RISK IS NOT A FOUR LETTER WORD: TEN YEARS OF SUCCESS USING A RISK-BASED DAM SAFETY APPROACH IN WASHINGTON

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INTRODUCTION

This paper discusses the application of probability and risk concepts in the state of Washington's dam safety program. Our approach can be characterized as employing risk concepts in a standards-based framework, and using a risk-based prioritization scheme to correct dam safety deficiencies. Under this approach, probability methods, risk concepts, and elements of risk assessment are combined with decision making in setting performance standards that provide acceptable minimum levels of protection. This approach has been quite successful since its implementation in 1990. For similar downstream hazard settings, it has provided consistent levels of protection against flood induced overtopping failures across diverse climatic regions. It has been less successful in addressing the difficult, rapidly evolving seismic concerns confronting the Pacific Northwest. Furthermore, this approach has allowed us to make great progress in repairing the backlog of dams with identified safety deficiencies, as well as design new dams to more consistent standards across the State of Washington.

Why Choose Probabilistic Over Deterministic Approach?

The use of risk-based approaches in the dam safety community is still highly controversial. There is much fear and trepidation among dam safety engineers when "risk" is mentioned in conjunction with dam safety. To many, the word risk implies that we would be designing to accept failure and loss of life, or more insidiously that risk assessment is a way of avoiding making expensive structural repairs to a dam. In addition, many think that using risk entails quantitative risk assessment, a highly complex and time-consuming analysis. Conversely, many dam safety professionals believe that using deterministic standards imply that a dam can pose zero risk to the public (as well as no liability risk to the engineer). Unfortunately, this viewpoint is based on misconceptions in the engineering community about the Probable Maximum Precipitation (PMP) and the Maximum Credible Earthquake (MCE). In reality, these values are estimates of the theoretical maxima that commonly approach, rather than meet, the theoretical upper limits. For example, studies have shown[1] that the annual exceedance probabilities (AEPs) of PMP events vary widely across the nation, from about 10^{-5} to perhaps 10^{-9}. In the Pacific Northwest, PMP events have AEPs that vary from about 10^{-5} on the coast, to 10^{-6} in the Puget Sound region to 10^{-9} in some areas of Eastern Washington[1]. Thus, the use of these values may not only not provide zero risk, they likely do not provide consistent levels of protection across broad geographic areas.

The situation is further complicated when we look at smaller dams where only a few lives would be at risk. This situation represents the majority of dams regulated by Washington and, we believe, most other states (Figure 1). Regulatory organizations have long recognized that PMP and MCE loadings are too stringent for the design/analysis of these smaller projects. Consequently, some percentage of the theoretical maximum PMP is used for hydrologic assessment. An earthquake with a larger probability of exceedance is utilized in the seismic stability assessment. For example, 50% of the PMP is frequently used by many regulatory agencies as the lower bound for smaller dams where only a few lives are at risk. However, when ratios of the PMP are taken, wildly differing levels of protection may result. For example, based on a regional analysis of some 10,000 station-years of precipitation data covering the Pacific Northwest, 50% of the PMP is only about a 100-year event in the marine climate on the Pacific Coast, while being closer to a 10,000-year event in parts of the arid eastern half of the state. Thus, by using ratios of PMP for design or repair of smaller, lower hazard dams, not only are we accepting that the dam is not zero risk, we often have no idea what the level of risk is!

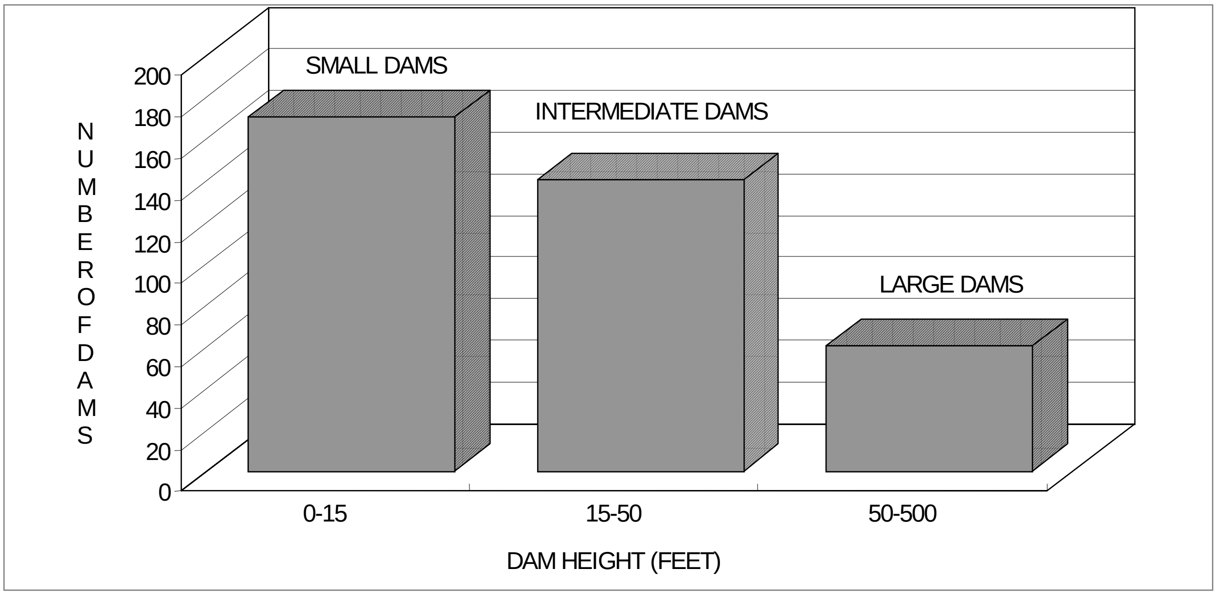


Figure 1 – Dams Sited Above Populated Areas in Washington State

Selection of Risk Based Approach

Recognizing that the PMP/MCE (much less % PMP) approach is not zero risk and provides unbalanced protection across the state, the Dam Safety Office elected to employ a risk-based design approach. This approach was selected based on a number of considerations. The first consideration was the need to provide consistent minimum levels of protection across the state for similar downstream hazard settings. There was also a need to provide methods of analysis that were manageable with limited resources. The state is responsible for over 800 dams, and has limited staffing and resources to apply toward detailed risk assessment. Likewise, most of the regulated community has smaller dams with limited project budgets. Finally, we needed an approach that could be used for the design of new projects as well as for analysis of existing dams. Performing quantitative risk assessments for every project would not be feasible given these considerations. However, employing risk concepts and procedures in a standards-based framework allowed us to address these issues, while realizing the benefits of using a risk-based approach in a relatively simple and inexpensive manner.

We decided to utilize probability and risk concepts in two main areas. The first was to develop risk-based standards for dam design and evaluation of existing dams. These standards were applied through the design step format, which is detailed later in this paper. The second area where these concepts were applied was in the development of a risk-based ranking scheme to prioritize compliance and enforcement efforts on existing dams with identified safety deficiencies.

The combination of both areas was integral to the success of Washington's dam safety program and is detailed in the following sections.

Design Philosophy

The philosophy of the Washington dam safety program utilizes several design principles that provide a framework for evaluating and establishing what design/performance levels are appropriate for the various elements of a dam project. The primary principles related to risk are *Balanced Protection* and *Consequence Dependent Design Levels.*

Balanced Protection - A dam is comprised of numerous critical elements, and like the old chain adage, "is only as strong as the weakest link". The goal of the *Balanced Protection* concept is to establish an appropriate common Annual Exceedance Probability (AEP) as the minimum design level for the evaluation of each critical project element. The term critical project element refers to an aspect of the structure, whose failure could precipitate an uncontrolled release of the reservoir. This office has only achieved partial success in this endeavor. As is noted below, the seismic design aspects lag behind the progress made in the hydrology arena.

Consequence Dependent Design Levels – Standard practice in the civil engineering community is that the degree of conservatism in design should correspond with the consequences of failure of a given element. If failure of a given element could pose a threat of loss of life, design levels are typically much more conservative. That conservatism increases with an increase in the potential magnitude of loss of life and property at risk. This concept is called *Consequence Dependent Design Levels*.

Design Step Format

The philosophies of Balanced Protection and Consequence Dependent Design are implemented through the Design Step Format. This format utilizes eight steps, where the design events become increasingly more stringent as the consequences of failure become more severe. Design Step 1 has an annual exceedance probability of 1 in 500, and would apply where the consequences of dam failure are minimal and there would be no chance for loss of life. Design Step 8 applies to large dams where a dam failure would be catastrophic, with hundreds of lives at risk. In this situation, extreme design loads are used to provide the extremely high levels of reliability needed to properly protect the public. Thus, the AEP of Step 8 is set at 1 in 1,000,000, or the theoretical maximum events (PMP, MCE), whichever is smaller. The design Step 8 AEP of 10^{-6} is based on existing design standards (EPRI[2]) and a review of recommendations for engineered structures with extreme consequences of failure, such as nuclear power plants.

The design step format was completed by providing uniform performance increments between the design steps such that the AEP's decrease tenfold for every two design steps. Figure 2 shows the 8-step format employed by the Washington dam safety program.

Figure 2. Design Step Format

Design Step	Exceedance Probability	Consequence Rating Points
1	1 in 500	< 275
2	1 in 1000	275 - 325
3	1 in 3000 (actually 3160)	326 - 375
4	1 in 10,000	376 - 425
5	1 in 30,000	426 - 475
6	1 in 100,000	476 - 525
7	1 in 300,000	526 - 575
8	1 in 1,000,000 (or theoretical maximum)	> 575

Benchmarks for Selecting Design Steps

A critical question when using risk-based design is "what is 'acceptable' (or tolerable) risk?" This is probably the most controversial aspect of using risk assessment in dam safety. This implies that above some threshold design event/performance level, loss of life would be tolerated. This is actually a common engineering precept used in bridge design, the UBC, and other engineering codes and standards. At the time we were developing our standards, there was very little guidance on tolerable risk criteria in the dam safety field. Thus, rather than try to come up with a definition of tolerable risk on our own, we decided to utilize design levels that would be consistent with the levels of safety provided by other engineering disciplines and governmental regulation. Because the actual levels of protection in many engineering applications are obscured by standards and codes (sometimes intentionally), the actual design levels and probabilities of failure had to be back calculated. This back calculation had been done for the establishment of performance goals in the design and evaluation of Department of Energy facilities[10]. That information, as well as other sources provided background information for setting the benchmarks shown in Figure 3.

Figure 3 – Benchmarks for Calibrating Point rating Algorithm For Use in Decision Framework

BENCHMARK	CHARACTERISTICS OF IDEALIZED PROJECTS	MINIMUM DESIGN STEP	DESIGN/PERFORMANCE GOAL AEP
1	1 or More Lives at Risk	3	3×10^{-4}
2	Large Dam, over 50 feet High No Downstream Hazard	3	3×10^{-4}
3	Intermediate Dam No Commercial Development 10 Residences at Risk	4	10^{-4}
4	Large Dam Limited Commercial Development 34 Residences at Risk	6	10^{-5}
5	Large Dam Significant Commercial Development 100 Residences at Risk	8	10^{-6}

Note: AEP - Annual Exceedance Probability

Additional guidance in setting design levels was obtained by examining the levels of risk to which the public is exposed to in ordinary life. Several of those risks are shown in Figure 4.

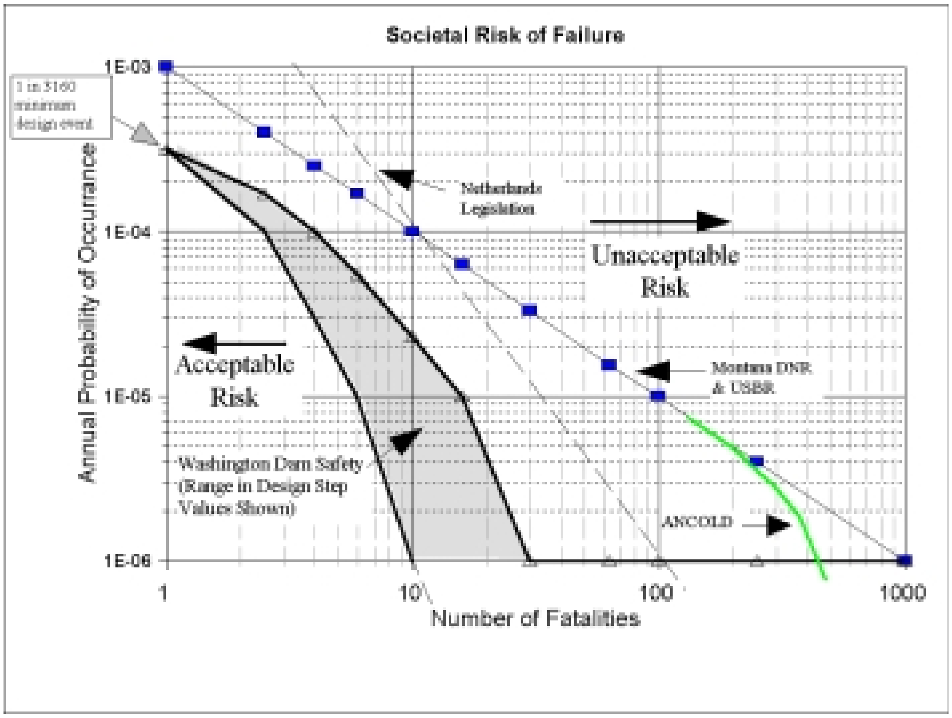
Figure 4 – Listing of Risks and Performance Levels

ACTIVITY/ITEM	TYPICAL NUMBER OF PERSONS AT RISK	RISK LEVEL	PERFORMANCE LEVEL
NATIONAL FLOOD INSURANCE PROGRAM • Risk from Natural Flooding	Varies Widely		1/100 AEP 100 Year Flood
FATAL DISEASE[3] • All Causes	1	1/120 AC	
ASCE STRUCTURAL CODE[4] • Performance of Individual Structural Members for Ordinary Buildings Subject to Natural Hazards due to Wind and Earthquake Loads	Typically 1-20		1/1000 AEP
EXISTING OFFSHORE DRILLING PLATFORMS[5] • Performance Subject to Wind, Wave and Earthquake Loads	Varies 0 – 25		1/1000 AEP
ACCIDENTAL DEATH[6] • All Causes	Few 1-3	1/2000 AC	
ACCIDENTAL DEATH[4] • Motor Vehicles	1-6	1/3000 AC	
ACCIDENTAL DEATH[4] • Non-Motor Vehicles	Few 1-3	1/6000 AC	
UNIFORM BUILDING CODE[7] • Performance of Essential Buildings such as Hospitals and Emergency Response Facilities to Maintain Building Functionality and Protect Occupants for Buildings Subjected to Wind and Earthquake Loads	Typically 50-200		1/5,000 AEP
BRITISH SPILLWAY DESIGN[8]	Small Community More than 30		1/10,000 AEP 10,000 Year Flood
DEPT. OF ENERGY BUILDINGS[9] • Performance of Building to Contain Radioactive or Toxic Materials and Protect Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads	Varies - Often Large Numbers of People at Risk		1/10,000 AEP
DEPT. OF ENERGY BUILDINGS[7] • Very High Confidence of Containment of Radioactive and Toxic Materials and Protection to Occupants for Buildings Subjected to Wind, Flood or Earthquake Loads	Varies - Often Large Numbers of People at Risk Both Onsite and Offsite		1/100,000 AEP
NUCLEAR POWERPLANTS[10] • Damage to Core of Nuclear Powerplant from Earthquakes	Varies Potentially Very Large Numbers of People		1/100,000 AEP
AIR TRANSPORTATION[4] • Fatalities - All Aircraft	Varies 1-300	1/150,000 AC**	
AIR TRANSPORTATION[4] • Fatalities - Commercial Airlines	Varies 50-350	1/700,000 AC**	
NUCLEAR POWERPLANTS[8] • Performance Goal for Radioactive Releases Greater than 25 REM	Varies Potentially Very Large Numbers of People at Risk		1/1,000,000 AEP

Note: AC - Annual Chance of Occurrence AEP - Annual Exceedance Probability ** - Based on an "Average Traveler"

A review of both these tables shows a basic trend. In those activities where few lives are at risk, the public accepts nominal values of protection. Conversely, as the number of persons at risk and the consequences of a failure increase, the level of protection expected by society and the engineering profession increases significantly. This viewpoint is termed "risk-averse" with regard to loss of life. This is illustrated in Figure 6, which shows DSO criteria compared to other risk criteria such as Montana and the USBR[11], which are risk neutral (i.e., a constant value of risk of 1 in 1000 loss of life/year).

Figure 5 – Comparison of Societal Risk Criteria



Additive Point Rating Scheme

The next step in developing the risk-based standards was the development of an additive weighting scheme to determine numerical ratings of the consequences of dam failure. This scheme reflects the relative importance and range of severity of the impacts posed by each consequence. Cumulative rating points with values between 200 and 800 points were used to define the working range for the eight-step format. Factors were selected within the 3 general categories shown in Figure 6, which described the nature of the consequences of dam failure.

Utility curves or consequence rating tables were developed for each of the indicator parameters in Figure 6 to implement the additive weighting scheme. A worksheet (Appendix B, Ref 14) was then developed for compiling the rating points and selecting an appropriate design step. The point rating scheme was calibrated using a wide cross-section of project types and downstream settings to yield results (design steps) consistent with the 5 benchmarks shown in Figure 3.

Figure 6 – Numerical Rating Format for Assessing Consequences of Dam Failure

CONSEQUENCE CATEGORIES	CONSEQUENCE RATING POINTS	INDICATOR PARAMETER	CONSIDERATIONS
CAPITAL VALUE OF PROJECT	0 - 150	DAM HEIGHT	Capital Value of Dam
	0 - 75	PROJECT BENEFITS	Revenue Generation or Value of Reservoir Contents
POTENTIAL FOR LOSS OF LIFE	0 - 75	CATASTROPHIC INDEX	Ratio of Dam Breach Peak Discharge to 100 Year Flood
	0 - 300	POPULATION AT RISK	Population at Risk Potential for Future Development
	0 - 100	ADEQUACY OF WARNING	Likely Adequacy of Warning in Event of Dam Failure
POTENTIAL FOR PROPERTY DAMAGE	0 - 250	ITEMS DAMAGED OR SERVICES DISRUPTED	Residential and Commercial Property Roads, Bridges, Transportation Facilities Lifeline Facilities Community Services Environmental Degradation from Reservoir Contents (Tailings, Wastes.)

Probabilistic Design Data

Before we could implement the risk-based standards described above, magnitude-frequency relationships were needed for extreme events such as floods and earthquakes. Unfortunately, this type of information is not readily available to most states, and much work is still needed around the United States to develop probabilistic precipitation and seismic data for extreme events. In Washington State, we benefited from Dr. Mel Schaefer's detailed studies of extreme storms in the Northwest[12,13], and his development of probabilistic based procedures[14] for generating precipitation magnitude-frequency relationships for any location in the state. Thus, Washington State has the necessary hydrologic data to employ them in a logical and consistent manner in our risk based design/performance practice. This data is used in determining a design storm event with an appropriate AEP to match the design/performance step for the dam in question. This storm is then used to compute the inflow design flood to size the spillway(s) for a new project, or to determine the adequacy of the spillway for an existing dam.

In the seismic arena, we are encountering difficulties on design Step 1 and above in Western Washington and Step 3 and above in Eastern Washington in dealing with the population of existing dams. Our difficulties stem from the severity of the earthquake loadings projected for the Pacific Northwest. Seven interface earthquakes of Moment Magnitude (M_w) 8 or larger are believed to have struck the coast in the last 3500 years[15]. The last event in 1700 was estimated from Japanese tidal records to have been a M_w 9. Thus, all projects in the western half of the state must consider a seismogenic source capable of generating minutes of strong ground motion at a mean recurrence interval of 500 years. With the exception of California, Oregon and Alaska, few other states have to deal with such intense ground motion on so short a mean recurrence interval. In addition, the intensity and duration of shaking yields a high probability of liquefaction. Thus, a significant fraction of the analyses must predict the post-liquefied, deformation response of soils. This is an area of active research in the geotechnical profession. While data is being generated at considerable expense on high profile projects, little guidance is available for extrapolating to the small dams that comprise the majority of the projects under our purview.

Here, any rigorous assessment scheme would face the same difficulties confronting us. In much of the rest of the country the appreciably less intense seismic setting would minimize the difficulties of implementing our design step scheme.

Design Standards for Other Critical Elements

For critical elements at new dam projects where a design loading is not readily applicable (e.g. conduits, seepage), a qualitative approach is used, where redundancy and survivability concepts are employed to achieve adequate reliability against failure. For these critical elements on existing dams, a qualitative approach is used, rather than a quantitative assessment. This is achieved through review of the design and identification of deficiencies for the critical element, coupled with a qualitative assessment of the likelihood of failure based on past experience and engineering judgement. However, we are considering the utilization of some of the more formal risk assessment procedures for these elements currently employed by the Bureau of Reclamation.

Risk Prioritization Scheme

At the close of the 1980's, the Dam Safety Office had over 60 dams listed as having safety deficiencies. Many of these dams were projects inspected under the National Dam Safety Program from 1977-81, and had no action toward making repairs in 10 years. With such a large number of unsafe dams, and limited staffing, it became clear to the DSO that some way of prioritizing these projects was in order. Thus, in conjunction with the development of the risk-based standards described previously, in 1990 the DSO developed a prioritization ranking scheme for dams with safety deficiencies.

The scoring and ranking algorithm developed by the DSO is simple in concept and application, but was been found to be more than adequate for producing an initial ranking of projects. The algorithm is contained within our Microsoft Access database, and a report showing the ranking of projects can be generated by the touch of a key. This ranking is then used as a starting point where other project specific intangibles can be considered by management. The number of projects targeted for enforcement action at any time are chosen to maximize compliance, while not jeopardizing other critical functions of the dam safety program. Typically, this represents an active enforcement workload of about 10 projects.

The underlying logic in the development of this algorithm is fairly simple, and includes the following key ideas:

- For dams with similar deficiencies, those dams with the greatest consequences should be given higher priority.
- For dams with similar consequences, those dams with the more serious deficiencies should be given higher priority.
- For dams with similar deficiencies and similar consequences, those dams with a poorer chance for warning to the public should be given higher priority.
- Dams with only minor deficiencies should be ranked lower than dams with significant deficiencies, regardless of the consequences.
- The risk associated with three minor deficiencies is ranked just below that of one moderate deficiency.
- The risk associated with two moderate deficiencies is ranked just below that of one major deficiency.

- All things being equal, older dams should be given a higher priority.

These concepts were then incorporated into developing the equations for computing the number of priority points. Two different equations were developed for computing the priority points. The first equation is for dams where one or more of the safety deficiencies are rated moderate major or emergency. The second equation is for a project where all deficiencies are rated minor. These equations are shown in Figure 7. Rating points were then developed for the consequences, adequacy of warning, and seriousness of deficiencies, as shown if Figure 8. The points were selected and calibrated to meet the underlying logic goals discussed previously.

Figure 7: Equations for Prioritization Ranking

One or More Safety Deficiencies Rated Moderate, Major or Emergency	**Priority = [*Hazard Class*] + [*Warning*] + [∑(*Seriousness of Deficiencies*)] + [*Age*/2]**
All Safety Deficiencies Rated Minor	**Priority = 0.5 ∗[[*Hazard Class*] + [*Warning*] + [∑(*Seriousness of Deficiencies*)] + [*Age*/2]]**

Figure 8: Rating Points for Prioritization

RATING POINTS FOR CONSEQUENCES – BY HAZARD CLASS	
High Hazard	
Hazard Classification 1A - (100+ homes at risk)	500 points
Hazard Classification 1B – (11-99 homes at risk)	400 points
Hazard Classification 1C – (3-10 homes at risk)	300 points
Significant Hazard	
Hazard Classification 2 – (1 or 2 homes at risk)	200 points
Low Hazard	
Hazard Classification 3 – (0 homes at risk)	100 points
RATING POINTS FOR ADEQUACY OF WARNING	
Inadequate Warning – (< 10 minutes advanced warning)	100 points
Marginal Warning – (between 10 and 30 minutes)	50 points
Adequate Warning – (greater than 30 minutes)	0 points
RATING POINTS FOR SERIOUSNESS OF EACH DEFICIENCY (Primary focus on deficiencies that could lead to a dam failure or uncontrolled release of reservoir)	
Emergency Condition	250 points
Major Deficiency	145 points
Moderate Deficiency	65 points
Uncertain Seriousness	65 points
Minor Deficiency	20 points

The seriousness of safety deficiencies are evaluated based on the matrix in Figure 9. This matrix is intended for guidance only, and ultimately, the final rating of seriousness of deficiencies is based on knowledge of the project and on engineering judgement.

Figure 9 – Matrix for Evaluating Seriousness of Deficiencies

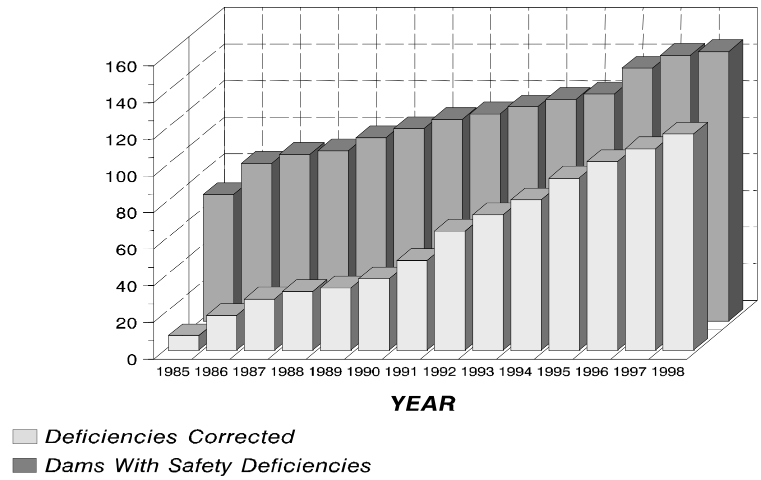
CONDITION	HYDRAULIC ADEQUACY	EMBANKMENT STABILITY	SEEPAGE ON EMBANKMENTS, FOUNDATION, ABUTMENTS	OUTLET CONDUIT(S)
SATISFACTORY	Can accommodate IDF	Meets criteria for static & seismic stability	Minimal seepage consistent with past behavior	KSU Conduit Rating > 8
MINOR DEFICIENCIES	Can only accommodate flood 1 step below Design Step	Meets criteria for static stability, marginal seismic stability under design earthquake	Minor seepage quantity, inconsistent with past behavior No evidence of internal erosion	KSU Conduit Rating 6-8
MODERATE DEFICIENCIES	Can only accommodate flood 2 steps below Design Step	Marginal static stability 1.3 < FS < 1.5 inadequate seismic stability or liquefaction under design earthquake	Moderate seepage quantity Or Anomalous increase in quantity Minor concerns of piping	KSU Conduit Rating 4-6
MAJOR DEFICIENCIES	Can only accommodate flood 3 steps below Design Step	Inadequate static stability 1.0 < FS < 1.3 inadequate seismic stability or liquefaction under design earthquake	Relative Large Seepage Quantity Multiple Points of Seepage And/or Significant concern of piping	KSU Conduit Rating 2-4
EMERGENCY	Cannot Accommodate 25-year Flood	Significant slope failures that intercept dam crest or involve major portion of the embankment	Large or rapidly changing seepage quantity Multiple points of seepage and ongoing piping	KSU Conduit Rating 0-2

CONCLUSIONS

Since its implementation in 1990, the use of the risk-based standards approach has been quite successful in Washington State. It has provided a consistent level of protection against failure between projects located across the state, despite significant differences in seismicity and rainfall. For new dams, we have been able to apply risk concepts in a standards-based approach that is fairly straightforward and easy to use.

For the evaluation of existing dams, we have been able to utilize a combination of probabilistic methods, risk concepts and risk-based standards to determine if the dam has an adequate level of protection against failure. If dams do not meet state standards, we are able to estimate the relative level of risk they currently pose, and prioritize our compliance efforts on those projects with the greatest risk. It has also allowed us to inform dam owners not only that their dams are “unsafe”, but also educate them as to what level of risk their unsafe project poses to the downstream public. In addition, we have utilized a prioritization scheme for compliance efforts on unsafe dams, based on the relative risk of each project. These combined approaches have resulted in great progress in repairing the backlog of dams with identified safety deficiencies in the State of Washington. For example, of the 46 dams inspected under the National Dam Inspection Program still listed as unsafe in 1990, 40 had been repaired by 1999. In addition, 78 of the 101 additional dams identified by the state dam safety program since 1985 have been repaired. Figure 10 shows the cumulative summary of corrective action since 1981.

Figure 10 – Cumulative Number Of Dams Repaired in Washington Since 1981



ASPECTS OF RISK ASSESSMENT THAT MAY BE VALUABLE TO STATE PROGRAMS

Based on our experience, we feel that several aspects of risk assessment and risk management can be of benefit to other dam safety organizations. No matter what standards are used, all dam safety professionals are in the business of managing risk, and the more knowledgeable we are about risk, the better we can make decisions that protect public safety. Using probability and risk concepts allows a dam safety professional to understand the risks and manage them better.

At the 1999 ASDSO/FEMA Specialty Workshop on Risk Assessment for Dams in Logan, Utah, several areas were identified as being potentially of use to state dam safety programs. The areas showing the most promise for the states included qualitative risk assessments such as Failure Mode Evaluation and Analysis (FMEA), prioritization and portfolio approaches, and developing risk-based standards for spillway and/or seismic design, as in Washington and Montana. These areas are highlighted as follows:

- FMEA can be a useful tool, even for those regulators that exclusively use deterministic standards. FMEA allows the regulator a better understanding of the potential site-specific failure modes, the possible failure scenarios and potential consequences, and effective risk reduction measures and dam safety related actions.
- Risk prioritization and portfolio approaches, such as Washington’s, can be valuable tool for states to manage their limited resources toward fixing unsafe dams. Using a prioritization scheme, unsafe projects can be ranked for compliance and enforcement activity, based on the risk that they pose to downstream population. The most critical projects can then be targeted for enforcement action.
- Washington’s risk-based standards approach may be of interest to some states, especially in spillway design. In fact, Montana’s dam safety program has used our example to develop risk based spillway standards of their own. The drawback to implementing these standards on a broader scale is the current lack of probabilistic precipitation data in the U.S. beyond the 500-year event. It can be quite expensive for states to undertake this effort on their own. The Logan workshop identified the need for large-scale regional studies to be performed for probabilities of extreme rainfall events across the U.S. If these studies are completed, then it may be more attractive for some states to implement risk-based spillway standards.

- States using %PMP as a design level for analysis of spillways are already using a non-deterministic standard and by default are accepting risk, but the probability of the %PMP event, and corresponding risk to public safety is unknown. These states may benefit from the aforementioned regional precipitation studies, which would allow them to learn the probability of their %PMP standards. Depending on the results, the states may elect to go to risk-based standards, or may decide to adjust the percentage of PMP to increase or decrease the risk level.

- Quantitative risk assessment is not likely to be a useful tool for most state dam safety programs, due to the lack of probabilistic data, inadequate staffing levels, and amount of effort required to perform an assessment for each dam. Most states regulate a large number of small to medium sized dams, and would not have adequate staffing or resources to complete comprehensive studies on each dam.

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