# APPLICATION OF PROBABILITY RISK ANALYSIS TO THE SAFETY OF DAMS

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## SUMMARY

Federal guidelines recommend that risk analysis techniques should be considered in establishing priorities for examining and rehabilitating dams for improving their safety. In 1981 Stanford University, under contract with the Federal Emergency Management Agency (FEMA), embarked on a research program to develop a methodology for prioritizing dams based on probabilistic methods of safety assessment. The authors of this paper are the co-principal investigators of this project which is still underway. This paper presents a first-step risk assessment procedure referred to as a screening process. A second-step detailed procedure is being developed.

## INTRODUCTION

The Federal Guidelines for Dam Safety (Ref. 1) recommend that research be conducted to apply probabilistic risk analysis methods to dam safety evaluations such that probabilities of dam failure and potential losses can be estimated. In addition, the guidelines state that "risk analysis techniques should be considered in establishing priorities for examining and rehabilitating dams". On that authority the Federal Emergency Management Agency contracted with Stanford University in 1981 to develop a risk analysis procedure for ranking the existing dams in a jurisdiction. The ultimate objective is to provide the dam owner who must budget limited resources, a means to decide which dams should be upgraded first. To do this, the ranking must be based on the relative safety and cost-effectiveness of alternatives for improvement. The work on this project is still underway. This paper provides a brief summary of a first-step risk assessment procedure referred to as a screening process (Refs. 2 and 3). A second-step detailed procedure is being developed.

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## PROBABILITY OF DAM FAILURE

The events that can initiate the failure of a dam can be grouped in two general categories - internal events associated with deterioration of the dam and the capability of a dam to resist static reservoir loading, and external events such as floods and earthquakes which are isolated situations that impose additional loads on a structure for a limited duration. In our initial approach to the problem, we have defined failure as the uncontrolled release of the contents of a reservoir. Though we have dealt with concrete dams as well as earth dams (Refs 2 & 3), only earth dams will be considered in this paper. The major initiating events that an earth dam may experience are assumed to be independent. For example, the dependence between earthquakes and flood-producing storms can be considered nil. This then leads to:

$$\lambda_T = \sum_{i=1}^{n} \lambda_i \qquad (1)$$

where $\lambda_T$ is the total annual frequency of dam failure and $\lambda_i$ is the annual frequency of failure of a dam to each initiating event. Similarly, $\lambda_T$ could be expressed as a sum of component failure frequencies, where each component may fail due to a number of possible loading conditions. For example, embankment failure may occur as a result of seismic loading, overtopping or piping. In this case the frequency of failure of the embankment is the sum of the individual failure frequencies due to each loading condition.

For a mean failure rate per year, $\lambda_T$, the probability of dam failure in a single year is

$$P(f, t=1) = 1 - e^{-\lambda_T} \qquad (2)$$

In this work all risk assessments are expressed on an annual basis. For example, annual probabilities of dam failure and expected annual losses are typical results that will be determined. However, the user can easily make assessments for the expected lifetime of the dam, if desired.

To evaluate $\lambda_T$ and the probability of dam failure, two steps are required, first the potential initiating events are identified, and second, the frequency of failure to each event is assessed.

### Frequency of Failure due to Hydrologic Events

Failure of a dam can occur from overtopping as a result of inadequate capacity of the spillway to pass the inflow flood. Also, structural failure of the spillway may result at a flow less than spillway capacity, leading to embankment damage and collapse. The inflow may result from natural flows into the reservoir behind the dam, or may be augmented by the failure of an upstream dam. Failure from overtopping is assumed to occur when the depth of overtopping exceeds that which the dam is capable of resisting. Thus, in this case, the depth of overtopping above the dam crest is used as the loading parameter. Determining the frequency of occurrence of different depths of overtopping is achieved through hydrologic analysis which will not be discussed in this paper.

## Frequency of Failure Due to Internal Events

In most preliminary safety evaluation methods an assessment of the structural integrity of a dam is accomplished by observing certain features to assess the level of distress in the structure. For example an earth embankment may be inspected for signs of cracking, depressions, or excess seepage. The severity of an observed pattern of distress is usually assessed using engineering judgment coupled with experience from past dam failures. A similar approach is taken in the screening process.

A Bayesian probabilistic model is used to combine an engineer's evaluation of the condition of a dam with observed historical frequencies of failure. The Bayesian model provides a theoretically sound means of using an engineer's assessment of the reliability of a dam as a basis to modify an observed historical frequency of failure. A set of evaluation scales to assess the condition of earth and concrete dams has been developed for various modes of internal of failure (Refs. 2 and 3).

## Frequency of Failure Due to Seismic Events

Seismic hazards and modes of dam failure due to earthquakes include: failure of the dam due to fault movement, failure due to dynamic slope failure or liquefaction, and overtopping due to a seismic failure of an upstream dam.

The annual frequency of seismically induced dam failure is treated as follows:

$$\lambda_E = -\int \frac{d(\lambda(x))}{dx} P(f|x)\, dx \qquad (3)$$

where:

$\lambda_E$ = annual frequency of dam failure due to seismic events.

$\lambda(x)$ = annual frequency of exceedance of load level x (e.g., peak ground acceleration).

$P(f|x)$ = probability of dam failure given the seismic load level x, where x varies depending on the failure mode (e.g., x may be peak ground acceleration for ground shaking input); this function, is known as a seismic fragility curve.

Procedures for evaluating the seismic hazard $\lambda(x)$ and the fragility $P(f|x)$ are discussed in a later section of this paper.

## CONSEQUENCES OF DAM FAILURE

The level of safety of a dam is related to the direct losses that would occur if the dam were to fail. The direct losses are:

- loss of life
- damage to personal, commercial and public property (e.g., homes, factories, public buildings, roads, bridges, etc.)
- damage to agricultural land and corps.

Other losses which are not considered in this work include the inconvenience and trauma from the disaster, and secondary consequences such as the economic impact of lost revenues and cost of emergency services.

Though we have dealt with economic losses (Refs. 2 and 3), only loss of life will be discussed in this paper.

Quantitative estimates of life loss can be computed for the inundation produced by a particular failure mode as follows:

$$L_i = \sum_j \phi(d) \cdot r \cdot P_j \qquad (4)$$

where $L_i$ is the number of lives lost in inundation area i. In the screening process two types of downstream inundation are considered, floods associated with a hydrologic failure and the floods for all other failure modes[1]. The term $\phi(d)$ defines the percentage of inhabitants that lose their life for a depth of inundation d, and r accounts for the fraction of the inhabitants in zone j at the peak of the inundation. The term r is a function of distance from the dam and whether a warning and evacuation system is in effect. Values of $\phi(d)$ and r have been proposed (Ref. 2).

The depths of inundation in the flooded area downstream of the failed dam are determined through hydraulic and topographic analysis (Ref. 4). The flooded area is broken down into a number of zones based on the depth of inundation and distance from the dam.

## RANKING

### Evaluation of Risk

The risk due to dam failure may be evaluated in terms of the expected annual life loss. The expected annual life loss is determined by,

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[1] Hydrologic failure results from overtopping of the dam while other failure modes may occur at lower reservoir water levels and result in smaller flood waves.

$$E(L) = \sum_i P_i(f, t=1) \cdot L_i \tag{5}$$

where $P_i(f, t=1)$ is the annual probability of dam failure due to failure mode i.

## Ranking

The next step toward assigning priorities to the dams in a jurisdiction is to assess the opportunities to improve the level of safety. That is, a set of safety related remedial measures and the cost of implementing each of them must be determined. The objective is to establish a ranking based on safety assessments and the effectiveness of achieving improved safety levels. For each dam a single, optimum remedial alternative is selected, and then the dams under consideration are ranked according to those that offer the greatest improvement in safety.

A number of alternatives are available to calculate the effectiveness of risk mitigation alternatives. Among these, the cost-per-life-saved is recommended. For each structure being evaluated, a cost-per-life saved ratio is evaluated. A ranking is then established by assigning priorities to those dams with the lowest cost-per-life saved ratio. Alternative criteria can be used to establish the ranking of the dams in a jurisdiction. These include ranking systems based on the probability of failure, economic consequencies (i.e., - annual dollars of reduced damages per annual cost of remedial works), or a combination of life loss and economic risks. Details of such analyses are presented elsewhere (Ref. 2).

## SEISMIC RISK ANALYSIS

A basic step in evaluating the risk of a seismically induced failure is to assess the critical failure modes and develop a fragility curve for each mode which describes the probability of failure as a function of an appropriate seismic load parameter (e.g., peak ground acceleration, peak ground velocity). The other key step is to perform a seismic hazard analysis to evaluate the frequency of the seismic loading parameter associated with each failure mode. The fragility curve for each mode of failure and the seismic hazard input are combined to estimate the frequency of failure for each failure mode. The one with the highest frequency is taken to represent the frequency of dam failure due to seismically induced events. Each of these key steps will now be discussed in turn.

## Seismic Fragility

A seismic fragility curve describes the likelihood of failure as a function of seismic load level. The purpose of the fragility curve is to express the capacity of the dam to resist seismic loads and to incorporate therein the uncertainty in evaluating the capacity. In the case of ground shaking a lognormal distribution is assumed to express the fragility, while a linear distribution is assumed for fault offset. Only the ground shaking mode will be discussed here. The lognormal distribution is used extensively to describe the reliability of structures, dams and equipment subjected to seismic loads (Ref. 5). Given that a fragility curve is assumed to have a lognormal shape, it can be expressed by,

$$P(f|x) = \Phi\left(\ell n(x/\bar{X})/\sigma_x\right) \tag{6}$$

where $\Phi()$ is the standard cumulative normal distribution. The term inside the parenthesis is the standardized normal variate, where $\bar{X}$ is the median value, and $\sigma_x$ is the logarithmic standard deviation. The median, by definition, is that value which has a 0.50 chance of being exceeded. From Eq. 6 it can be seen that the fragility curve is fully described if the median and the logarithmic standard deviation are known. The median corresponds to the best estimate of the capacity of the dam, while the standard deviation represents the uncertainty in the capacity prediction.

Failure of earth embankments by strong ground shaking is usually caused by dynamic instability or liquefaction of saturated cohensionless zones, while failure of concrete dams results most commonly from overstressing of the concrete.

By conducting a series of seismic analyses of a dam employing typical levels of uncertainty in key variables the median value of the fragility and its logarithmic standard deviation can be estimated. Considerable engineering judgement is required in this endeavor. A typical fragility curve for strong ground shaking is shown in Figure 1.

## Seismic Hazard Analysis

A seismic hazard analysis involves an assessment of the frequency that levels of a particular hazard such as ground shaking or fault offset will occur at a site. The frequency of occurence can be expressed on an annual basis or for some future time period.

There are a number of seismic hazards that could impact a dam. They include: ground shaking (vibratory ground motion), fault offset, reservoir waves due to seiche or landslide into the reservoir, and flood due to failure of an upstream dam. Ground shaking and fault offset are generally considered to be the hazards that pose the greatest contribution to seismic risk. The vast majority of failures or instances of damage during seismic events have been the result of ground shaking. Consequently, emphasis in this paper is on ground shaking hazards.

The probabilistic description of ground shaking hazards due to earthquakes is an established element of engineering practice. The probabilistic format to conduct a seismic hazard analysis is well accepted and has been quite stable for many years (Ref. 6). The objective of a probabilistic analysis is to establish the likelihood that levels of the seismic loading parameter of interest will be experienced at a dam site. The steps to conduct a seismic hazard analysis for ground shaking are: review of historic seismicity, identification of seismic source zones, development of earthquake recurrence relationships, selection of an appropriate ground motion attenuation model, and application of a probabilistic model to describe the occurrence of earthquakes. A number of computer programs with user manuals are available to conduct the hazard analysis (Ref. 7). The results of the analysis are generally expressed in terms of the annual frequency of exceeding levels of a ground motion parameter (e.g., peak ground acceleration). A typical seismic hazard curve is shown in Figure 1.

## Frequency of Seismic Failure

To determine the frequency of dam failure the fragility curve for the critical failure mode is properly weighted by the frequency of the seismic load. Figure 1 shows an example of seismic hazard and fragility curves to be combined to estimate a frequency of failure. In discrete form the calculation of the failure frequency is given by the following sum,

$$\lambda_E = \sum_{j=1}^{n} P(f|x_j)\ \nu(x_j) \qquad (7)$$

where n is the number of increments used to calculate the sum, x is the seismic load parameter, $P(f|x_j)$ is the seismic fragility curve for a load $x_j$ and $\nu(x_j)$ is the annual frequency of the seismic load $x_j$.

$$\nu(x_j) = \lambda(x_j) - \lambda(x_{j+1}) \qquad (8)$$

$\lambda(x_j)$ = frequency of exceedance at the beginning of internal j

$\lambda(x_{j+1})$ = frequency of exceedance at the end of interval j.

The fragility curve should be discretized at the center of each interval (Fig. 1).

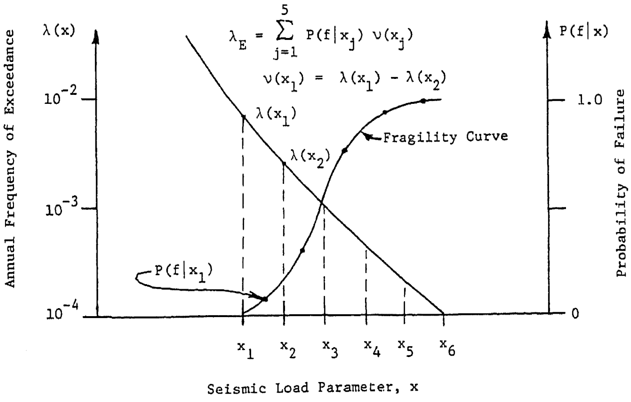

Figure 1

## CONCLUSION

In this paper a general outline of a probabilistic procedure to rank the dams in a jurisdiction is provided. Emphasis is given to the seismic aspects of dam safety assessment. Failure of dams due to hydrologic and internal causes are discussed elsewhere (Ref. 2).

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