

ALAMO DAM DEMONSTRATION RISK ASSESSMENT

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ABSTRACT

A demonstration risk assessment was conducted on the 283-foot high rolled-earthfill Alamo Dam as part of a U.S. Army Corps of Engineers (USACE) Research and Development program. The existing dam and 19 structural risk reduction alternatives were evaluated for flood, earthquake and normal operating conditions. The paper summarizes the risk assessment process, results, findings and recommendations. It also provides an evaluation of the risk assessment process and recommendations for better positioning the USACE to use risk assessment for dam safety evaluation and decision support.

INTRODUCTION

As part of a USACE initiative to explore the use of risk-based procedures to support dam safety decisions, a demonstration risk assessment (DRA) was conducted on Alamo Dam. The overall purpose was "To provide USACE staff with exposure to applying risk assessment (RA) techniques to dam safety decision making." In addition, experience gained from the project will provide a basis for formulating USACE policy on the use of RA in its Dam Safety Assurance Program (DSAP) and for identifying research and development needs.

Alamo Dam is a 283-foot high rolled-earthfill dam that was completed by the USACE in 1968 to provide flood control, water conservation and recreation. Although the dam is in good structural condition, recent estimates of the standard project flood (SPF) and the probable maximum flood (PMF) have increased above design values. As a result, overtopping of the dam would be expected to occur for events approaching the magnitude of these floods. The RA considered earthquake and static (normal operating conditions) loading cases in addition to flood loading.

The DRA involved an engineering team and a consequences assessment team from the USACE Los Angeles (LA) District. Facilitation and coordination was provided by RAC Engineers & Economists. Through their participation in the project, the LA District desired to strengthen their dam safety program and decision making in the public interest, to make progress in addressing Alamo Dam DSAP efforts, and to evaluate the risk-enhanced approach for addressing hydrologic deficiencies.

The remainder of this paper is divided in six sections, as follows: a brief description of the Alamo Dam; the general dam safety RA process; the Alamo Dam RA; a summary of results; a summary of overall findings and recommendations for the Alamo Dam; and an evaluation and recommendations relating to the RA process.

ALAMO DAM

Alamo Dam is located on the Bill Williams River, 39 miles upstream from its confluence with the Colorado River in Lake Havasu. The 4,770 square mile drainage area for Alamo Dam is in west central Arizona, and is generally mountainous. Discharges from the U.S. Bureau of Reclamation's (USBR) Parker Dam, which forms Lake Havasu, flow through the Parker Strip, Blythe, Yuma and Mexicali, Mexico.

The top of Alamo Dam is at elevation 1265 feet and the spillway crest is at elevation 1235 feet. Reservoir storage at the spillway crest is about one million acre-feet and at the top of the dam it is about 1.3 million acre-feet. Existing spillway capacity is 41,500 cfs. The USACE Threshold Flood is about 33% of the PMF. The PMF

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inflow event has a peak flow rate of 820,000 cfs and a volume of 1.39 million acre-feet. It is estimated that the existing dam will overtop by 20 feet during the PMF, with a peak outflow of 362,000 cfs, assuming that embankment failure did not occur. Dam breach floods are estimated to have a peak flow rate of about 3 million cfs.

RISK ASSESSMENT PROCESS

Demonstration Risk Assessment

The concept of a demonstration risk assessment was developed by RAC for the state dam safety regulator in Victoria, Australia, as a key part of a statewide program for introducing RA into dam safety management (Watson 1998). A DRA can provide an effective way for a dam owner or regulator to gain practical experience with RA and to evaluate its benefits within the context of their organizational mission.

The Alamo Dam DRA began with a meeting of the RA Team to review available information, to make a site visit, and to identify potential failure modes, an event tree risk model, possible risk reduction measures and additional information and analyses needed to perform the RA. At the second team meeting the failure modes were reviewed and revised based on the additional information and analyses completed after first team meeting. In addition, system response probabilities for the existing dam and risk reduction measures were estimated and factors affecting warning times were assessed for use in the risk model.

After the second team meeting flood and earthquake loading relationships were developed, dam break inundation flood routings were performed, and cost estimates were made for risk reduction measures. Life loss, economic damages and environmental consequences were assessed for various breach-inundation cases. The risk analysis model was run for the existing dam, various sensitivity cases, and the risk reduction alternatives. Results were evaluated against various reference criteria and preliminary findings and recommendations were formulated. These were presented to the USACE RA Team and LA District and USACE Headquarters management and finalized in a project report. An evaluation of the DRA process was conducted and recommendations for strengthening it were developed. Throughout the DRA, observers from various USACE offices attended team meetings to become familiar with RA and to offer advice for strengthening the process.

Steps in Dam Safety Risk Assessment

The overall RA process comprises the following major steps: 1) risk identification, 2) risk estimation, 3) risk evaluation, and 4) risk reduction (Bowles et al. 1998a). The first two steps combine to form risk analysis. Risk identification is the process of recognizing the plausible failure modes for each type of initiating event. Typically, failure modes are represented using an event tree risk analysis model. Risk estimation consists of determining loading and system response probabilities, and the consequences of various failure and no-failure scenarios, so that incremental consequences can be estimated. Probability and consequence estimates are then input to the various branches of the event tree. Risk reduction alternatives are developed and analyzed by changing various model inputs to represent improved performance.

Estimated risks for an existing dam and for each risk reduction alternative, are evaluated against risk-based criteria and other considerations such as ALARP (as low as reasonably practicable) and de minimis risk (Bowles et al 1998b). It is emphasized that a RA process does not prescribe dam safety decisions. For the Alamo Dam, these decisions should be made by the USACE. Through using the risk-enhanced approach, which supplements traditional engineering approaches with insights obtained from RA, the USACE should be in a better position to make informed decisions and to prioritize dam safety work.

RAs should be staged, with more detail being justified by the value expected to be added for decision making. The Alamo Dam DRA was conducted at a “moderate” level of detail. It was based both on existing information (e.g. engineering reports, analyses, and monitoring records) and additional supporting analyses conducted by the LA District.

ALAMO DAM RISK ASSESSMENT INPUTS

Failure Modes

Overtopping, toe erosion, and wave action were identified as the flood failure modes and foundation and embankment liquefaction as earthquake failure modes. Earthquake failure modes comprised a sequence of events beginning with liquefaction, followed stability failure, and leading to a breach. Embankment piping and slope stability were considered for internal (static or normal operating condition) failure modes. Foundation failure was not included because of the excellent foundation conditions. Piping along the outlet works, which is located in bedrock in the left abutment, was not considered to be a credible failure mode.

Loading Probabilities

Relationships were needed to define the likelihood of flood, earthquake and static loading conditions over a full range of these loads. Flood loading was characterized using a peak reservoir elevation annual exceedance probability (AEP) relationship for the existing dam (Figure 1) and each flood risk reduction alternative using the following procedure. A volume frequency analysis was performed for the 1929-1998 period of recorded inflows to establish 1- to 30-day volume-frequency curves out to an AEP of 1 in 100. These relationships were extrapolated to the PMF, SPF+PMF with 23 days spacing, and SPF+PMF with 5 days spacing, with assigned AEPs of 1 in 10^6 , 1 in 10^7 , 1 in 10^9 , respectively. Balanced hydrographs of reservoir inflow were constructed for a range of events up to the PMF, based on the volume frequency relationships and using the HEC-1 model. These hydrographs and the SPF+PMF events were routed through the reservoir using the HEC-5 model with the Bill Williams River Corridor Technical Committee (BWRCTC) dam operation plan modified to reflect the Colorado River reservoir system operations for flood control. The appropriate spillway rating relationships for the no-failure dam and abutment overtopping. Upper and lower bounds were estimated based on typical uncertainty in key parameters in precipitation-runoff modeling and assigned notional uncertainties on the AEP of the PMF and SPF+PMF events.

Earthquake loading was characterized using a peak ground acceleration versus return period relationship (Figure 2) based on seismic risk studies reported by Bausch and Brumbaugh (1997) out to a best estimate of 0.12g, which has an AEP of about 1 in 2,200. This relationship was extended to smaller AEP events using regional information and upper and lower bound curves were estimated.

Static loading was represented using a reservoir stage duration relationship that was obtained from an HEC-5 simulation of 1929-1998 daily inflow record using the modified BWRCTC dam operation plan.

System Response Probabilities

System response probability relationships were estimated for each branch on the event tree model based on laboratory testing, engineering analysis, experimental evidence, engineering judgement and historical performance of comparable dams. In some cases these estimates were calculated directly, and for other cases they were estimated based on deterministic analysis and judgement. Depending on the purpose for which a RA is performed, different levels of effort are justified for system response probability estimation, with more detailed approaches aimed at narrowing the uncertainty and increasing the confidence in estimates. Figures 3 and 4 are examples of overtopping and foundation liquefaction system response probability relationships, respectively, for the existing dam.

The probability of failure for internal failure modes was based on the historical failure record for dams taken from McCann et al. (1985), Hatem (1985) and Foster et al. (1998). For piping and slope stability, these probabilities were estimated for different reservoir elevation intervals. The probability of failure by piping was estimated using Foster et al. (1998).

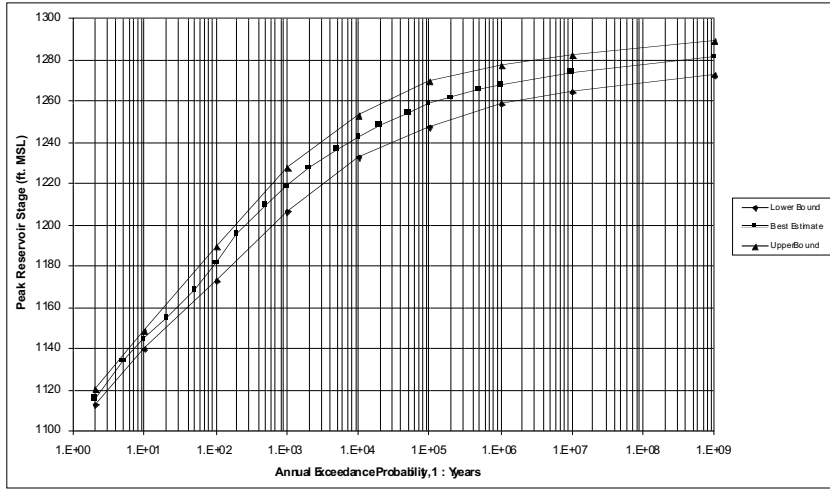


Figure 1. Existing dam flood loading — AEP relationship

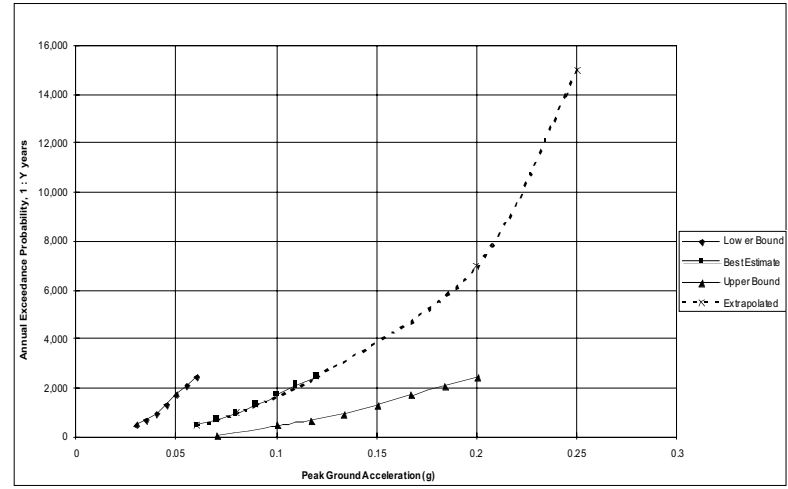


Figure 2. Earthquake loading — AEP relationship

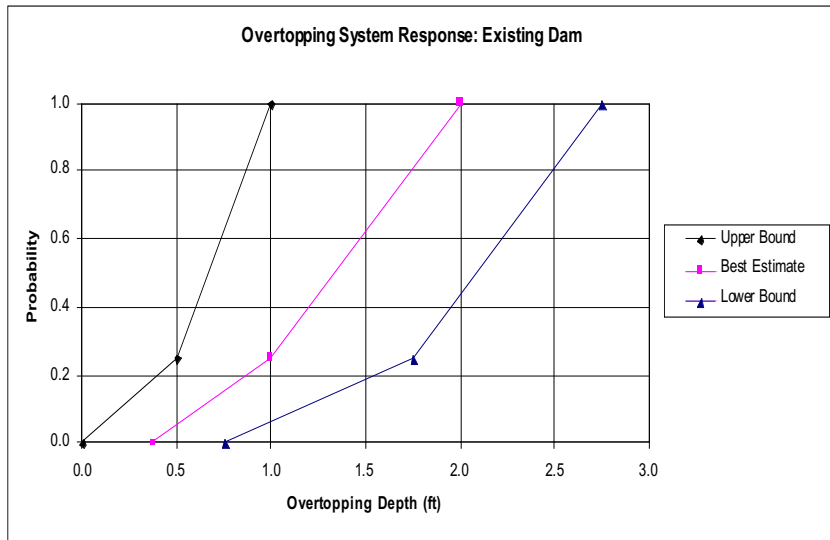


Figure 3. Existing dam overtopping system response

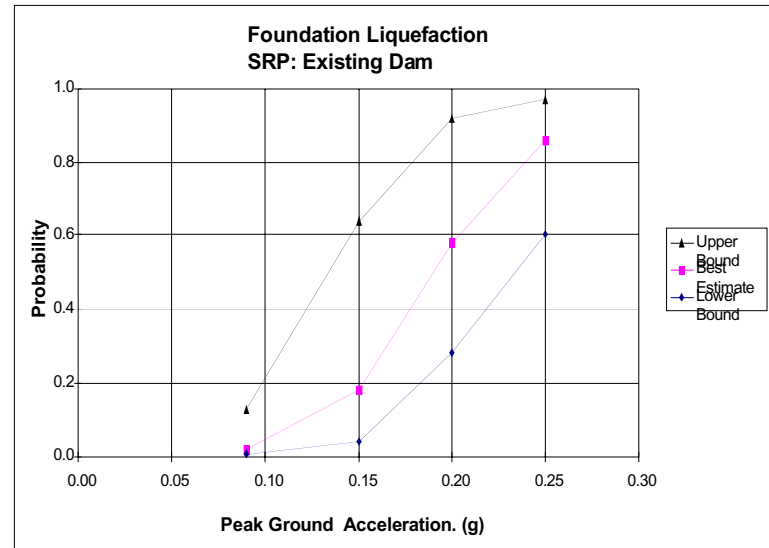


Figure 4. Existing dam foundation liquefaction system response

Breach-inundation Runs

Inundation areas and various flood routing characteristics, such as travel time, are needed to estimate life loss, economic and environmental consequences. A total of 13 breach-inundation runs were made covering flood no failure and flood and sunny day failures.

Dam breach analysis for RA requires realistic estimates of breach parameters. These parameters were estimated through a process that combined information from empirical relationships, historical experience, and professional judgement. All empirical methods predicted that the size of the breach would be larger than the size of Alamo Dam and this was used as a basis for the breach-inundation runs.

Consequences

The Bill Williams and Colorado rivers from Alamo Dam into Mexico and back to the Salton Sea were divided into eight major consequence centers. Economic damages were assessed for the following cases based on information from the 13 breach-inundation runs:

- Flood no failure cases - as a function of peak (no failure) discharge rate.
- Flood failure cases – as a function of reservoir breach stage at the time of failure.
- Earthquake and static failures cases – as a function of reservoir stage at the time of failure.

Examples of these three relationships are shown in Figures 5, 6 and 7 for Center 4. For each loading condition economic damages were interpolated in the risk model.

An inventory of the number and square footage of single family residential, multi-family residential, mobile homes, commercial, industrial, and public structures was completed based on previous reports, telephone conversations with city officials, and assessor's data retrieved through TRW. These structures were valued in 1998 dollars by the depreciated replacement value method using the Marshall and Swift Real Estate Valuation Service. Structure and content values were then applied to the national FEMA depth-damage relationship to obtain estimates of the damages for each breach-inundation case.

The population at risk (PAR) was estimated for each consequence center using the number of structures (adjusted for unoccupied structures) within flood boundaries and multiplying by the household densities for the major communities using Census data. These estimates were then adjusted for employment patterns, weekend activities, and school children allocations to arrive at PAR projections for two seasons (floods - November to March and non-flood - April to October) and four daily exposures (week day, week night, weekend day, and weekend night). Life loss was estimated using the DeKay and McClelland (1993) method, which relates life loss to PAR, warning time and the intensity of flooding. Warning time was estimated as travel time plus an adjustment, which was provided by the engineering team. The adjustment accounted for the estimated time needed for detection, decision to notify, and notification for each failure mode (breach) type. As with all approaches to estimating life loss, there are significant limitations to the DeKay and McClelland approach. However, based on a consideration of these limitations in the context of the Alamo DRA and an evaluation based on case histories, it was concluded that it is very unlikely that any incremental life loss would result for the flood failures. The nearest population is located almost 40 miles away around Lake Havasu with best estimate warning times ranging from 12 to 21 hours (travel time + 6 hours). Warning times are much greater below Parker Dam on the Colorado River and are several days near the Mexican border. During the flood season, the most exposed individual is located near Lake Havasu with best estimate warning time ranging from 12 to 19.7 hours.

For earthquake and internal failure cases the most exposed individuals are a work crew that is located near Lincoln Ranch for a period during the non-flood season. There is no known mechanism for warning this crew and travel time is close to an hour.

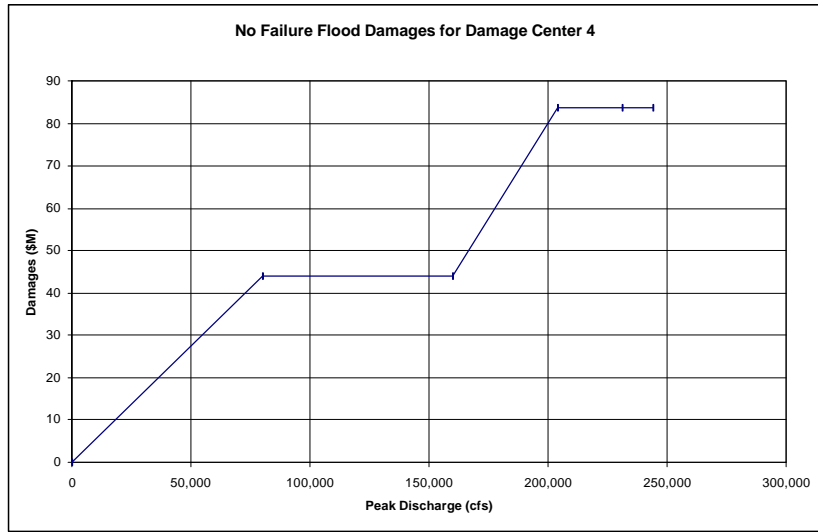


Figure 5. Example of no failure flood economic damages

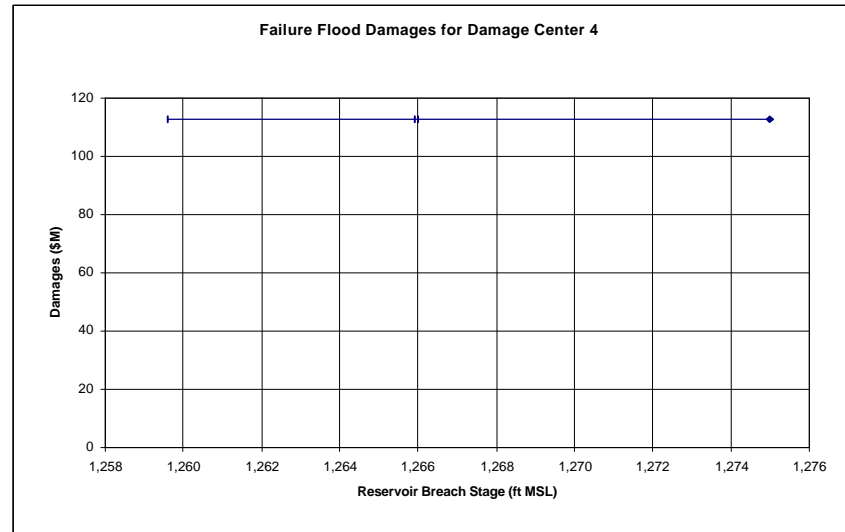


Figure 6. Example of flood failure economic damages

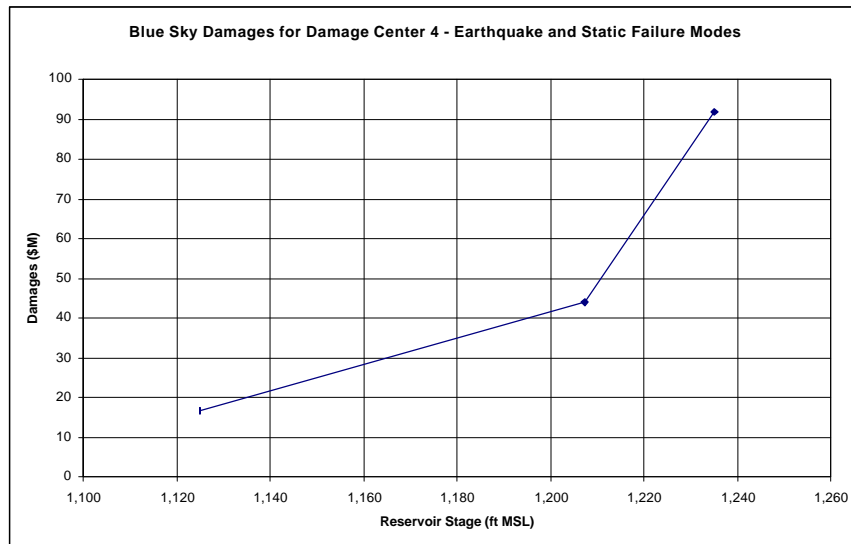


Figure 7. Example of earthquake and static failure economic damages

A qualitative inventory of existing environmental conditions and resources was developed to provide an initial assessment of the environmental impacts of projected flooding due to dam failure. Ideally, an analysis of the incremental impacts of dam failure flooding relative to no-failure conditions should be made. The assessment was made with incomplete data since the Bill Williams River corridor has not been systematically surveyed for cultural and environmental resources. There are 13 different species that would be adversely affected by flooding projected at the blue sky failure conditions, with 7 of these species being significantly affected. Cottonwood, Goodding willow and salt cedar are the common flora within the Bill Williams corridor. High mortality of seedlings of cottonwood and willow is likely to result at the projected depths and velocities of flooding, but seed dispersal would be enhanced by high water flows in the area. The cottonwoods are the least tolerant of inundation.

There are considerable cultural resource sites in the Bill Williams and Colorado River corridors. These are mainly associated with the three native American populations that abut the rivers. Many of these sites are already inundated by existing reservoirs.

Risk Criteria

Quantitative criteria can serve a useful role in the risk evaluation process. When they are used, the effects of uncertainties in the risk analysis process should be considered. However, dam safety decisions should be made by those responsible for ensuring dam safety after all the relevant factors have been assessed and weighed; they should not be the automatic result of applying a criterion to the outcomes of a risk analysis. Thus, the use of RA enhances the decision-making process, but does not replace reference to traditional engineering criteria and other relevant factors.

Table 1 is a summary of life safety (societal and individual) and economic/financial risk criteria (or guidelines) from the USBR, BC Hydro and the Australian Committee on Large Dams (ANCOLD). These criteria were used on a reference or benchmarking basis in the DRA since the USACE does not have risk criteria for dam safety. However, it is important to remember that the degree of risk accepted, and the risk criteria established, by one organization may not be appropriate for adoption by another organization.

All criteria listed in Table 1, except the ANCOLD individual criteria, are interim. The ANCOLD criteria are being widely used on a reference basis in Australia with limited examples of dam safety decisions being made that incorporate these criteria as at least a part of their justification. The USBR guidelines are being routinely used as a significant consideration in decision making on both the priority and level of risk reduction. BC Hydro's criteria were not formally adopted by management, or approved by their regulator, although it is understood that they were used to support several significant dam safety decisions (Salmon 1999).

Risk Model Runs

Risk model runs were made for the existing Alamo Dam and various risk reduction alternatives. Sensitivity runs were made for the following: flood loading, flood system response probabilities (SRPs), earthquake loading, earthquake SRP's, and static failure mode probabilities. No sensitivity runs were made for warning times since life loss was estimated to be extremely unlikely for all reasonable warning times using the Decay-McClelland method.

Risk model runs were made for 19 combinations of risk reduction measures listed in Table 2 with their estimated costs and codes that are used to refer to them in this paper.

Table 1. Summary of risk evaluation criteria.

Risk Evaluation Type			Rating Code	Explanation
Life Safety-Societal Risk	ANCOLD (1998) Interim Amended Societal Risk Criteria <i>(for all failure modes combined)</i>	Limit	N	Does not meet limit criterion - F-N plots above limit criterion
			Y	Meets limit criterion - F-N plots below limit criterion
		Objective	N	Does not meet objective criterion - F-N plots above objective criterion
			Y-ALARP?	Meets objective criterion, but ALARP must be evaluated - F-N plots below objective criterion
	USBR (1997) Interim Tier 1 Public Protection Guidelines <i>(for flood, earthquake and static failure modes separately)</i>		N-StrongL&S	Strong justification for long- and short-term risk reduction measures - Expected incremental loss of life exceeds 0.01 lives/year
			N-StrongL	Strong justification for long-term risk reduction measures - Expected incremental loss of life between 0.01 and 0.001 lives/year
			Y-ALARP?	Diminished justification for long-term risk reduction measures (i.e. ALARP must be evaluated) – Expected incremental loss of life less than 0.001 lives/year
	USBR (1997) Interim Tier 2 Public Protection Guidelines <i>(for total of failure modes)</i>		N	Increasing justification to reduce probability of failure - Probability of failure exceeds 1×10^{-4} /year
			Y-ALARP?	Decreasing justification to reduce probability of failure (i.e. ALARP must be evaluated) - Probability of failure less than 1×10^{-4} /year
	BC Hydro (1993) Interim Societal Risk Criteria <i>(for total of failure modes)</i>		N	Does not meet criterion - Expected incremental loss of life exceeds 0.001 lives/year
Y-ALARP?			Meets criterion, but ALARP must be evaluated - Expected incremental loss of life less than 0.001 lives/year	
Life Safety-Individual Risk	ANCOLD (1994) Average over PAR <i>(for total of all failure modes)</i>	Limit	N	Does not meet limit criterion – Incremental probability exceeds 1×10^{-5}
			Y	Meets limit criterion - Incremental probability less than 1×10^{-5}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1×10^{-6}
	Y-ALARP?		Meets objective criterion - Incremental probability less than 1×10^{-6} , but ALARP must be evaluated	
	ANCOLD (1994) Person at most risk <i>(for total of failure modes)</i>	Limit	N	Does not meet limit criterion - Incremental probability exceeds 1×10^{-4}
			Y	Meets limit criterion - Incremental probability less than 1×10^{-4}
		Objective	N	Does not meet objective criterion - Incremental probability exceeds 1×10^{-5}
	Y-ALARP?		Meets objective criterion - Incremental probability less than 1×10^{-5} , but ALARP must be evaluated	
BC Hydro (1993) Interim Person at most risk <i>(for total of failure modes)</i>		N	Does not meet criterion - Incremental probability exceeds 1×10^{-4}	
		Y-ALARP?	Meets criterion - Incremental probability less than 1×10^{-4} , but ALARP must be evaluated	
Economic/Financial	NSW Total Asset Management Risk Example Guidelines <i>(for flood, earthquake and static failure modes separately)</i>		N-Major	Major risk - Imperative that risk reduction be implemented
			N-Medium	Medium risk - Risk reduction required in a reasonable time
			Y-ALARP?	Low risk - Risk reduction to be ALARP

Table 2. Risk Reduction Alternatives

Group	Code	Description	Cost (\$M)
Existing Dam	E	Do Nothing	-
Partial Flood Fixes	FR10	Downstream toe protection	1.59
	FR15	Wave protection at crest	1.47
	FR14	Raise embankment 5 ft., includes FR15	2.61
	FR16	Combine FR10 and 14	3.80
	FR12	Raise embankment 9 ft., includes FR10 & FR15	9.03
Complete Flood Fixes (Each includes FR10 and FR15)	FR1	Raise embankment 17.3 ft	13.92
	FR8a	Hardening downstream embankment face (concrete)	31.22
	FR8b	Hardening downstream embankment face (RCC)	18.64
	FR2a	Widen spillway to 220 ft, raise embankment 13.5 ft	21.35
	FR3a	Lower spillway 10 ft, raise embankment 15.4 ft	14.07
	FR3b	Lower spillway 20 ft, raise embankment 13.6 ft	13.88
	FR3c	Lower spillway 30 ft, raise embankment 11.9 ft	13.96
	FR6	Fuse gates, raise embankment 15.5 ft, lower spillway 10 ft	18.32
FR9	Widen spillway to 220 ft, lower 10 ft, raise embankment 10.5 ft	21.38	
Earthquake and Internal Fixes	ER1	Upstream & downstream berm	47.86
	ER2	Downstream berm	14.81
	ER3	Soil mixing of foundation material/chemical grouting	40.09
Combined Flood, Earthquake and Internal	FER1	ER1 and FR9	48.52
	FER2	ER2 and FR3c	25.12

SUMMARY OF RESULTS

Existing Dam

- 1) Life loss is extremely unlikely based on the long warning times that are expected.
- 2) The existing dam appears to meet all life safety risk criteria based on best estimates and all sensitivity cases.
- 3) The best estimate of total probability of failure for the existing dam is about 5×10^{-6} (1 in 500,000) per year, which is a low probability of failure. Earthquake failure modes are estimated to comprise approximately a third of the best estimates for flood and static failure modes (Figure 8). The upper bound sensitivity estimate for flood loading is about 2×10^{-5} (1 in 50,000) per year, for earthquake loading is about 1.1×10^{-5} (1 in 90,000) per year, for earthquake system response is about 3×10^{-5} (1 in 30,000) per year, and for static failure probabilities is about 1.5×10^{-5} (1 in 70,000) per year.
- 4) Incremental (dam failure) damages are estimated to range between about \$350M and \$1B for the failure modes considered for the existing dam. They are of a similar order of magnitude for all loading types. Considering their associated probabilities, they would be categorized as “low risk” using the NSW TAM economic consequence example criteria, with risk reduction recommended according to the ALARP principle.
- 5) “Without project” flood damages are estimated at about \$200,000/year for the existing dam and to vary from about \$80,000/year to almost \$320,000/year for lower and upper bound flood loading cases.

Risk Reduction Alternatives

- 1) The largest benefit:cost ratio (B:C) is estimated to be 0.004 for FR14 (raise embankment 5 ft. and wave protection). Therefore no fixes have a B:C justification (Figure 9).
- 2) The least total economic cost complete flood alternative is the existing dam (Figure 10).

- 3) The existing dam appears to meet all life safety risk and economic/financial criteria, and thus there is no justification for fixes based on changes in these criteria.
- 4) The ALARP condition for life loss appears to be met by the existing dam since life loss was estimated to be extremely unlikely.
- 5) Smaller cost fixes may have a possible de minimis risk justification for implementation, even though they are not cost effective based on ALARP considerations.
- 6) Toe protection (FR10) and wave protection (FR15) are estimated to have an imperceptible effect on probability of failure (Figure 11), incremental risk costs (or rehabilitation benefit), and incremental probability of individual life loss for the person at greatest risk (Figure 12). There is no justification for these fixes based on B:C or CPLS. However, since the costs for each of these fixes are estimated to be about \$1.5M, there may well be a de minimis risk justification for them. This justification is further strengthened because both measures are considered normal dam engineering practice.
- 7) Similar to FR10 and FR15, FR14 (raise embankment 5 ft. and wave protection) and possibly FR16 (same as FR14 plus toe protection) may have a de minimis risk justification, since their estimated costs are \$2.6M and \$3.8M, respectively.
- 8) Reductions in annualized flood control benefits are largest (approximately \$250,000/year) for the 30 ft. spillway lowering, representing roughly a doubling of the no failure flood control damages for the existing dam from about \$200,000/year to \$450,000/year (Figure 13). Spillway widening also reduces flood control benefits, but not as significantly as lowering. All other fixes (i.e. raising, hardening downstream embankment face, toe protection and wave action protection) reduce flood control benefits to a lesser degree than changes in spillway geometry. These other fixes affect flood control benefits because they extend the range of AEPs over which no failure damages exist for the fix – this actually represents a shift in probability from dam failure to no failure. However, the relative magnitude of incremental (failure minus no failure) damages and no failure damages determines whether rehabilitation benefits are more or less than the reduction in flood control benefits, and hence, whether net benefits are positive or negative, respectively.
- 9) Combining the FR9 flood fix and the ER1 earthquake and internal fix into FER1, the total probability of failure is estimated to be reduced by two orders of magnitude from 5×10^{-6} (1 in 500,000) per year to 5×10^{-8} (1 in 50,000,000) per year. Similarly, total incremental probability of individual life loss for the person at greatest risk is estimated to be reduced by two orders of magnitude from 2.1×10^{-9} (1 in 500,000,000) per year to 2.4×10^{-11} (1 in 40,000,000,000) per year.

OVERALL FINDINGS AND RECOMMENDATIONS FOR ALAMO DAM

Overall findings

An evaluation of the risk analysis results against various risk-based criteria, indicates that a basis does not appear to exist for proceeding with any but the lower cost fixes. These fixes are toe protection, wave protection, and raising the embankment 5 ft. (i.e. FR 10, FR 14, FR 15 and FR 16). However, even though RA does not appear to provide an economic or life safety justification for proceeding with the more costly fixes, the USACE may choose to do so for other reasons, such as environmental protection or policy requirements to pass the SPF + PMF. It is likely that there are many other USACE projects that would return a much greater risk reduction than investing in these measures at the Alamo Dam. Such projects could be identified through a portfolio risk assessment (Bowles et al 1998b).

Since Alamo Dam is a well-engineered modern dam, which is located away from any significant populations, it does not appear to pose any significant risk of loss of life. Hence, the Alamo Dam DRA does not provide a typical example of the how risk based life safety criteria can be used to evaluate and justify risk reduction measures.

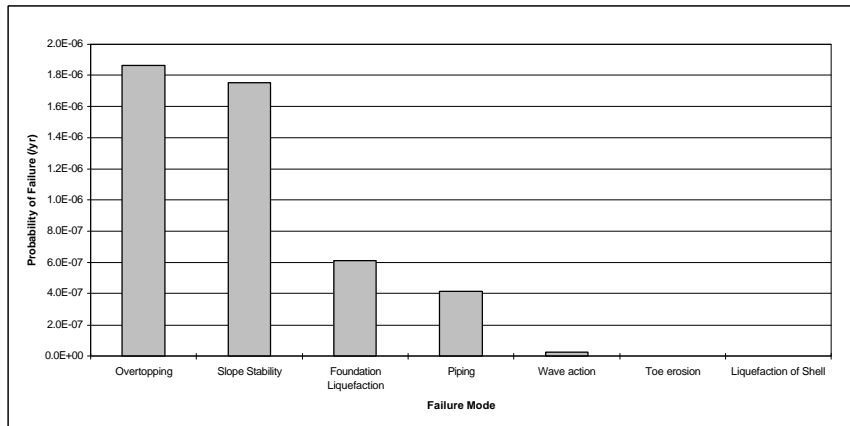


Figure 8. Contributions to total probability of failure

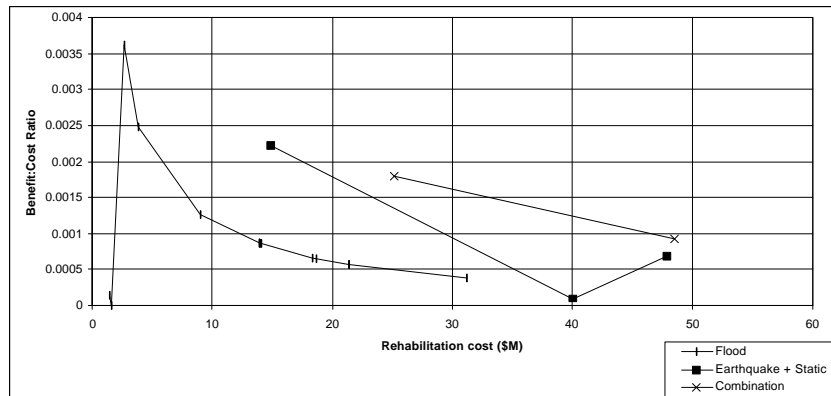


Figure 9. Benefit:cost ratio vs. rehabilitation cost

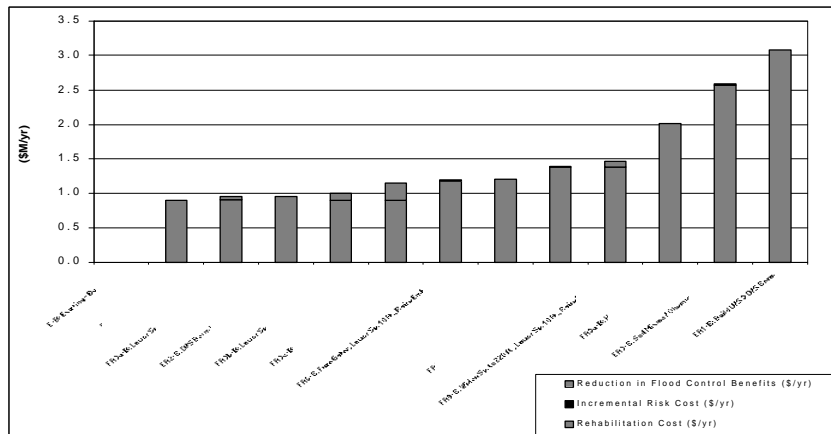


Figure 10. Total economic costs including reduction in flood control benefits

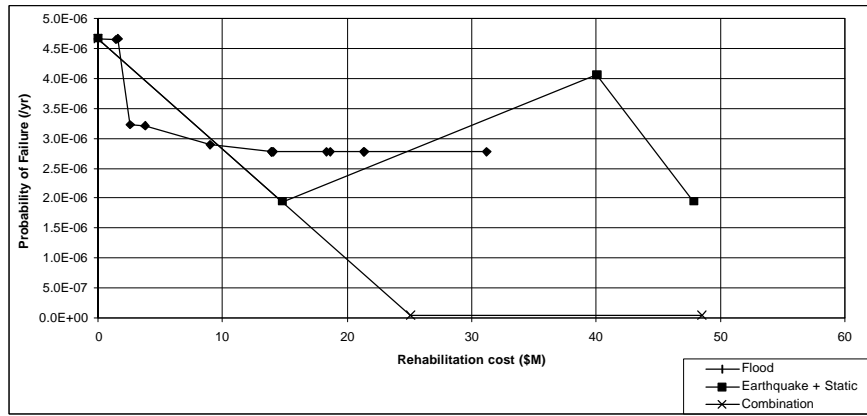


Figure 11. Probability of failure vs. rehabilitation cost

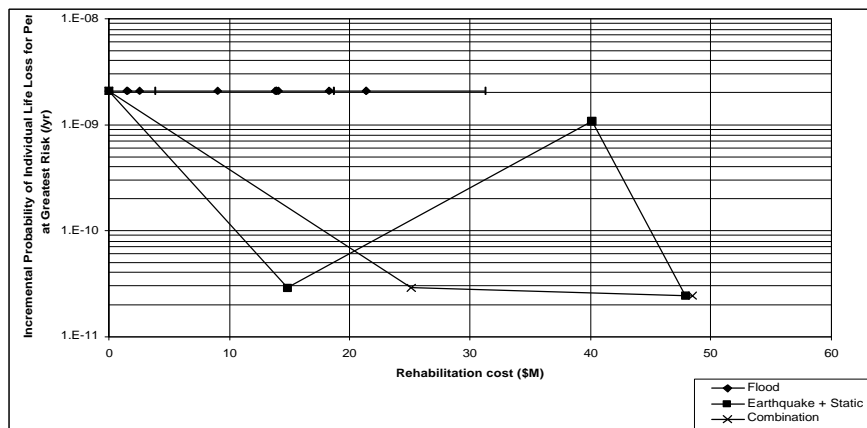


Figure 12. Incremental probability of individual life loss for person at greatest risk vs. rehabilitation cost

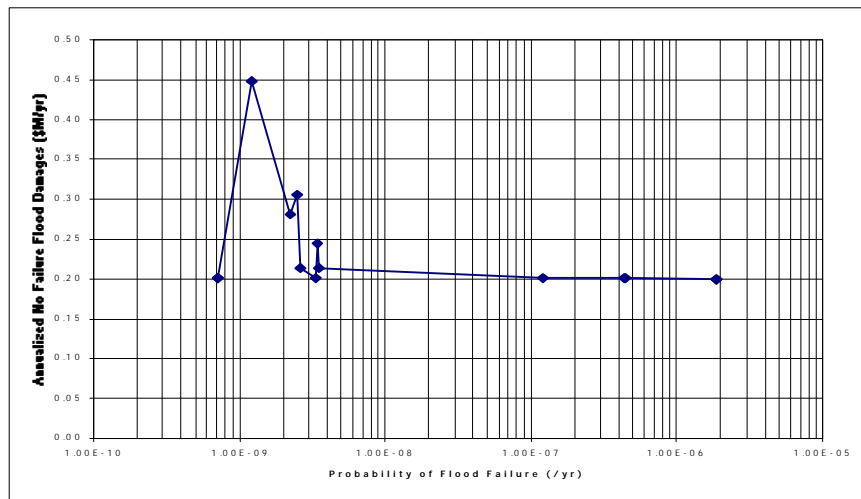


Figure 13. Annualized no failure flood damages vs. probability of flood failure

Recommendations

Before any long term risk-decisions are made on fixes for the Alamo dam, other than perhaps the less costly toe erosion and wave protection measures, various inputs to this DRA should be reviewed and strengthened to the extent that they will affect RA results. The RA should be rerun with the improved inputs. The following inputs are listed in order of their expected cost effectiveness, that is, the expected improvements in the quality, defensibility and confidence in the RA outcomes relative to the expected costs of obtaining them:

- 1) Static slope stability failure probabilities.
- 2) Potential for failure of Parker Dam.
- 3) Life loss estimates.
- 4) Potential for liquefaction through a better definition of foundation conditions.
- 5) Flood SRPs.
- 6) A site-specific earthquake loading relationship.
- 7) Flood loading relationship.

RISK ASSESSMENT PROCESS: EVALUATION AND RECOMMENDATIONS

Evaluation

The DRA showed that with experienced facilitation USACE District technical staff can conduct a dam safety RA and that a reasonably detailed RA can be accomplished for about the same budget as most USACE major rehabilitation studies. Some savings in effort could have been achieved if it were not for the demonstration nature of this project. Through portfolio risk assessment, resources available to perform RAs can be allocated to those dams which are most likely to yield returns. Some supporting analyses could have been improved with additional time and funding, but in the spirit of a staged approach to RA, these are addressed in recommendations for a more detailed update to the DRA.

LA District team members stated that the RA approach appeared to be a natural and holistic approach that should lead to better dam safety evaluation and design. They also stated that the RA results from the RA seemed to make sense. Improved insights into the dam safety issues of Alamo Dam were obtained through the RA process and it is unlikely that these insights would have been developed through the traditional approach.

Recommendations

Procedures should be developed so that the USACE can carry out RAs with achieve quality and consistency across the agency. Some requirements of the USACE DSAP and the Major Rehabilitation Program will need to be revised so that the results of RA can be incorporated into them. Other USACE R&D needs that were identified included the following:

- Characterization of the AEPs for a wide range of floods and earthquakes.
- Procedures for estimation of SRPs, including analytical approaches, subjective estimation protocols, and case histories.
- Procedure for characterizing flood travel times for failure and no failure flood waves.
- Improved procedures for obtaining life loss estimates.
- A practical uncertainty analysis approach.
- Development of guidance for risk-enhanced evaluation of dams.

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