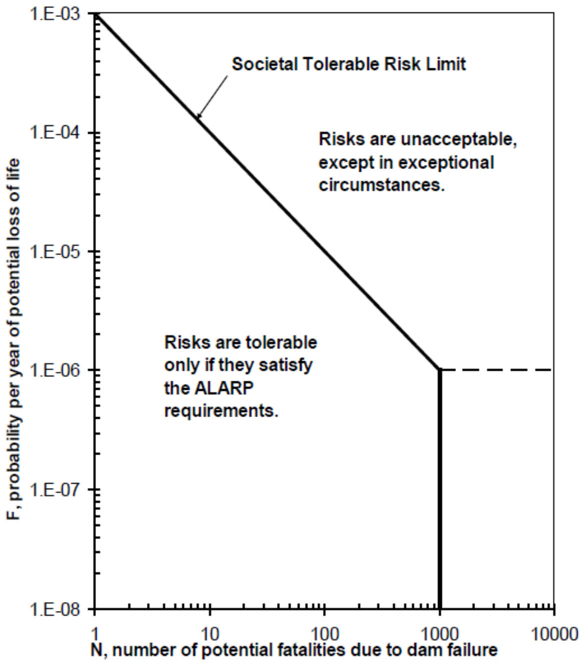

Figure 9. USACE Societal Risk Guideline for Existing Dams

The second part of the risk evaluation process is a determination of whether risks have been reduced to be as low as reasonably practicable (ALARP). This evaluation is both qualitative and quantitative in nature and should take the following into account: the level of risk in relation to the tolerable risk limits; 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; compliance with essential USACE guidelines; and societal concerns as revealed by consultation with the community and other stakeholders.

The consideration of the cost effectiveness or "disproportionality" associated with the cost of achieving life-safety risk reduction relative to the life-safety benefit achieved is a quantitative aspect of an ALARP evaluation. This introduces the consideration of cost, but only to justify further incremental risk reduction below the tolerable risk limits, and not to justify achieving those limits in the first place. Hence, there should be no consideration of "balancing" the economic impacts of operating restrictions and reductions in life-safety risk in meeting the tolerable risk limits.

SUMMARY OF FINDINGS – NO RESTRICTION ALTERNATIVE

Engineering Assessment against USACE Dam Safety Requirements

An Engineering Assessment identified the following confirmed deficiencies against USACE engineering guidelines: liquefaction and stability in the embankment and foundation under Earthquake loading; control tower stability under Earthquake loading; abutment, foundation and outlet works piping; PMF flood capacity; and spillway and stilling basin system erodibility. Apparent deficiencies against USACE Guidelines, which need confirmation through further investigation, were identified for the following: outlet works - intake structure under Earthquake loading; the Main Dam embankment piping; and wave action under Flood loading. Several other Earthquake and Flood factors were found to apparently meet USACE guidelines, but need further investigations to satisfy the normal level of confidence required by USACE.

Risk Estimates and Evaluation against USACE Tolerable Risk Guidelines

The following summarizes some key outcomes of the Risk Assessment of the existing Success Dam for the No Restriction alternative:

1) The existing Success Dam with No Restrictions does not meet any of the proposed USACE tolerable risk guidelines.
2) The total probability of failure is estimated to be about 1 in 3,600 /year. Flood, Flood-internal and Earthquake failure modes are estimated to contribute about 18%, 59% and 23% to the total probability of failure, respectively. The highest contributions to total probability of failure are from the following failure modes, listed in decreasing order of their contributions:

    - Piping into terrace deposits left

- abutment - Flood-internal: 39%
- Frazier Dike overtopping – Flood: 14%
- Initial TIP – Earthquake: 12%
- Piping into rock right abutment - Flood-internal: 11%
- Piping through rock foundation - Flood-internal: 9%
- Initial SEC – Earthquake: 5%
- Main Dam overtopping – Flood: 4%
- Initial ACE – Earthquake: 4%

3) The estimated range of life loss is about 10 – 600 lives for the initial ACE, SEC or TIP failure modes. The highest fatality rates are projected for night-time failures associated with high reservoir pool elevations that lead to the most rapid failures with the shortest warning times in downstream areas nearest to the dam. Delayed Earthquake-induced failure modes are estimated to have life loss in the range of 10 – 20 lives. Flood and Flood-internal failure modes are estimated to have life loss of about 10 - 15 lives.
4) Total estimated annualized life loss of about 0.005 lives/year exceeds the ALL limit guideline of 0.001 lives/year. Flood, Flood-internal and Earthquake failure modes are estimated to contribute about 4%, 45% and 51% to the total ALL, respectively. The much higher percent contribution to total ALL than to total probability of failure from Earthquake failure modes is due to the potential for earthquake-induced failure to occur with little or no warning time. The highest contributions to total ALL are from the following failure modes, listed in decreasing order of their contributions:

- Piping into terrace deposits left abutment - Flood-internal: 30%
- Initial ACE – Earthquake: 25%
- Initial TIP – Earthquake: 16%
- Piping into rock right abutment - Flood-internal: 8%
- Initial SEC – Earthquake: 8%
- Piping through rock foundation - Flood-internal: 7%
- Main Dam overtopping – Flood: 4%

5) The estimated range of economic damages for Earthquake-induced failures is US$270M - US$745M. Most of these damages are expected to occur in the Eastern Porterville Area, although estimated damages in Kings County range up to US$33M. For Flood and Flood-internal failure modes, the incremental economic damages are estimated to range between about US$515M and US$545M and about US$515M and US$745M, respectively.
6) Total Incremental Risk Cost, or annualized economic damages, is estimated to be about US$0.17 M/year. Flood, Flood-internal and Earthquake failure modes are estimated to contribute about 4%, 70% and 26% to the total incremental risk cost, respectively.

SUMMARY OF FINDINGS - POTENTIAL OPERATING RESTRICTIONS

Risk Assessment against USACE Tolerable Risk Guidelines

Table 3 provides a summary of risk assessment results for the potential operating restriction alternatives. Estimated residual risks associated with implementation of each potential operating restriction alternative are summarized as percentages of the No Restriction risk for the following risk measures: a) total annual probability of failure (/year) in Column 2.1; b) total annualized life loss (lives/year) in Column 2.2; and c) total risk cost (US$M/year) in Column 2.3. Columns 3.1 – 3.4 include the outcomes of evaluating these residual risks for each potential operating restriction alternative against the four types of USACE tolerable risk limit guidelines listed above. Columns 4.1 – 4.4 contain the estimated annual economic impact costs of the operating restrictions.

Figure 10 shows estimated total annual probability of failure (APF) and individual risk (IR) for all potential operating restriction alternatives plotted with the USACE APF and IR tolerable risk limit guideline. The individual risk differs from APF in that the former is based on only the probability of failure for the Main Dam and not for Frazier Dike. Under a conservative assumption that someone is present 24 x 7 below both the Main Dam and Frazier Dike, the individual risk for the Success Dam Project is equal to the greater of the two failure probabilities for the Main Dam and Frazier Dike. Currently that is the probability of failure for the Main Dam but could change if other failure modes were considered for Frazier Dike.

Figure 11 is a similar plot to Figure 10 showing estimated total Annualized Life Loss (ALL) with the USACE ALL tolerable risk limit guideline.

The following summarizes some key outcomes of the risk assessment of the potential operating restriction alternatives:

1) Increasingly severe operating restrictions lead to a diminishing amount of reduction in all measures of the estimated total dam failure risk (see APF and IR on Figure 10, ALL on Figure 11). These reductions are most rapid for Earthquake failure modes but are also significant for Flood-internal failure modes.
2) All measures of the estimated dam failure risk for Flood failure modes are shown to be unaffected by the potential operating restrictions because they only reduce annual peak reservoir levels at levels that are well below the estimated threshold levels for all Flood failure modes (see Figure 6a).
3) The No Restriction alternative is estimated not to meet any of the proposed USACE tolerable risk limit guidelines (see Columns 3.1 – 3.4 in Table 3 and Figures 10 and 11).

Table 3. Summary of Decision Options

(1)	(2.1)	(2.2)	(2.3)	(3.1)	(3.2)	(3.3)	(3.4)	(4.1)	(4.2)	(4.3)	(4.4)
DECISION OPTION: OPERATING RESTRICTION ALTERNATIVE	**ESTIMATED RESIDUAL DAM FAILURE RISK AS PERCENT OF NO RESTRICTION RISK**			**EVALUATION AGAINST PROPOSED USACE TOLERABLE RISK GUIDELINES**				**ANNUAL AVERAGE ESTIMATED IMPACT COSTS** (Range of Estimated Annual Impact Costs)			
	TOTAL Annual Probability of Failure (APF)	**TOTAL Annualized Life Loss (ALL)**	**TOTAL Risk Cost (RC)**	**TOTAL Annual Probability of Failure (APF)**	**TOTAL Individual Risk (IR)**	**TOTAL Societal Risk (SR)**	**TOTAL Annualized Life Loss (ALL)**	**Impact on Agricultural Water Users**	**Flood Damages in Tulare Lakebed**	**Impact on Recreation**	**Total**
	(/year)	Life Loss x Probability (lives/year)	Dam Failure Damages x Probability ($M/year)					($M/year)	($M/year)	($M/year)	($M/year)
No Restriction (100% Normal Capacity)	100% (1 in 3,600 /year)	100% (0.0046 lives/year)	100% ($0.17 M/year)	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE				
OR.640 (68% Normal Capacity)	61% (1 in 5,900 /year)	41% (0.0019 lives/year)	52% ($0.087 M/year)	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE	UNACCEPTABLE	$0.4M ($0 - $3.0M)	$0.6M ($0 - $3.1M)	$2.1M	$3.1M
OR.630 (50% Normal Capacity)	48% (1 in 7,400 /year)	28% (0.0013 lives/year)	37% ($0.062 M/year)	UNACCEPTABLE	TOLERABLE if ALARP	TOLERABLE if ALARP	UNACCEPTABLE	$1.0M ($0 - $2.2M)	$0.6M ($0 - $3.1M)	$2.1M	$3.7M
OR.620 (35% Normal Capacity)	39% (1 in 9,100 /year)	21% (0.0010 lives/year)	26% ($0.044 M/year)	UNACCEPTABLE	TOLERABLE if ALARP	TOLERABLE if ALARP	TOLERABLE if ALARP	$1.4M ($0 - $3.0M)	$0.6M ($0 - $3.2M)	$2.8M	$4.9M
OR.600 (16% Normal Capacity)	34% (1 in 10,600 /year)	17% (0.0008 lives/year)	21% ($0.035 M/year)	TOLERABLE if ALARP	TOLERABLE if ALARP	TOLERABLE if ALARP	TOLERABLE if ALARP	$2.4M ($0.9M - $3.8M)	$1.5M ($0 - $7.5M)	$2.8M	$6.7M
OR.580 (5% Normal Capacity)	32% (1 in 11,000 /year)	16% (0.0008 lives/year)	19% ($0.032 M/year)	TOLERABLE if ALARP	TOLERABLE if ALARP	TOLERABLE if ALARP	TOLERABLE if ALARP	$3.1M ($1.1M - $4.8M)	$1.9M ($0 - $9.4M)	$2.8M	$7.7M

UNACCEPTABLE except in exceptional circumstances	**TOLERABLE providing all ALARP considerations are met on an on-going basis**

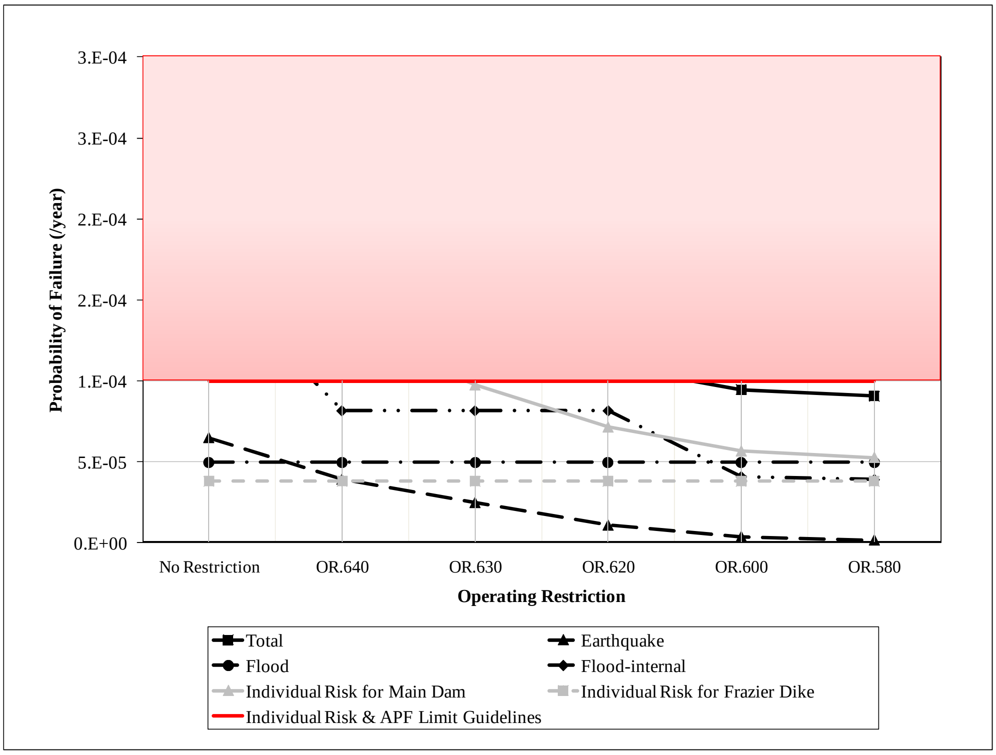

Figure 10. Annual Probability of Failure and Individual Risk for Potential Operating Restriction Alternatives and USACE APF and IR Tolerable Risk Limit Guidelines

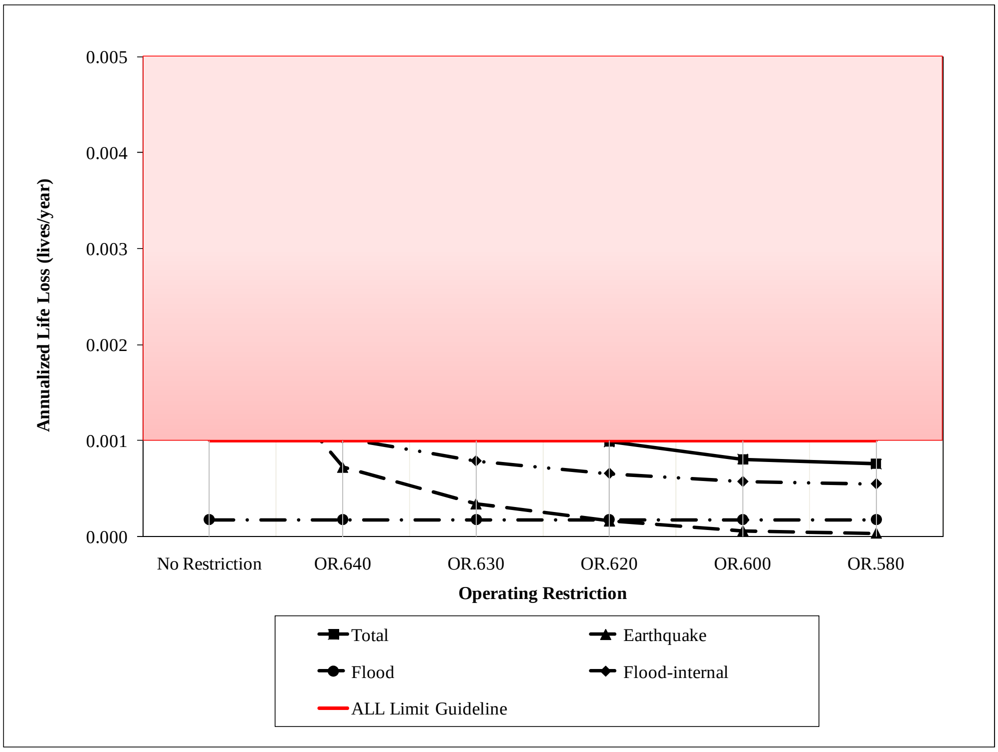

Figure 11. Annualized Life Loss for Potential Operating Restriction Alternatives and USACE ALL Tolerable Risk Limit Guideline

4) OR.600 is the least restrictive operating restriction that is estimated to meet all USACE tolerable risk limit guidelines (see Columns 3.1 – 3.4 in Table 3 and Figures 10 and 11).

5) OR.630 is the least restrictive operating

restriction that is estimated to meet the proposed USACE societal risk and individual risk limit guidelines but not the APF and ALL limit guidelines (see Columns 3.1 – 3.4 in Table 3 and Figures 10 and 11).

6) OR.620 is the least restrictive operating restriction that is estimated to meet the proposed USACE societal risk, individual risk and ALL limit guidelines and to almost meet the APF limit guideline (see Columns 3.1 – 3.4 in Table 3 and Figures 10 and 11).

   Based on proposed USACE guidance for cost effectiveness and disproportionality under ALARP considerations a justification for adopting the next more restrictive operating restriction does not exist for any of the cases for which some or all USACE tolerable risk guidelines are estimated to be met.

Comparison With 2004 Study Results

The following observations are made based on a comparison of the results from this Update Study with the final estimates from the 2004 Study (Bowles et al 2005):

- The total and Earthquake probabilities of failure for the No Restriction alternative are estimated to be more than an order of magnitude lower than in the 2004 Study. This reduction is due to a decrease in the estimate of the Earthquake probability of failure, which more than offset increases in the estimates of the Flood and Flood-internal probabilities of failure. These changes are mainly attributed to improvements in the information from more detailed site investigations that were available to use in this Update Study.
- The estimated annualized life loss in this Update Study decreased compared with the 2004 Study due to the reductions in the estimated probability of failure and some decreases in estimated life loss that resulted from a reassessment of the estimated times from the occurrence of the earthquake to initiation of an ACE, SEC or TIP breach. These resulted in longer estimated warning times, and hence, lower life-loss estimates for many of these Earthquake failure cases compared with those estimated in the 2004 Study.

THE CORPS' DECISION ON OPERATING RESTRICTIONS

Following this Update Study the District decided to slightly relax the operating restriction from OR.620 to OR.630. The following are some of the factors that were considered in that decision:

1) Under the proposed USACE tolerable risk guidelines, the least restrictive potential operating restriction alternative that is demonstrated to meet all limit guidelines should be considered as the candidate operating restriction. The next more restrictive operating restriction alternative should then be evaluated to determine if the further estimated risk reduction associated with that alternative can be justified because it does not represent a significantly disproportionate additional impact cost relative to its additional life-safety benefits.
2) Following the procedure summarized in 1), would lead to the adoption of OR.600. However, it is noted that OR.630 is estimated to meet the proposed USACE SR and IR limit guidelines, which are the most widely-used types of life-safety guidelines, but not the APF and ALL limit guidelines.
3) The proposed USACE tolerable risk guidelines interpret risks that exceed the tolerable risk limit as "*unacceptable except in exceptional circumstances*." The explanation of the exceptional circumstances qualifier refers to a situation in which "*the probability of failure is very low*" (USACE 2009a, Munger et al 2009). It is noted that for OR.630, while the total probability of failure estimated for Success Dam exceeds the APF tolerable risk limit guideline of 1 in 10,000 /year, the estimated individual risk, based on failure of the Main Dam, is estimated to meet the IR limit guideline.
4) The proposed USACE tolerable risk guidelines do not provide for a less restrictive tolerable risk target for interim risk reduction measures than for long-term risk reduction measures. Thus the use of Reclamation's 0.01 lives/year guideline, which was used as a key basis for the 2004 decision to implement OR.620 following the 2004 Study, is not consistent with proposed USACE guidance or other tolerable risk guidelines. Instead the ALL limit value of 0.001 lives/year should be used along with the limit values for the APF, IR and SR tolerable risk limits and the requirement to satisfy ALARP considerations. This is the basis on which risk evaluations have been performed and reported in this Update Study.

CONCLUSIONS

The use of risk assessment was found to be valuable in providing a rational and defensible basis for exploring the justification for implementing potential operating restrictions at Success Lake. It provided new insights and understanding of the potential failure modes, including the relative likelihood of sudden vs. delayed failure modes, and the relationship between pool elevation and dam failure risk, including the potential for large scale life loss and major economic damages. The evaluation against the USACE tolerable risk guidelines provided a basis for decision making.

Unlike most other dam safety risk reduction measures, the cost of operating restrictions is borne by the project beneficiaries through reduced water supply, flood control and recreation benefits. It was therefore important that the agricultural water users undertook the estimation of their economic impacts from the potential operating restrictions.

This Update Study illustrates the effect of having improved information available to conduct a dam safety risk assessment in significantly changing the estimated risk of failure, the addition of the effects of control tower performance, a decrease in the estimated risks of earthquake failure modes and an increase in the importance of piping failure modes. While Earthquake-related failure modes were the initial reason for considering the need for operating restrictions, this Update Study demonstrated that piping failure modes are also a significant contributor to the risk of failure. It also illustrates a strategy of approaching interim risk reduction decisions from the conservative side in the face of uncertainty about life-safety risks.

The loss of project benefits associated with the loss of outlet works gates operation resulting from earthquake-induced damage to the control tower are not considered in this risk assessment for non-dam failure cases and for the controlled breach case. This approach is consistent with the USACE consideration of only dam failure consequences in dam safety risk assessments. However, these non-dam failure economic losses should be estimated in future risk assessments for Success Dam so that they can be considered in the overall USACE decision process for both interim and long-term risk reduction for Success Dam.

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