DAM SAFETY POLICY FOR SPILLWAY DESIGN FLOODS

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ABSTRACT: Dam safety risks are abhorred by the public due to the high impact of dam failures and the subjective way that people perceive risk. Therefore dam safety policies are extremely conservative, often ignoring the cost-benefit question. Unnecessary expenditures made consequent to this are unknown, but would seem to be significant. Cost-benefit issues need a more thorough airing, from both a professional and public perspective. This paper examines different approaches to selection of the spillway design flood (SDF). Opinions concerning dam safety issues were solicited from the heads of the dam safety units in the 50 states. It was found that most states pattern their SDF requirements after the Corps of Engineers guidelines developed pursuant to the National Dam Inspection Act of 1972. Dam safety professionals generally do not believe that the probable maximum flood (PMF) is unreasonably conservative, nor do they believe that existing spillway criteria are too conservative. Further, even though ASCE and the National Research Council endorse the risk analysis concept, it is not popular and is little-used.

INTRODUCTION

The public abhors dam safety risks due to the high impact of dam failures and the subjective way that people perceive risk. As a result dam safety policies are extremely conservative. Policies for selection of the spillway design flood (i.e. policies for protection against overtopping failure) are among the most conservative of dam safety policies. For most important dams, the spillway is designed to pass the probable maximum flood (PMF), essentially a "no risk" policy. In an era when demands on the public treasury are becoming too great, it is essential to allocate funds as efficiently as possible. Efficient allocation of funds for spillways requires a cost-benefit approach that utilizes risk analysis, a much better approach than a "no risk" policy.

In the United States, dam safety regulatory programs are carried out by the federal government for dams in their ownership and by the individual states for nonfederal dams. The resulting patchwork of regulatory approaches leaves considerable room for standard-setting by states, often with little guidance. The question of spillway design flood is a policy area where guidance is generally lacking, and where practices vary considerably.

The purposes of this paper are to report on current practices in determining spillway design floods, to review the history and methods underlying these practices, and to explore the rationale and appropriateness of these practices. Questions of risk relating to both ordinary activities and dam safety standards are discussed. The need for a better understanding of risk issues and consequently a more rational and cost-effective approach to risk issues is highlighted. After a review of the literature about the dam safety practices of states and the federal government, a survey was conducted of state dam safety officials.

A survey questionnaire was mailed to the head of the dam safety unit in each state and Puerto Rico (federal agencies were not included). Names and addresses of these individuals were obtained from the membership directory of the Association of State Dam Safety Officials (ASDSO). Respondents were promised anonymity. The survey asked a total of 34 questions concerning regulations currently in effect in the respondent's organization, and respondent's opinion regarding aspects of early warning systems (EWS), probable maximum precipitation (PMP) and PMF, and risk analysis. Forty-seven of 51 questionnaires were returned. This unusually high rate of response indicates a high level of interest in these issues.

The paper examines different approaches to selection of the spillway design flood (SDF). Methods for selecting the SDF may be generally described as either prescriptive or risk-based. Prescriptive methods are generally rules promulgated by the agency that has jurisdiction. Risk-based methods seek to minimize the total project cost, including the expected cost of damages due to failure. Historical development and theory underlying these methods are examined, and advantages and disadvantages of the various methods are discussed. As risk analysis is a cost-benefit approach, application of risk analysis usually involves quantifying the benefits of saving lives. This has been a major point of contention. A technique known as "cost to save a life" offers an alternative to this stumbling block, and is discussed.

General societal risks, dam safety risks, risk perception, and risk management are discussed. It is found that hydrologic dam safety risks are less than other types of dam safety risks, and far less than other societal risks.

Dam safety professionals who responded to the survey generally do not believe that the PMF is an unreasonably conservative criterion, nor do they believe that existing spillway criteria are too conservative. Further, even though ASCE and the National Research Council (NRC) endorse the risk analysis concept, it is not popular and is little-used. Most states pattern their SDF requirements after the U.S. Army Corps of Engineers (COE) guidelines developed pursuant to the National Dam Inspection Act of 1972.

HISTORICAL OVERVIEW

Dams and the need to protect them with spillways predate recorded history. Interestingly enough, one of the oldest known dams, Sadd el-Kafara near Cairo, may have failed from overtopping. Although some seventh and eighth century dams were built with spillways, the universal use of spillways (in Europe) did not occur until after the Middle Ages. Even then, the widely varying spillway capacities (when measured in relation to drainage area) give evidence that dam builders had no rationale for their designs (Smith 1971; Schnitter 1994).

In 1764, Bossut wrote an empirical text on dam design emphasizing adequate spillways (Smith 1971; Schnitter 1994). During the latter part of the 19th century and the first part of the 20th, projections of stream discharge were based on a variety of "rational" formulas, statistical procedures, or simply taking the flood of record and increasing it by some selected

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factor. These techniques were more or less dependent on the skill and experience of the individual engineer. Factors of safety could not be evaluated (Schnitter 1994; Chow 1964; Cudworth 1989).

In the 1920s, engineers in Ohio's Miami Conservancy District began to develop depth-area-duration relationships based on historic data for use in planning and design (NRC 1985). In the 1930s hydrologic and meteorologic techniques began to be developed for what came to be known as the hydrometeorologic approach to finding an upper limit to precipitation. In 1932 Sherman proposed the unit hydrograph, a keystone concept ever since. In 1933, Horton proposed his infiltration theory, allowing the rational computation of runoff from rainfall (Cudworth 1989).

Even though the 20th century saw a veritable explosion of hydrologic knowledge, there was no professional consensus concerning spillway design criteria. A review of professional literature of the 1950s and 1960s shows a good amount of discussion on the subject but disagreement as to what constituted appropriate design standards.

Present-day spillway design policies are rooted in the National Dam Inspection Act of 1972. The COE was charged with carrying out the provisions of this act; consequently they promulgated a system of dam sizes, dam hazard classifications, and spillway design floods based on those parameters (Tables 1, 2, and 3). Although the COE system was developed as a guideline for use in the Phase 1 screening inspection, these guidelines have been adopted in whole or in part as design standards by many states.

In the 1980s, a different approach to the spillway design flood question emerged: risk analysis. Risk analysis seeks to minimize the total project cost, including the expected cost of damages due to failure (risk cost). This approach is generally superior to traditional prescriptive standards in that it is a rational problem-solving method that addresses the cost-benefit question. It has received a lukewarm reception from the professional community.

TABLE 1. U.S. Army Corps of Engineers Spillway Design Floods (1979)

Hazard classification (1)	Dam Size		
	Large (2)	Intermediate (3)	Small (4)
High	PMF	PMF	0.5 to full PMF
Significant	PMF	0.5 to full PMF	100-year flood to 0.5 PMF
Low	0.5 to full PMF	100-year flood to 0.5 PMF	50 to 100-year flood

TABLE 2. U.S. Army Corps of Engineers Dam Sizes (1979)

Dam size (1)	Impoundment, $m^3 \times 10^3$ (acre-ft) (2)	Dam height, m (ft) (3)
Small	$62 \leq I < 1{,}233$ ($50 \leq I < 1{,}000$)	$7.6 \leq H < 12.2$ ($25 \leq H < 40$)
Intermediate	$1{,}233 \leq I < 61{,}674$ ($1{,}000 \leq I < 50{,}000$)	$12.2 \leq H < 30.5$ ($40 \leq H < 100$)
Large	$\geq 61{,}674$ ($\geq 50{,}000$)	≥ 30.5 (≥ 100)

Note: Criterion placing dam in largest category governs.

TABLE 3. U.S. Army Corps of Engineers Hazard Classifications (1979)

Hazard classification (1)	Loss of life (2)	Economic loss (3)
Low (or III)	None	Minimal
Significant (or II)	Few	Appreciable
High (or I)	>Few	Excessive

RISK

Risk assessment is at the heart of dam safety programs. Risk is part of life. We all encounter risks every day. The relevant question then is, "How can we manage risk?", not "How can we eliminate risk?"

Dam safety risk standards are found to be different for different design events, and more conservative than standards for other societal risks. People perceive risk subjectively, complicating the issues.

Dam Safety Risks

Dams are designed to resist destruction from such natural forces as are expected to act on them. Two major items of design consideration are the SDF and the maximum credible earthquake (MCE). The function of the (emergency) spillway is to safely pass flood flows and thus protect the dam from overtopping failure. The cost of the spillway may be a significant portion of the cost of the dam. As the SDF approaches the PMF, the probability of overtopping failure approaches zero but the cost of the spillway approaches its maximum. The question then becomes, "What is the appropriate probability of overtopping failure, and consequently the appropriate SDF to incorporate into the design?" For most important dams, the PMF is chosen as the SDF. This says in effect "We want the probability of overtopping failure to be zero." Two chief criticisms of this policy are: (1) zero failure probability is a "no risk" policy—and "no risk" is not a reasonable goal, and (2) the cost-benefit question is ignored. This is not to say that the PMF is never the appropriate SDF; in fact it may be the appropriate choice in many instances. However, the choice of the PMF as a "no risk" criterion ignores the economic facts of life and is counter to stated policy of the NRC and ASCE (NRC 1985; ASCE 1988).

It should be noted that while the probability of occurrence of the PMF is virtually zero, it is not literally zero. The exceedence probability is generally taken to be in the range of 10^{-4} to 10^{-7} for calculation purposes, however this is considered conservative (in most cases), i.e. the actual exceedence probability is smaller. It is easy to postulate combinations of possible, but unlikely, events leading to PMF probabilities smaller than 10^{-12}. "The exceedence probability of the PMF, assuming it is correctly defined, is essentially zero" (ASCE 1988). Therefore when we state herein that the use of the PMF as a prescriptive criterion represents a "no risk" policy having "zero" probability of failure, it is understood that the probability is virtually, not literally, zero.

The MCE is often the earthquake criterion for important dams, but, like the PMF, it has no well-defined exceedence probability. In general, earthquakes of like magnitude occurring in the eastern United States have return periods five to 10 times longer than similar events in the west. Along the southern portion of the San Andreas fault in California, the return period for earthquakes of magnitude 8+ is about 150 yr (NRC 1985). The return period for earthquakes of the same magnitude in other areas in California is estimated to be twice as long. In general, the return period of the MCE is about 500–1,000 years, less along major faults. "It seems clear that the earthquakes adopted for safety evaluations do not represent as rare phenomena as do probable maximum precipitation estimates . . ." (NRC 1985). "Thus an individual dam is 10–1,000 times more likely to experience the design earthquake than it is to experience the design flood" (Lave et al. 1990). It does not seem reasonable that design criteria specify, in effect, different probabilities of failure for different modes of failure.

The vast majority of existing dams were built under regulations less stringent than those now existing. Thus it is quite common to find spillways on existing dams that fail to meet current hydrologic criteria. An estimate of the amount needed to correct this problem nationwide is not available, but is thought to be in the billions of dollars (NRC 1985). Also, precipitation estimates tend to increase as time goes by, resulting not only in more dams being found deficient, but possibly rendering retrofitted dams deficient again.

These kinds of problems are common in risk management. New information is always becoming available. We frequently find our existing standards or criteria do not square with our new information. The question then becomes whether or not these kinds of things should constantly trigger rehabilitative work. It is the opinion of the Committee on Safety Criteria for Dams, Water Science and Technology Board, Commission on Engineering, and Technical Systems of the National Research Council that the answer is to balance the costs and benefits. This not to say that "unsafe" dams are to be tolerated. Rather it is a situation where some dams will be "extremely safe," while others are "very safe" (NRC 1985).

An alternative to structural retrofitting can be an early warning system (EWS). Such a system is commonly an integrated hardware-software system used to collect and process data concerning extreme events, e.g. heavy precipitation. If analysis of incoming data shows danger is imminent, warnings are issued. This approach may not only be less costly than structural measures, but may also be more effective in saving lives. The opinion survey found lukewarm reception to the EWS concept: 43% of respondents do not permit EWSs in their states and 57% "somewhat" or "strongly" disagreed that an EWS was a viable substitute for a regulation-sized spillway. Note: some respondents apparently confused EWS with an emergency action plan (EAP).

General Societal Risks

Accidents cause about 4% of all deaths in the United States. About half of all accidental deaths are motor vehicle deaths. Deaths resulting from dam failure are, on average, less likely than those from lightning strikes or bee stings (National Safety Council 1994; Lave et al. 1990). In general, people seem unconcerned about dying in a car wreck, which is relatively likely, but seem concerned about high-impact disasters such as dam failures, which are relatively unlikely. This is due to the subjective way that people perceive risk. People are adverse to high-impact, single-source risks, imposed risks, and risks that they seem to have no control over (Wium 1988). Although efforts to quantify risk perception have had some success, it is found that laypersons and risk professionals do not perceive risk in the same way (Hohenemser 1983).

It appears failure probabilities attached to other technologies may be significantly greater than failure probabilities attached to dam failure. The Uniform Building Code, as applied to multistory apartment buildings in Los Angeles, implies, in effect, that the probability of total collapse in an earthquake is about 9.3×10^{-4}, i.e. a return period of about 1,000 years (based on a 1976 model) (Lave et al. 1990). Use of the PMF as the SDF costs more per life saved than "virtually any other social decision" (Lave et al. 1990).

Risk Management

Interestingly, people often seem more concerned with effort to manage risk than with the risk itself (Wium 1988). When setting risk management standards, government is continually faced with the problem of making optimum use of assets. For example, dams could be made extremely safe from overtopping if spillways were designed for storms much greater than the PMF. Similarly, traffic deaths could be markedly reduced if all vehicles were modified so as to have a top speed of 40 km/h (25 mph). Most would agree such radical measures are not within the realm of reason. Government has not set specific target levels for acceptable risk. Owing to the multifaceted nature of the problem it is unlikely a comprehensive risk policy embracing all activities can be developed. The National Research Council attempted to compare dam safety standards regarding flood and earthquake criteria to other standards for public safety. It found safety standards were so subject-specific that such comparisons were not practical (NRC 1985).

Lave (1981) identified eight regulatory frameworks, one that he termed "no risk." This concept says that the public should be exposed to no additional risk from the proposed activity. While offering initial appeal, this policy provides simple answers to complex problems, misallocates resources, and closes the door on future solutions. Lave says although it has been written into legislation, it is "a straw man unworthy of serious consideration." The PMF SDF is a "no risk" policy.

Some risk management standards appear to be so expensive that they are not within the realm of reason. For example, the Occupational Safety and Health Administration (OSHA) requirement to reduce acrylonitrile from 1.0 parts per million (ppm) to 0.2 ppm carries a price tag of $169,200,000 per life saved (Graham and Vaupel 1981). There are no data regarding life value which can justify such expenditure. Regulatory costs in the United States are enormous. The Harvard Center for Risk Analysis (directed by John Graham) has estimated federal risk regulations cost nearly $600 billion annually while returning annual benefits of only $200 billion (Bradford and Powers 1995). It is important that regulations consider cost-benefit. Dam safety regulations are not "bad," and may be reasonable in many instances. What has not happened, and what is needed, is rational effort to determine the cost effectiveness of spillway criteria.

APPROACHES TO SELECTION OF THE SPILLWAY DESIGN FLOOD

There are essentially two approaches to selection of the SDF: prescriptive standards and risk analysis. Prescriptive standards prescribe the required SDF on the basis of some system of dam size and hazard classification. Risk analysis attempts to minimize the total cost of the structure, including the expected cost of damages due to failure.

Prescriptive Standards

This approach classifies the dam according to hazard, i.e. the anticipated effects downstream in the event of failure. Usually three, sometimes four classification levels are used (Table 3). A second classification of the dam is made on the basis of size. Again, usually three, sometimes four classification levels are used. As the destructive potential of the impounded water depends on the head (dam height) and the volume impounded, classification is usually based on these parameters (Table 2). The SDF is found by consulting the regulations of the authority having jurisdiction.

Risk Analysis

Risk analysis is based on the idea that the appropriate SDF is that producing the minimum total project cost, where that total cost is the sum of the structure cost and the expected cost of damages due to failure. As the spillway size is increased, the structure cost is also increased, but the probability of (overtopping) failure becomes less and so the expected cost of failure damages becomes less. There is some point that the sum of the two costs is minimum; this is the appropriate SDF/spillway choice. The concept is simple but the application is not.

A common format for formal risk assessment follows these five steps (NRC 1983):

1. Identification of critical events and occurrence probabilities associated with those events.
2. Identification of potential failure modes associated with the events from step one.
3. Consideration of a range of load levels for the previously identified loading conditions and calculation of the probability of failure in the failure mode of interest for each load increment. This step is "perhaps the most difficult" and "one of the fundamental differences between a risk-based safety assessment and the 'maximum event' analysis that is in common practice."
4. Determination of downstream failure consequences.
5. Calculation of the risk costs (expected losses) pursuant to each failure scenario. This cost is the sum of the "product of the likelihood of the loading condition, the likelihood of dam failure in different modes given the loading condition, and the cost of the damages resulting from that failure mode." The total risk cost is the sum of the risk costs for each failure mode.

Incremental Damage Analysis

Incremental damage analysis (IDA) is a variation of risk analysis. IDA looks only at the hydraulic aspects of the problem; it does not address the economic aspects. The idea behind IDA is that if the storm flood is large in relation to the dam break flood, downstream damages may be insignificantly different with the dam break flood than without it. A series of floods is routed with and without dam break, and downstream damages are analyzed for each case. The smallest flood that the damage increment due to the addition of the dam break flood is inconsequential becomes the SDF.

The opinion survey found 57% of respondents recognize the IDA concept, 15% do not, and 23% have never had the occasion to consider it.

ANALYSIS OF CURRENT PRACTICES

Most state and federal agencies use prescriptive standards and a situation matrix similar to Table 1. The ideas underlying this can be traced back to the 1950s and 1960s. The COE "Phase I" dam inspection program undertaken pursuant to the National Dam Inspection Act consolidated and formalized these ideas into the prescriptive approach often seen today. Although risk analysis is a rational site-specific approach to the SDF selection problem, it is laborious to apply and is generally unpopular. Application of risk analysis involves valuing human life, long a major sticking point. Litigiousness contributes to the problem.

Background

In 1955, the Committee on Hydrology of the Hydraulics Division of ASCE formed the Task Force on Spillway Design Floods. The Task Force developed this hazard classification system (Banks 1964):

- Class 1: Failure cannot be tolerated.
- Class 2: Failure results in serious economic loss.
- Class 3: Failure results in minor damage.

Clearly, the I–II–III hazard classification system (Table 3) in widespread use today is directly descended from this. One of the Task Force members, Franklin Snyder, developed a SDF selection matrix (Table 4). His matrix used the I–II–III hazard classification and recommended SDFs ranging from the PMF to the 50-yr flood (Snyder 1964).

TABLE 4. Snyder's Classification of Dams (1964)

	Danger Potential		Damage Potential		
Category (1)	Impoundment, $m^3 \times 10^3$ (acre-ft) (2)	Height, m (ft) (3)	Loss of life (4)	Damage (5)	SDF (6)
Major; failure intolerable	>61,674 (>50,000)	>18.3 (>60)	Considerable	Excessive or policy-defined	PMF
Intermediate	1,233 to 61,674 (1,000 to 50,000)	12.2 to 30.5 (40 to 100)	Possible but small	Owner ability to pay	SPF
Minor	<1,233 (<1,000)	<15.2 (<50)	None	Dam cost	50–100 yr

On August 8, 1972, the National Dam Inspection Act became law. The COE was charged with implementing provisions of the Act. The Act did not set dam safety requirements; it provided that the COE would "carry out a national program of inspection of dams for the purpose of protecting human life and property" (COE 1975). A survey of state and federal dam safety programs was conducted and found dam safety efforts were very irregular from state to state and agency to agency, and were poor in many instances (ASCE 1976). The COE began what was known as the "Phase 1" inspection program. The purpose of this Phase 1 inspection was to "identify expeditiously those dams which may pose hazards to human life or property" (COE 1975).

The COE adopted the dam size and hazard classification criteria shown in Tables 2 and 3, and the SDF matrix shown in Table 1 (COE 1979). Similarities between Snyder's matrix (Table 4) and Tables 2 and 1 are obvious. It is interesting to note in Table 1 the use of partial PMF. This is open to criticism due to pronounced differences in exceedence probabilities for partial PMP-sized storms from one area of the country to another (ASCE 1988). The COE offers no rationale for this, saying only "where a range of SDF is indicated, the magnitude that most closely relates to the involved risk should be selected" (COE 1975). The origin of the partial PMF idea seems to have been Snyder's matrix, where he shows the standard project flood (SPF) as the SDF for some dams. He notes that the SPF is usually about 50% of the PMF.

It is significant to note that the Phase 1 inspection program was a screening effort; these criteria were adopted as guidelines to that effort. In the words of the COE:

> The recommended guidelines for the safety inspection of dams were prepared to outline principal factors to be weighed in the determination of existing or potential hazards and to define the scope of activities to be undertaken in the safety inspection of dams. *The establishment of rigid criteria or standards is not intended.* Safety must be evaluated in the light of peculiarities and local conditions at a particular dam and in recognition of the many factors involved, some of which may not be precisely known. This can only be done by competent, experienced engineering judgement, which the guidelines are intended to supplement and not supplant. The guidelines are intended to be flexible, and the proper flexibility must be achieved through the employment of experienced engineering personnel. . . .
>
> The guidelines were developed with the help of several Federal agencies and many State agencies, professional engineering organizations, and private engineers. In reviewing two drafts of the guidelines they have contributed many helpful suggestions. Their contributions are deeply appre-

ciated and have made it possible to evolve a document representing a consensus of the engineering fraternity. As experience is gained with use of the guidelines, suggestions for future revisions will be generated. All such suggestions should be directed to [address] (COE 1979) (emphasis added).

Although the COE guidelines were not promulgated as design standards, they have been adopted as such by many states. The opinion survey found 46% of respondents "closely follow" these guidelines, while an additional 27% "loosely follow" them.

The guidelines have been criticized as being arbitrary and failing to address the cost-benefit question. The COE stated (in the preceding paragraphs) that the guidelines were a "consensus of the engineering fraternity." One critic countered that the COE had influenced this fraternity for years, implying that consequently their thinking was COE thinking, and vice versa (ASCE 1976, 1988; NRC 1985).

Prescriptive Guidelines for SDF

Prescriptive guidelines for determination of the SDF are those such as the COE guidelines discussed previously. They prescribe the required SDF based on a situation matrix, usually that based on dam size and hazard classification. Usually the prescribed SDF will be either PMP-based or be a flood of some given exceedence probability. These sorts of guidelines or standards have long been used in most aspects of engineering. Advantages and disadvantages of such standards may be summarized as follows (Krouse 1986):

Advantages:

- Standards represent a procedure easy to teach and transfer to new engineers
- Standards provide equity, as like projects have like criteria
- Standards in use have been proven over time
- Any standard implies a level of risk which is generally understood and agreed on by the profession
- Standards provide a practical way of making decisions
- Standards integrate a large body of experience into a decision
- Standards may limit legal liability and protect the integrity of the design organization
- Standards are economical to use, i.e. no large study costs

Disadvantages:

- The economic efficiency of the standard is unknown
- Standards may be obsolescent
- Standards may limit design flexibility
- Standards may be irrationally based
- Standards do not promote a clear definition of the problem
- Standards tend to discourage innovation
- Standards obscure information about risks, costs, and benefits

The opinion survey found 50% of respondents have regulations which are primarily prescriptive, but consider risk-based designs on a case by case basis. Thirty-eight percent use prescriptive regulations exclusively. Thus 88% of respondents make heavy use of prescribed standards.

Deterministic SDF Criteria

The PMF is widely used as the SDF for important structures. There is basic agreement regarding the events to postulate in a PMF determination, however there is significant disagreement regarding the appropriate magnitude of events to combine. As a result, there can be significant differences in computed flood peaks, volumes, and exceedence probabilities (ASCE 1988).

Other criticisms of the PMP/PMF criteria are

1. Use of the PMP/PMF criteria "suggests that the ability to predict future extreme floods is greater than that which actually exists and leads to unrealistic expectations on the part of the public" (Dawdy and Lettenmaier 1987).
2. Use of the PMP/PMF criteria may give the illusion of absolute safety, thus diverting our attention from the greater flood risk which often may result from less extreme but more likely events (NRC 1985).
3. The extremely small exceedence probability of the PMF as a standard for public safety is not used elsewhere in society, with the possible exception of the nuclear industry.

The opinion survey (Table 5) addresses these topics.

Probabilistic SDF Criteria

Probabilistic SDF criteria are those based on selection of a storm (flood) having some desired exceedence probability. There are two objections to this practice.

1. Selection of the appropriate exceedence probability is purely judgmental. Hence no consistency is inherent in the criteria.
2. It must be recognized that (annual) exceedence probability and the length of the planning period (structure life) are pertinent. The "chance of failure" is not equal to the selected exceedence probability.

Risk Analysis

The risk analysis concept has been described. Risk analysis is considered to be the superior approach to the SDF question because it is a rational problem-solving site-specific approach that considers cost-benefit. The NRC and ASCE endorse this concept (NRC 1985; ASCE 1988). Risk analysis is criticized because (NRC 1985; ASCE 1988):

- It is time consuming and expensive to perform.
- There is lack of professional consensus regarding its application.
- It is difficult to estimate the probability of extreme events (Stedinger and Grygier 1985; Prakash 1989).

TABLE 5. Professional Opinion regarding PMF/SDF (Percent Response)

Statement (1)	Agree strongly (2)	Agree somewhat (3)	Undecided (4)	Disagree somewhat (5)	Disagree strongly (6)	No opinion (7)	No response (8)
There is no generally recognized method for developing PMP values	10	38	10	13	23	4	2
Public believes probability of PMP is too remote	53	23	4	11	6	2	0
Respondent believes probability of PMP is too remote	0	17	2	17	60	2	2
Nationally, spillway hydrologic criteria are too conservative	2	21	11	17	40	9	0
Locally, spillway hydrologic criteria are too conservative	6	15	2	21	49	4	2

TABLE 6. Professional Opinion regarding Risk Analysis (Percent Response)

Statement (1)	Agree strongly (2)	Agree somewhat (3)	Undecided (4)	Disagree somewhat (5)	Disagree strongly (6)	No opinion (7)	No response (8)
RA is the best, most logical approach to selecting the SDF	0	23	21	15	26	9	6
RA is not useful due to aspects that cannot be quantified	17	38	13	19	4	6	4
RA is too complex to be useful	15	19	6	32	13	11	4
Economic analysis is meaningless; only the dam owner benefits	15	47	13	9	6	6	4
Economic analysis is invalid without enforced victim compensation	13	30	13	9	6	26	4
Defining probabilities of extreme events is a big problem	30	36	4	11	4	13	2
Defining probabilities of uncertain events is a big problem	26	40	9	13	2	9	2
Too many intangibles and judgement decisions	11	43	11	19	4	11	2
Downstream hazard changes are a problem	28	34	11	15	4	6	2

- It is difficult to accurately predict dam behavior under extreme loads.
- Engineering judgement is said to be precluded.
- Certain aspects of the problem cannot be quantified.
- Economic considerations are not straightforward.
- Changing downstream conditions may render economic evaluations invalid. Regarding this last point, the opinion survey found 74% of respondents consider changing conditions in the downstream hazard zone to be a "big" or "moderate" problem. Eighty-one percent of respondents cannot control development in the downstream hazard zone. (Such control is usually effected through land-use regulation, normally addressed at the local, rather than state level.)

Advantages of risk analysis are:

- It is site-specific.
- It provides an additional source of information.
- It may identify aspects of the problem otherwise undetected.
- It addresses the cost-benefit question. Therefore, significant construction expenses, including retrofitting expenses may possibly be avoided (Bowles 1990). Over-design practices once considered acceptable are not longer economically viable (NRC 1985).

Proponents of risk analysis do not declare that risk analysis is "the answer," rather it is a tool providing information to the decision maker. In 1979, the Federal Emergency Management Agency (FEMA) was cautiously optimistic about risk analysis, stating, "With further refinement and improvement, risk-based analysis will probably gain wider acceptance . . . as a major aid to decision-making . . ." FEMA also noted that risk analysis could not become a substitute for "sound professional judgement" (FEMA 1979). A 1989 report noted, "states appear to be making growing use of risk-related rationale or methods for selecting spillway design floods . . ." (ASDSO 1990). Nevertheless, virtually all states name the full or partial PMF as the SDF criterion for major dams. (ASDSO 1992, 1995) Many states will, however, consider alternate designs which are risk-based.

The opinion survey asked a number of questions regarding risk analysis and found:

- Thirty-four percent of respondents are familiar with *Evaluation procedures for hydrologic safety of dams* (ASCE 1988). Thirty-eight percent are "somewhat" familiar with it and 28% are not familiar with it.
- Forty-three percent permit risk-based designs, while 19% do not.
- Forty-eight percent stated their agency had never reviewed a risk-based design.
- Forty-five percent stated risk analysis is a viable method for selecting the SDF in "most" or "some" instances. Twenty-three percent stated it was viable in "isolated" instances. Fifteen percent stated it should never be used.
- Other risk analysis opinions from the survey appear in Table 6.

Monetary Value of Human Life

A basic tenet of risk analysis is economic analysis. Loss of life often results from dam failure. Therefore the economic analysis must somehow address loss of life. This has been and is a problem in the application of risk analysis. People are adverse to placing a dollar value on human life. FEMA states ". . . loss of lives can only be quantified, but not evaluated" (FEMA 1979).

The life value question has been addressed by a number of investigators. Some values found for human life are:

- ≈$250,000 (Buehler 1975)
- $170,000–$715,000 (Graham and Vaupel 1981)
- $300,000–$3,000,000 (Graham and Vaupel 1981)
- $50,000–$8,000,000 (Graham and Vaupel 1981)
- $250,000–$500,000 (Lave 1981)

An interesting alternative to explicitly valuing life was presented by Graham and Vaupel (1981). They analyzed a number of policy alternatives and calculated the "cost to save a life" incurred by moving from one policy to the other. They found that in most instances, the cost to save a life was obviously less than or greater than the ranges they had identified as being reasonable for life value. Thus, the decision to adopt or not adopt the policy could be made without explicitly placing a dollar value on life. Admittedly, one still must establish the "reasonable" range, however, when the cost to save a life becomes $169,200,000, as it did in one case, there can be little defense for the policy.

Litigiousness is a problem in our society. The current legal climate appears to be an impediment to the use of risk analysis. Courts find a way to compensate those perceived as victims (ASCE 1988). Litigiousness is stifling design innovation and causing engineers to reject projects deemed high-risk ("News Briefs" 1995). The opinion survey found 77% of respondents "strongly" or "somewhat" agree that litigiousness forces the professional to choose the most conservative design option.

CONCLUSIONS

Spillway design flood levels, the most conservative element of dam safety policies (which are themselves very conservative) are mostly based on concepts that evolved during the 1950s and 1960s and were formalized at the federal level during implementation of the National Dam Safety Inspection Act of 1972. These criteria have been accepted in a rather uncoordinated way by most states. Spillway design flood criteria are extraordinarily conservative, resulting in what are probably many instances of unjustified expenditures. Dam safety managers do not perceive these criteria as being too conservative, however, and apparently neither does the public as there is no outcry against expenditures required to bring spillways into compliance with stringent standards.

A study was conducted to find the nature, basis and origin of current SDF criteria. As part of this effort, an opinion survey was conducted of dam safety officials in the 50 states to find current opinion regarding regulatory matters, PMP/PMF questions, and risk analysis. It was found that about half the states closely follow the prescriptive guidelines developed by the COE pursuant to the National Dam Inspection Act of 1972. An additional quarter of the states loosely follow these guidelines. The guidelines were developed for use in the Phase I dam safety inspection program, which was a screening effort to identify dams posing a threat to life or property. The SDF criteria used in the Phase I effort were not promulgated as design criteria, and in fact the COE literature stated that the intent was not to establish "rigid criteria or standards." At the time of the 1972 act, dam safety programs in the states were in disarray and were generally poor. As the states moved toward improved dam safety programs, the COE guidelines were often adopted as state regulations. Thus, that which was not intended came to pass.

The basic alternative to the prescriptive COE-type approach is the risk analysis approach. This is an effort to minimize the total project cost, where that total includes the expected cost of dam failure. This approach, endorsed by ASCE and the NRC, is generally unpopular and little used, according to results of the opinion survey. The unpopularity of this method seems to have two roots. First, it is laborious to apply and the review process may raise numerous judgement questions that are difficult to evaluate. Second, from a philosophical viewpoint, many object to the explicit acknowledgement of risk, especially if it affects human life.

It is interesting to note that most risks commonly encountered in daily life are, probability-wise, more significant than the risk of dam failure. Unfortunately, public perception of risk is mostly subjective and these types of situations are difficult to communicate to the public. The public receives much, perhaps most, of its information from television. Since TV news is presented in the most dramatic manner possible, this does not facilitate information transfer or promote a genuine understanding of issues.

Dam safety standards for other design aspects, e.g. seismic loads, are less stringent than SDF standards when measured in terms of failure probability. Dam safety standards are generally more stringent than other societal risk standards, e.g. building codes. These differences in risk standards are unjustified.

Use of the PMF as a prescriptive criterion for the SDF implies a "no risk" stance. The "no risk" stance as a policy statement has obvious attraction, but cannot be justified. This does not mean conservatism (or use of the PMF as SDF) is never appropriate. It means funding for any program or project is finite. Achievement of "no risk" requires "infinite expenditure." Achievement of very low risk may often mean very large expenditure. The public does not seem to understand this, or if they do, they believe "others" will or should pay.

As is often the case with policy issues, the question becomes: "How do we want to allocate the money?" In order to answer this it is necessary to have public debate on the cost-benefit question. It appears that both the profession and the public have neglected this. It seems some believe it is wrong for public policy to explicitly acknowledge that for some stated endeavor a certain degree of risk exists. The unfortunate fact is that risks do exist and accidental deaths do occur. We as a society must decide what portion of our resources we are willing to allocate to reduce such deaths. Clearly, certain expenditures involving construction or retrofitting of spillways are not justifiable. It is the duty of the engineer, and in fact of everyone, to make optimum use of resources.

APPENDIX. REFERENCES

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