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A Framework for Risk Analysis of Earth Dams

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Loren R. Anderson

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OF EARTH DAMS

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ACKNOWLEDGMENTS

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ABSTRACT

Risk Analysis of Earth Dams

by

Jon Clair Howell, Master of Science

Utah State University, 1980

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Department: Geotechnical Engineering

The purpose of this thesis is to present in a logical and straightforward manner, the types of probabilistic, deterministic and judgment methods which should be part of a risk analysis process for earth dam planning, design, construction and operation. In doing this, an attempt was made to include all of the elements (components of the risk analysis procedure defined herein) which were considered to be important. Descriptions of these elements as well as how they are used to estimate probabilities for the occurrence of each of three failure conditions (i.e. no failure, partial failure, complete failure) are also presented. Explanations are given as to how these failure probabilities can be used in estimating the consequences resulting from the failure of an earth dam. The potential use of the failure probabilities in conjunction with estimated consequences in decision making related to all phases of a dam project as well as land use planning near the dam are discussed. The possibility of performing a case study using the data base of Soldier Creek Dam, a project of the Water and Power Resources Service, is also presented.

(93 pages)

CHAPTER I

INTRODUCTION

In most conventional structural analyses, the safety of the
project is usually measured by means of a factor of safety against a
particular failure mode. The question can be raised, however, as to
the confidence which can be placed on such a factor. A-Grivas (1980)
indicates that much literature dealing with the safety factors
of soil structures suggests that failures have occurred with safety
factors being greater than one, while others have shown considerable
success even though the safety factor was less than one. Another
limitation of the safety factor approach is that two designs which
have identical safety factors would have very different probabilities
of failure if the variablity in the soil properties was significantly
different, but this is not accounted for by the conventional analysis.

As a result of recent earth dam failures, particularly Teton Dam
on June 5, 1976, there has been an increasing awareness of the lack of
a comprehensive risk analysis procedure for earth dams. Risk analysis
methods have not been used by engineers for the design of major earth
dams. This is true largely because the general public does not like
to think that there is any probability no matter how small, that a
large structure such as an earth dam could fail. Also, many engineers
question the accuracy of probabilities with computed values of 10^{-7}
or less, especially when they are based on methods using judgment or
past experience. Finally, earth dams are unique in terms of founda-
tion conditions, quantity and quality of available material,

hydrologic conditions, downstream exposure, and many other factors. Therefore, it is difficult to develop a rigorous, clear cut design method for a structure that has so many unique characteristics and is so variable with respect to quality control considerations.

Risk assessment is a method which could be used in an attempt to determine the safety of an engineering project based on probability theory and reliability analysis. The idea of using risk assessment in civil engineering is relatively new but it is becoming more popular in the hope that it might be a means of overcoming the shortcomings associated with the conventional analysis. Several approaches to risk analysis in engineering projects have been proposed in recent years. Bowles, Anderson, and Canfield (1978) proposed a phased risk analysis procedure which utilizes a growing data base to determine the reliability of an engineering project at any time during its life. General risk assessment approaches have been discussed by Rowe (1977) where he emphasized the importance of technical and social value judgments relative to purely empirical scientific consideration in the assessment of risk. Methods have been proposed for earth dam classification by government organizations such as the Soil Conservation Service in an effort to evaluate the risk potential in earth dam projects. A handicap to the implementation of risk analysis procedures for earth dams is the lack of sound procedures for estimating the probabilities of various types of structural performance. One idea in which considerable progress has been made is probabilistic approaches to slope stability analysis which have been proposed by Wu and Kraft (1970), Matsuo and Kuroda (1974), Alonso (1976), Harr (1977), Vanmarcke (1977, 1979), Sharp et al. (1980) and others.

Purpose

As indicated above, there is a need for more research and
development with respect to risk analysis of earth dams. Since risk
analysis is still in its infancy, a foundation is required on which to
build further developments of the method in the future. As well as
a platform for further development, this study is an effort to famil-
iarize the engineer with the general procedure of a comprehensive risk
analysis for earth dams. In doing this, probabilistic modeling,
empirical, and judgment procedures will be proposed to estimate the
probabilities of various failure modes, with their corresponding
outcomes and the ultimate consequences resulting from these failure
modes. A discussion of the potential use of the probability and
damage estimates in decision making related to earth dam planning,
design, construction and operation will also be presented.

Objectives

The specific objectives of this study are summarized below:

A. The establishment of an organized sequential procedure to
estimate the probability of failure of an earth dam while taking as
many variables into account as are considered to be important.

1. Identification of various event-system response-outcome-
    exposure-consequence pathways linking events such as a flood
    or an earthquake to consequences such as property damage

2. Identification of existing or proposed procedures based on
    empirical, analytical, or engineering judgment approaches for
    estimating the probabilities of occurrence of:

    a.   each event

    b.   each system response given that an event takes place

    c.   each outcome given that a system response takes place

    d.   each consequence as a function of various exposure factors given that an outcome takes place

3. The evaluation of the statistical independence of the various probabilities identified in secondary objective 2 along with a proposed procedure for handling nonindependent probabilities

4. Identification of procedures and data needs for estimating the consequences (e.g. dollar damages) of various exposure factors (e.g. time of year, dam location, flood warning time)

5. Discussion of the potential use of the probability and damage estimates in decision making related to earth dam planning, design, construction, and operation (e.g. site selection, selection of design parameters, materials selection, quality control, and operating rules)

B. The establishment of a specific framework of a detailed risk analysis case study of Soldier Creek Dam which should also be applicable to similar structures. This will provide a basis for further development and refinement of this risk analysis method in the future. With the limited research development funds, extensive analytical work will not be performed on Soldier Creek Dam during this initial phase. The identification of the expanding data and information base for Soldier Creek Dam from conceptualization through construction and into operation will be made.

Significance

An advantage of the risk analysis procedure described herein is that the analysis can be tailored to the project's "growing data base." This refers to the data which is available from the initial project planning through operation and maintenance. As the data base grows through more and more investigations, calculations, and tests, the confidence which can be placed on the estimated probability of failure increases. This thesis will outline a probabilistic method which is combined with several empirical and judgment procedures for estimating the probability of failure of an earth dam at any stage in its life. This analysis will utilize state of the art deterministic slope stability methods such as Bishop's method of slices and hydrologic methods for estimation of maximum probable floods. The probability of failure can be used to make more rational decisions on site selection, materials selection, quality control, operating rules, and for reducing risks to acceptable levels. Since the procedure will estimate probability of failure from the beginning of construction throughout the life of the project, it will be very useful in making decisions at any stage before the completion of the project construction as well as through the rest of its life.

CHAPTER II

LITERATURE REVIEW

Introduction

Literature containing examples of methods in which statistical procedures were used to analyze any phase of earth dam construction and operation or to evaluate the overall risk analysis procedure are reviewed in this chapter. The review is divided into sections on risk analysis methods and failure mechanisms.

Risk Analysis Methods

General risk analysis

Rowe (1977) defines risk assessment as the total process of quantifying risk and finding an acceptable level of that risk for an individual group or society. This is illustrated in terms of a hierarchy of risk assessment terminology (see Figure 1). He explains that risk assessment involves both risk determination and risk evaluation. Risk determination involves risk identification and risk estimation and is generally an empirical scientific activity performed by planners. Risk evaluation comprises risk aversion and risk acceptance and is a normative (political) activity. Other pertinent definitions are:

1. Risk - magnitude and probability of occurrence of unwanted or negative outcomes of a water resources project

2. Benefit - magnitude and probability of occurrence of desirable or positive outcomes of a water resources project

```
                    ┌─────────────────┐
                    │      Risk       │
                    │   assessment    │
                    └────────┬────────┘
              ┌──────────────┴──────────────┐
    ┌─────────────────┐            ┌─────────────────┐
    │      Risk       │            │      Risk        │
    │  determination  │            │   evaluation     │
    └────────┬────────┘            └────────┬─────────┘
       ┌─────┴─────┐                  ┌─────┴─────┐
```

Risk identification	Risk estimation	Risk aversion	Risk acceptance

Observe
 	
  New risks
 	
  Change in risk
  parameters
	Determine
	
	  Probability of
	  occurrences
	
	  Magnitude of
	  consequence value
		Determine
		
		  Degree of risk
		  reduction
		
		  Degree of risk
		  avoidance
			Establish
			
			  Risk references
			
			  Risk referents
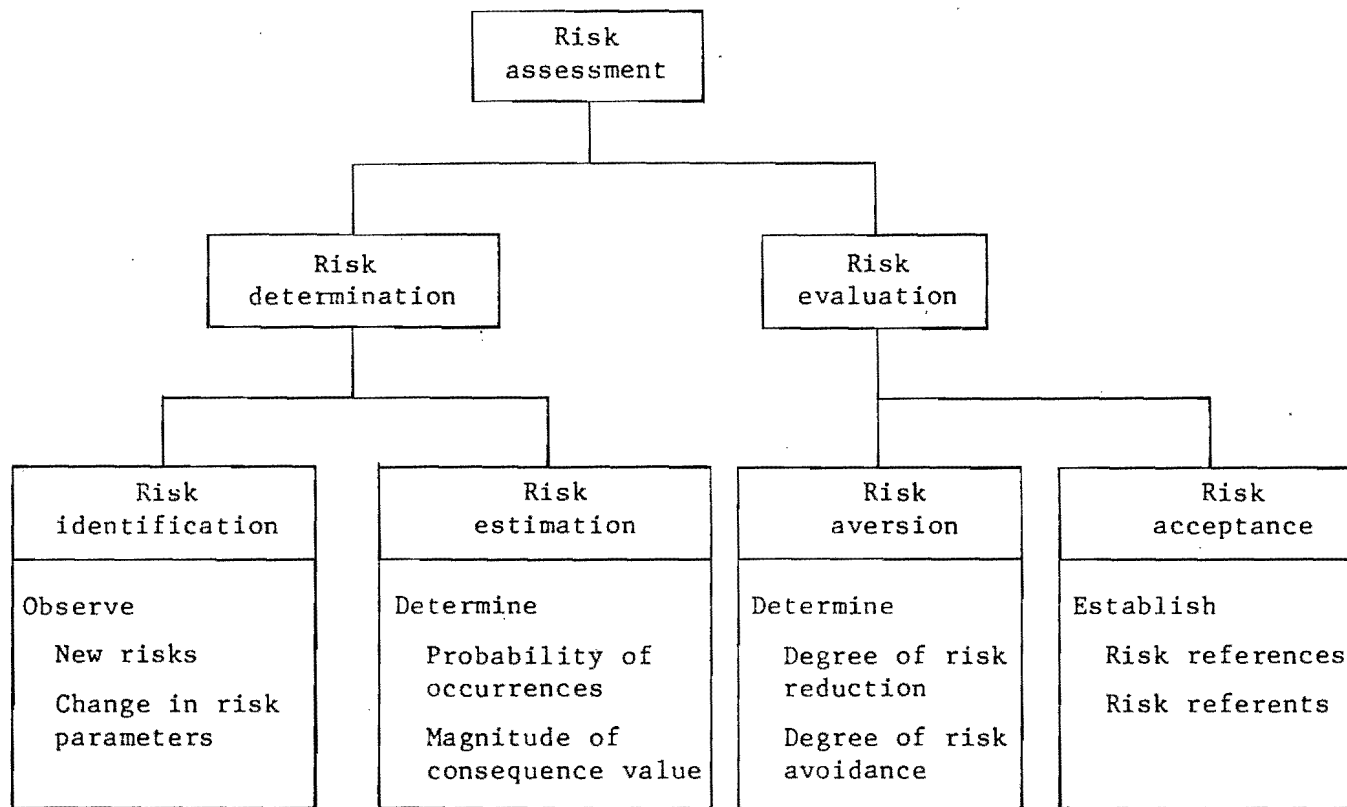
Figure 1. A hierarchy of risk assessment terminology (after Rowe, 1977).

3. Uncertainty - aspect of a water resources project which is unknown in the sense that its magnitude and probability of occurrence cannot be estimated with any reasonable degree of confidence

Bowles, Anderson, and Canfield (1978) introduced a phased risk analysis approach which utilizes the growing project data base to determine the reliability of a given earth dam at any point in the project life from conception through completion and operation. They also adopted a risk analysis format proposed by Rowe (1977) which consists of a set of event-outcome-exposure-consequence paths which allows the analysis to link the occurrence probabilities of each event which could lead to dam failure to the final consequences measured in commensurate and noncommensurate terms. This approach could be applied to all types of engineering projects.

McCuen (1980) suggests that risk assessment with regard to earth dams should be performed using a Bayesian decision theory approach. He proposes that the decision process of selecting design criteria be considered to consist of a set of alternative design criteria (actions), a set of possible outcome events that are associated with each action, and a utility function that describes the value of each outcome. Different design criteria would be adopted depending on the potential damages which might be received in the event of a dam failure. McCuen does not appear to address the issue of changes in the utility function with time.

A procedure for measuring and displaying the potential adverse contributions resulting from dam failures was presented by the Water

Resources Council (1980) in which the types of adverse effects were described and dams were defined according to height as well as storage capacity. Failure condition possibilities were also defined and the procedures for evaluating the potential consequences resulting from dam failures were outlined.

Probabilistic slope stability analysis

Vanmarcke (1977) introduced a three-dimensional static approach to the probabilistic analysis of earth slopes. This was done by using a two-dimensional mechanical slip failure model with the third dimension included by considering the variability of the averages of soil properties along the axis of the embankment. He defined a statistic called the scale of fluctuation which indicates the rate of fluctuation of the soil properties about the mean value due to natural or in-place variability in the soil properties. The scale of fluctuation can be considered to be the contributing parameter in the variance reduction function which describes the decrease in the variance of the varying average of soil properties as the averaging distance is increased. Vanmarcke's method involves estimate of a critical width (along the embankment axis) of failure at which the probability of failure of the embankment is maximized. The method requires the designer to include the end resistance of the failure mass in the analysis. The probability of failure is maximized due to the reduction in the influence of the end resistance on the mean factor of safety. As the width is increased, the variance of the factor of safety decreases as described by the variance reduction function.

Vanmarcke (1979) demonstrated how his probabilistic approach to earth slope analysis could be adapted to any deterministic plane strain stability analysis method by using the ordinary method of slices to estimate the probability $P_f(B)$ that a failure will occur anywhere along an embankment of length B. The method accounts for sources of uncertainty in the resisting moment due to natural or in-place variability in the soil strength parameters, pore pressure and unit weight provided the variability of these factors can be described.

Sharp et al. (1980) have extended Vanmarcke's method to the analysis of the stability of zoned embankments in terms of effective stresses. Probabilities of failure were found for each trial failure surface under static loading conditions.

A-Grivas (1980) performed a case study using the probabilistic seismic stability model of A-Grivas, Howland and Toleser (1979). The safety of the slope was measured in terms of its probability of failure with the numerical values being obtained through a Monte Carlo simulation of failure. The model was capable of accounting for significant uncertainties associated with conventional methods. Some of these uncertainties that are taken into account are:

1. The variability of material strength parameters

2. The location of potential failure surfaces

3. Value of the maximum ground acceleration during an earth-quake

Three different types of seismic sources were investigated by A-Grivas:

1. Point source

2. Line (or fault) source

3. Area source

Based on the Monte Carlo simulation of failure, "probability of failure" vs. "distance between source and site" relationships were plotted for all three types of seismic sources.

Inflow design flood analysis

Linsley and Franzini (1972) present methods for developing inflow design flood hydrographs as well as flow duration curves for specific drainage basins. Examples of these types of curves are given for various rivers and their corresponding drainage basins. Other hydrologic methods useful in predicting volume inflows over specific time intervals are also presented.

Failure Mechanisms

The geotechnical engineering literature contains much valuable information on past dam failures and failure mechanisms. This literature has been used in developing procedures for estimating the transition probabilities between events and system responses in the risk analysis procedure developed in the next chapter. Some of the failure mechanisms used in this study are discussed below.

Landslides

Jumikus (1979) presented several factors which determine the stability of natural slopes of rock walls. Those factors which are helpful in providing a basis for estimating the probability of the event "landslide into reservoir" are listed in Chapter IV. A static method for analyzing the stability of a natural slope with a geological discontinuity was also described.

Rapid drawdown

Sherard (1953) performed a study of upstream slides on twelve earth dams. He found that the majority of failures were caused by a drawdown between maximum water surface and mid-height of the dam at average rates varying between 0.3 and 0.5 feet per day.

Sherard et al. (1963) found that most drawdown slides have occurred when the reservoir was lowered the first time, though a few have occurred after many years of successful operation. In some of the latter, the delay may have been due to a decrease in the shear strength of a clay embankment or foundation with time. In every case they studied, however, the slide was caused by a drawdown which was either faster or over a greater range than had occurred previously.

Core cracking

Kulhawy and Grutowski (1976) discussed the phenomenon of load transfer with respect to zoned earth dams. They explained that the load transfer is due to differences in stiffnesses of the material in adjacent zones. When a condition exists where the dam has a soft core (low modulus) and a stiff shell (high modulus), the core will tend to settle with respect to the shell during construction. The results is that the core will tend to "hang" on the shell along the zone bound-aries. Placement of the embankment in successive layers tends to accentuate this process with stresses in the core being less than those due to gravitational forces alone. If the reservoir is filled rapidly under these conditions, the water pressure could exceed the low stresses in the core. This could lead to hydraulic fracturing in the core and possibly piping. If the reverse is true (i.e. soft shell

and stiff core) the shell would hang on the core causing overstressing to occur. The result could be either plastic yield or brittle cracking of the core.

Seismic loading

Schnabel and Seed (1973) developed relationships between distance to causative fault and maximum acceleration for accelerations in rock. These relationships pertain to earthquakes in the western United States.

Seed, Idriss, and Kiefer (1969) characterized bedrock motions by using several significant parameters:

1. Maximum amplitude of the accelerations

2. The predominant frequency or predominant period of the motion

3. Duration of the motion

They developed relationships for predominant periods vs. distance to causative fault for various earthquake magnitudes.

Algermissen and Perkins (1973) proposed a technique for seismic zoning. A source area and/or active fault are used to predict the seismic potential for a given site.

Haley and Hunt (1974) proposed a method to estimate the potential for the occurrences of earthquakes and their ground shaking characteristics. They were able to estimate the average number of earthquakes that would occur for a given magnitude earthquake and bedrock acceleration. This was applied from a predetermined study area and/or a major active fault. Exceedance probability vs. bedrock acceleration curves can then be developed for any given time interval such as 50 or 100 years for determining design earthquake parameters.

CHAPTER III

METHODOLOGY

Introduction

Methodology of the risk analysis procedure is characterized by its framework, details of the probabilistic procedure, and utilization of a growing data base. These components combine to describe a system of methods which can be used to evaluate the reliability of an earth dam as well as consequences resulting from its reliability.

Framework of the Risk Analysis Procedure

The framework of the risk analysis procedure is based on that proposed by Bowles, Anderson, and Canfield (1978) for earth dam projects. It is comprised of the following five major elements:

1. Event

2. System response

3. Outcome

4. Exposure (factors)

5. Consequence

The elements are related by transition probability linkages in such a way that the probability of specific consequences can be traced back to the probability of the initial event as illustrated in Figure 2.

| EVENT | SYSTEM RESPONSE | OUTCOME | EXPOSURE | CONSEQUENCE |
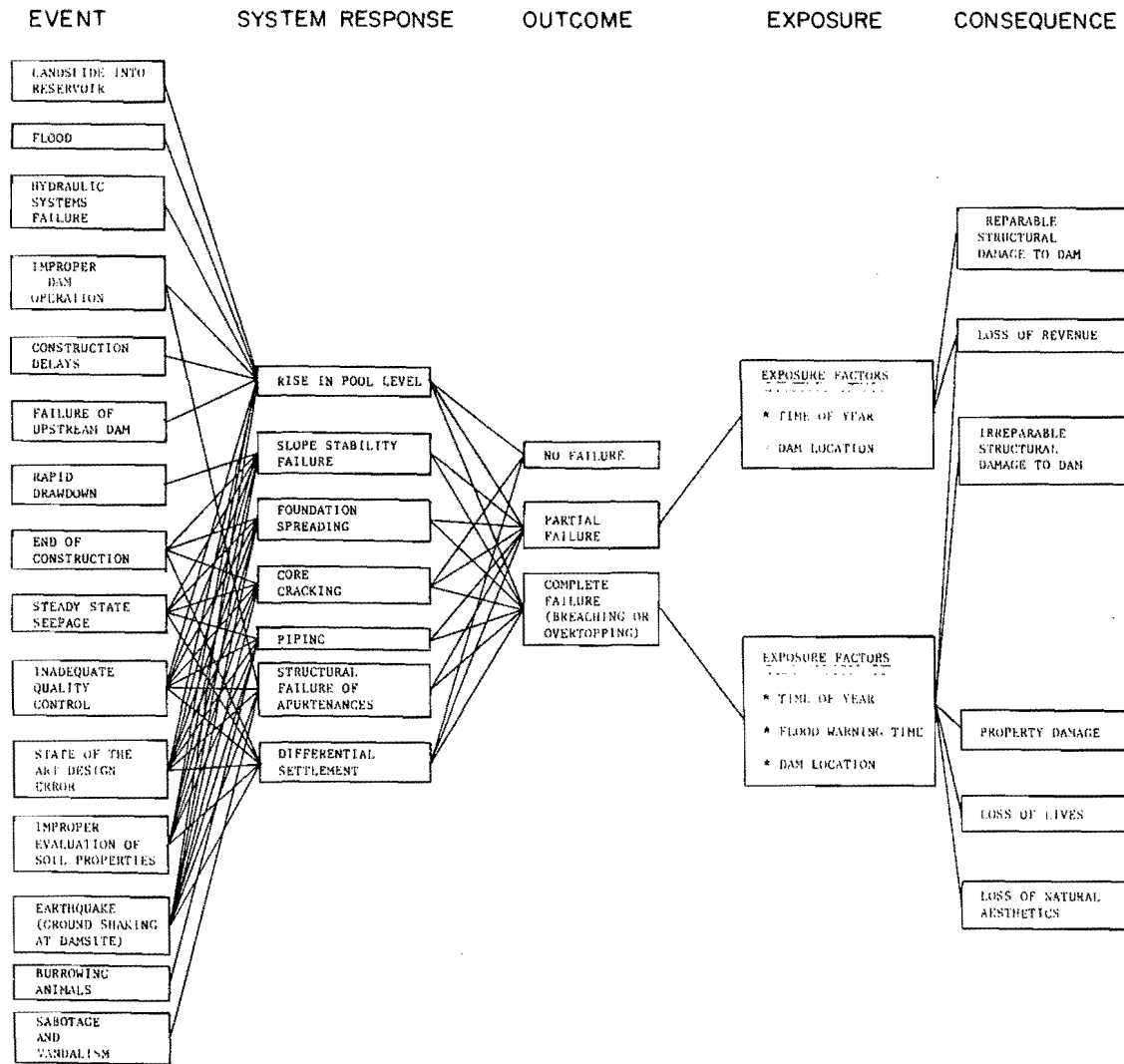
Figure 2. Event-system response-outcome-exposure-consequence diagram.

Event

Events can be considered to be the beginnings of potential failure conditions in dams and thus the "first cause" of the ultimate consequences of an earth dam failure. The magnitude of the process which forms the events is often described on a continuous scale (e.g. Richter scale for earthquakes). The event itself includes all magnitudes of the process which exceed the value at which failure will occur. An effort has been made to use every possible event which could occur sometime in the life of an earth dam but, as in all risk assessments, there is a problem of incompleteness in that it is impossible to foresee all possible events. Most of the events identified in Figure 2 are considered to be independent events (defined as the probability of two or more events occurring simultaneously being negligible). A few are considered to be correlated (defined as causally associated). Examples of the events which were used in this study are: flood, earthquake (ground shaking at damsite), failure of upstream dam, etc. (see Figure 2).

System response

The reaction of the earth dam structure due to the occurrence of one or more events has been called the system response. Again an effort was made to use as many probable system responses as could be conceived. Some examples of system responses are rise in pool level, slope stability failure, foundation spreading, etc. (see Figure 2).

Outcome

The result of a system response or combination of responses establishes the probability of occurrence of each degree of failure. The three degrees of failure considered are: no failure, partial failure (no breaching or overtopping of dam). and complete failure by breaching and overtopping of the dam. Probabilities of each failure condition are accumulated based on the degree of the response of the dam.

Exposure

The consequence of a dam failure will be determined by the structural damage, loss of utility of the reservoir water, and by the downstream damages. The location of the reservoir and the factors which affect the magnitude of losses by the downstream activities, at the time it fails, are the exposure factors. An attempt has been made in this study to use certain factors which determine the exposure to dam failure. Examples of these exposure factors are: time of year, dam location, and flood warning time.

Consequence

The ultimate loss in terms of lives lost, economic losses (e.g. structural damage, loss of revenue), and natural aesthetic value are the consequences of dam failure. The degree of exposure at the time of either a partial or complete failure determines the magnitude of the consequences. Those types of losses which are significant with respect to an earth dam failure are included in this study.

Details of the Probabilistic Procedure

Correlated event probabilities

In order to take into account instances in which one or more
events may occur simultaneously, a chart has been developed in which
comparisons have been made between each of the events (see Figure 3).
The instances in which a significant correlation can be considered
to exist have been so indicated by "CE" (correlated event) in the
square where the two events intersect. The subscripts on the "CE"
in Figure 3 are to show that each correlation is different in magni-
tude, but nevertheless significant in terms of the degree of corre-
lation.

A significant correlation is defined to exist if there is a
possibility that two or more simultaneous events can result from a
common cause. For example, heavy precipitation is a common cause for
the events "landslide into reservoir" and "flood" (see Figure 4a).
The degree of correlation indicates the likelihood that both events
will occur simultaneously. Care should be taken to distinguish
between correlated events and independent events. Even though there
is a remote probability that "end of construction" and "earthquake
(ground shaking at damsite)" could occur simultaneously, it should be
noted that there is no common cause to trigger both of the events (see
Figure 4b).

The simultaneous occurrence of two joint events will be treated
as a separate event in the risk analysis procedure. It should be
noted that these joint events are not shown in Figure 2 and that the

Figure 3. Classification of joint event pairs into independent and correlated pairs.

COMMON
CAUSE   EVENT   SYSTEM
                                                                 RESPONSE

LANDSLIDE INTO
RESERVOIR

HEAVY
PRECIPITATION   RISE IN POOL LEVEL

FLOOD
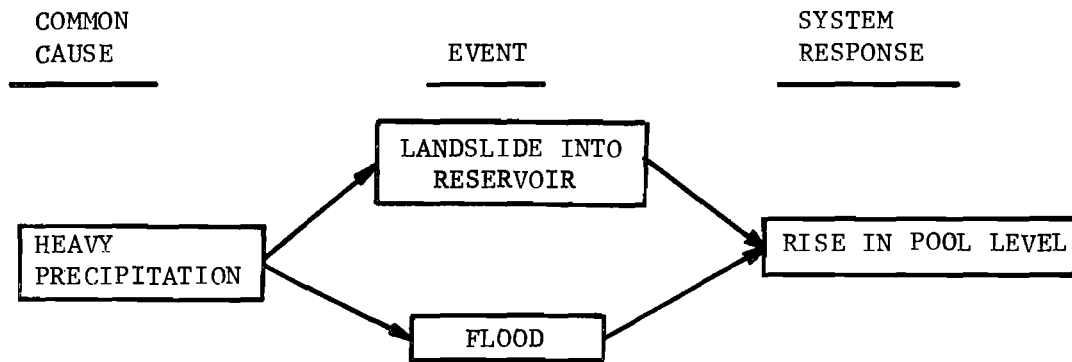
a) example of correlated joint events

NO
COMMON
CAUSE   EVENT   SYSTEM RESPONSE

END OF
CONSTRUCTION

SLOPE STABILITY

FAILURE

EARTHQUAKE
(GROUND SHAKING
AT DAMSITE)
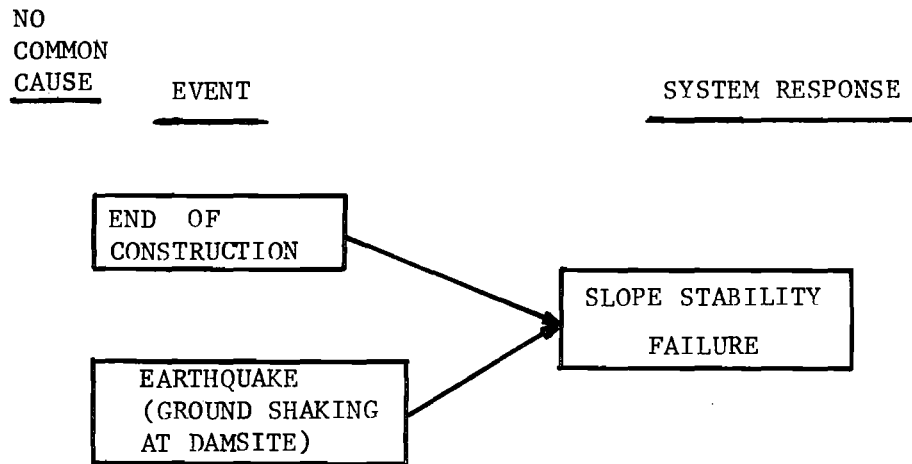
b) example of independent joint events

Figure 4.   Event relationships.

single events which are shown exclude the probability of the simul-
taneous occurrence of correlated events. The transition from corre-
lated joint event to system response will be linked to the same
system responses as were the separate events. The probability of
the occurrence of correlated joint events of a "landslide into reser-
voir" and a "flood" is given by:

$$P_{CE_1} = P(L \cap F)$$

where

L = event of a landslide into reservoir

F = event of a flood

The squares in Figure 3 which contain dashes (-) indicate that
two events are independent and although they could occur simultaneously,
the probability that this will occur is insignificant since it is the
product of two very small probabilities.

Independent event probabilities

The probability that single and correlated joint events will occur
(P_{E_i}, P_{CE_i}) must be found to begin the risk analysis procedure. P_{E_i}
values are to be found for each independent event and a transitional
procedure is performed for each of the probabilistic linkages to
obtain a probability of system response based on that event (transi-
tional probability). Descriptions of the procedures which will be
used are outlined in Chapter IV of this study. Likewise, P_{CE_i}
values are found for the correlated joint events and are treated as
additional independent events in the analysis.

System response probabilities

In the case of this risk analysis procedure, there are fifteen transition probabilities from single events as well as six from correlated joint events. Based on the transitional procedure performed for each linkage which joins independent and correlated joint events with a corresponding system response, a transitional probability of a given system response is obtained. To obtain the total probability of a particular system response, the summation of the transitional probabilities provides an estimate of the total probability of any one system response:

$$P_{SR} = \sum_{i=1}^{n} P_{S_i} + \sum_{i=1}^{m} P_{SC_i}$$

where

P_{S_i} = transitional probability of system response from linked independent events

P_{SC_i} = transitional probability of system response from linked correlated events

n = number of independent events linked to the specific system response

m = number of correlated events linked to the specific system response

P_{SR} = Probability that a specific system response will occur

In the case of the system response of "slope stability failure" for example:

$$P_{SS} = P(\text{slope stability failure}) = \sum_{i=1}^{7} P_{SS_i} + \sum_{i=1}^{3} P_{SSC_i}$$

where

$$\sum_{i=1}^{7} P_{SS_i}$$ = P(slope stability failure given that rapid drawdown

occurs)

+ P(slope stability failure given that end of construc-

tion occurs)

+ P(slope stability failure given that steady state

seepage occurs)

+ P(slope stability failure given that inadequate

quality control occurs)

+ P(slope stability failure given that design error

occurs).

+ P(slope stability failure given that improper evalu-

ation of soil properties occurs)

+ P(slope stability failure given that earthquake

occurs)

and where

$$\sum_{i=1}^{3} P_{SSC_i}$$ = P(slope stability factor given that simultaneous

rapid drawdown and landslide into reservoir occur)

+ P(slope stability failure given that simultaneous

earthquake and landslide into reservoir occur)

+ P(slope stability failure given that simultaneous

earthquake and upstream dam failure occur)

Outcome probabilites

Once the probability for each specific system response has been

obtained, the method for finding the outcome probabilities is very

similar to that used for finding the system response probabilities.

Transition probabilities for the appropriate failure condition (no

failure, partial failure, or complete failure) are found using methods

discussed in Chapter IV. This is done for each of the linkages which

join the system responses with the three outcome conditions. Since

the system responses are treated independently, the probability of any

one of the three outcome conditions is equal to the summation of the

transition outcome probabilities which were linked to that condition:

$$P_{O_j} = \sum_{i=1}^{n} P_{PO_i}$$

where

P_{PO_i} = transition probability of outcome from linked system

response

n = number of system responses linked to the specific outcome

P_{O_j} = probability that a specific outcome will occur

In the case of the outcome of "no failure" for example·

$$P_{NF} = P(\text{no failure}) = \sum_{i=1}^{3} P_{NF_i}$$

where

$\sum_{i=1}^{3} P_{NF_i}$ = P(no failure given that rise in pool level occurs)

+ P(no failure given that core cracking occurs)

+ P(no failure given that differential settlement occurs)

In this manner, probabilities for each failure condition can be obtained.

Estimation of Consequences

The final consequences are estimated using the probability values

obtained for partial failure and complete failure in conjunction with

the appropriate exposure factors. The probability of failure and the

degree of exposure at the time of failure dictate the magnitude of the

consequences. The consequences can be estimated by multiplying

the estimated consequences (assuming that the failure occurred) by the

probability of failure as shown in Table 1. The total consequence

estimation will be the summation of dollars lost due to both the

partial failure and complete failure conditions as well as the lost

lives and acres of aesthetically pleasing land due to the complete

failure. The consequences of each failure condition are estimated

individually because the partial failure and complete failure are

statistically mutually exclusive.

Growing Data Base

The available data pertaining to an earth dam increases with

time. In the very early stages of a dam project there may be no

specific information other than historical data on the reliability of

earth dams of similar height, design and location. As time goes on,

however, such information as borrow material properties, embankment.

compaction, in-place density, foundation investigation, flood studies.

etc. will develop and provide a basis for using the entire framework

of the risk analysis procedure. In the early stages of the project, a

risk analysis could be based on empirical evidence of reliability.

As the data base expands, the procedures used to evaluate risk can

become more detailed by considering each of the pathways in Figure 2

using increasingly improved parameter estimates and consequently the

analysis can be expected to be more representative of a particular dam

structure.

Table 1. Estimation of consequences.

Estimated Consequences	Failure Probability	Consequences
Partial Failure		
1. Repairable structural damage to dam (dollars)		
	x P_{PF} =	(dollars)
2. Loss of revenue (dollars)		
Complete Failure		
1. Irreparable structural damage to dam (dollars)		
2. Loss of revenue (dollars)		
3. Property damage (dollars)	x P_{CF} =	(dollars)
4. Loss of life (No. of lives)		+(no. of lives) +(no. of acres)
5. Loss of natural aesthetics (No. of acres)		
Total Estimation of Consequences	=	dollars (partial failure) + dollars (complete failure) + no. of lives (complete failure) + no. of acres (complete failure)

CHAPTER IV

DESCRIPTION OF RISK ANALYSIS PROCEDURE

Procedures for Estimating Probabilities

In order to estimate the probability of occurrence of each outcome condition and the resulting consequences, the probabilities of each joint event, correlated joint event, transition probability, and system response must be estimated. Chapter III of this thesis explains how these probabilities are combined. The following section describes possible procedures which can be used to estimate these probabilities for use in the risk analysis procedure.

Probability of events

Event 1. The probability of the occurrence of event 1 "landslide into reservoir," is P_{E_1}. There are four basic types of landslides (see Figure 5):

1. Falls

2. Rotational slides

3. Translational slides

4. Flows

As a result of the slope condition, a probability exists that a slope located somewhere on the rim of the reservoir will fail. Probabilities of failure will be different for each type of landslide which can occur at any given location on the rim of the reservoir. The value of P_{E_1} could be obtained from a probabilistic slope stability analysis. This analysis could be performed on those areas around the reservoir
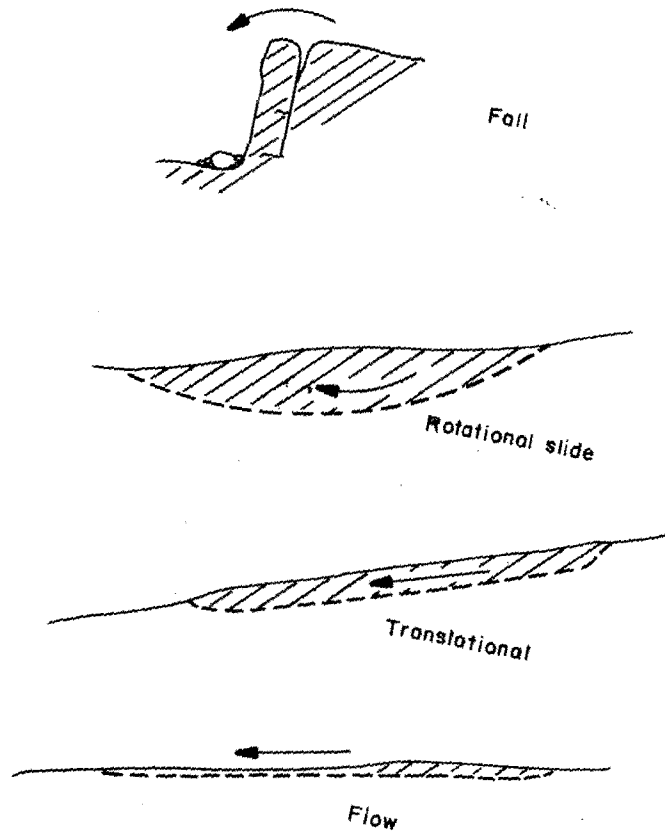
Figure 5. Main slide types.

which are considered to have the greatest landslide potential based on empirical (e.g. case history) landslide frequency information as well as factors such as those listed below. These factors, which determine the stability of the slope and those unique to the slope in question, should be used in conjunction with the results of the probabilistic slope stability analysis. Several factors can determine the stability of natural slopes. Jumikis (1979) suggests several factors:

1. Rock and soil type of which or in which the slope is made

2. Structure, stratification and attitude of the rock and soil formations (e.g. strata dip angle)

3. Presence of a potential failure surface in the slope (frequency of geological discontinuities) and the steepness of its angle of dip toward the reservoir

4. Presence of breccia zones and clay seams

5. Unit weight of slope material

6. Position of groundwater table

7. Moisture content (degree of saturation) in the slope material

8. Vibrations and seismic forces

9. Various environmental conditions and processes sculpturing the face of slopes (i.e. weathering, frost, and chemical action of pore water on soil and rock materials)

Therefore, based on these factors as well as other important considerations peculiar to the slope in question, an estimate of the landslide potential along the rim of the reservoir could be made.

Event 2. The probability of the occurrence of event 2 "flood,"
is P_{E_2}. The probability of P_{E_2} could be estimated using state-of-
the-art methods to predict the probable maximum flood for the region
in which the dam is located. This probable maximum flood would be
used for dams in which the expected consequences for dam failure would
be potentially large, or in other words, dams in which a risk analysis
would be strongly recommended. Linsley and Franzini (1972) present
methods for determining the probable maximum flood by means of a
meteorological estimate of the physical limit of rainfall over a
drainage basin.

Event 3. The probability of the occurrence of event 3 "hydraulic
systems failure," is P_{E_3}. It will be assumed in this study that the
main concern with respect to the hydraulic system failure will be with
regard to the outlet gate. To obtain a value for P_{E_3}, the uncertainty
of the quality or durability of a typical outlet gate must be dealt
with. It will also be assumed that a failure in this case means that
no water is allowed past the dam. A probability distribution could be
developed on the outlet gate based on manufacturers tests or tests
performed by the engineer. The distribution would be the probability
of failure vs. the number of years since its installation (see Figure
6). Factors such as climate or location of the dam would need to be
considered in the development of the distribution. Therefore, P_{E_3}
would be equal to the probability of failure of the outlet gate plus
the probability of failure of the remaining hydraulic systems. The
value of the latter probability would be an estimate based on judgment
and on how many other hydraulic systems there are and their relative
importance.
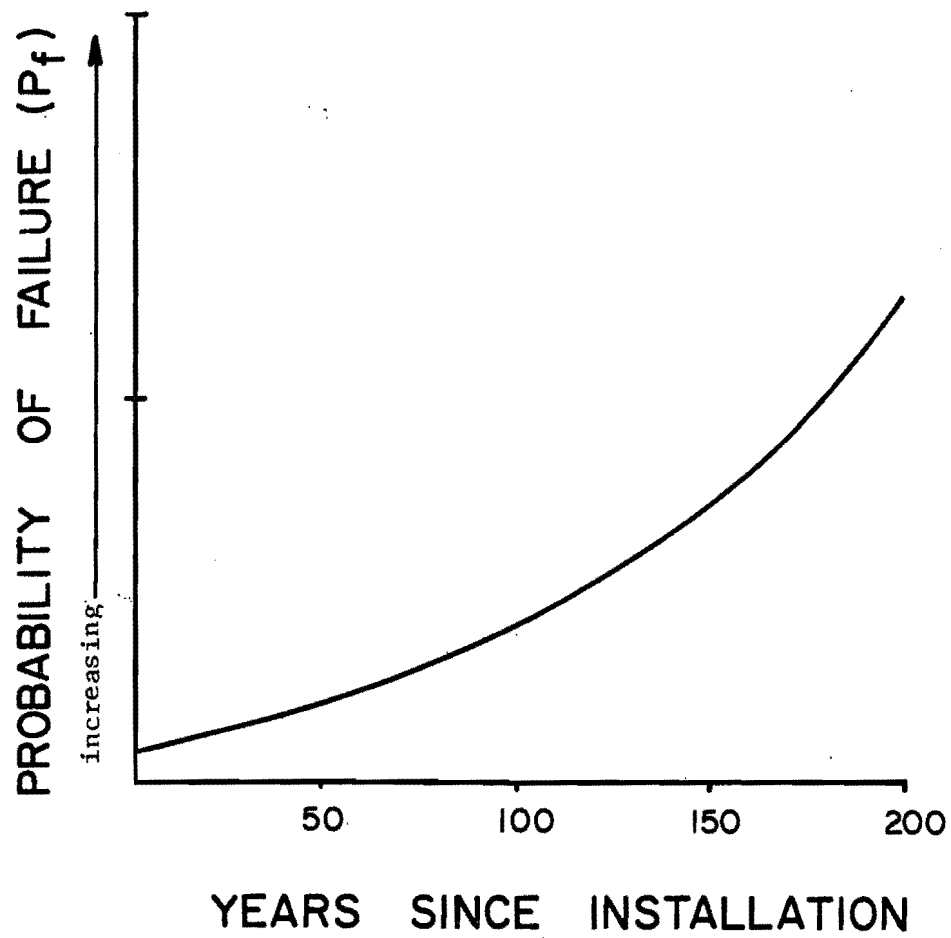
Figure 6. Possible probability curve for a typical outlet gate (hypothetical).

Event 4. The probability of the occurrence of event 4 "improper dam operation," is P_{E_4}. To obtain the value for the probability that the dam will not be operated properly, an understanding about human error would be needed. Based on case histories of engineering projects which have failed due to operator failure (mistakes) and on basic human behavioral studies, estimations of P_{E_4} could be made. Nuclear power plant operation of recent years has necessitated studies of a similar nature in order to predict the probability of failure due to operator failures. Although probably more complex than earth dam considerations, results of these studies for nuclear power operation failures could be very valuable in obtaining a value for P_{E_4}.

Event 5. The probability of the occurrence of event 5 "construction delays" is P_{E_5}. Several factors must be considered which contribute to construction delays, they are:

1. Problems with work force (striking, etc.)

2. Problems with equipment

3. Accidents and/or mistakes

4. Weather (or other natural phenomena)

5. Funding or budget delays

Based on the particular group of workers which are selected for the job, an evaluation can be made using the first three factors listed above. This evaluation would be based on the general performance of the work force on similar jobs as well as the current general attitude of the labor market. Also, available empirical information (e.g. cases histories) would be beneficial. Based on this information, an estimation of P_{E_5} could be made by means of a judgment decision.

Event 6. The probability of the occurrence of event 6 "failure of upstream dam," is P_{E_6}. Since P_{E_6} is the probability that a dam will fail upstream, it would be found using the risk analysis procedure for that specific dam, if it is an earth dam. All other types of dams could be assessed P_{E_6} using judgment based on inspection procedures such as risk assessment methods similar to those currently being used by several government institutions.

Event 7. The probability of the occurrence of event 7 "rapid drawdown," is P_{E_7}. The value of this probability would be estimated based on the characteristics and magnitude of the usage that the reservoir will receive. For example, if the reservoir is used for agricultural water supply, rapid drawdown would occur nearly every year and P_{E_7} would be high. Some of the factors which need to be considered in evaluating P_{E_7} would include:

1. Climate

2. Location (land use in vicinity)

3. Stream inflow and duration as a function of the time of year

4. Reservoir water usage (outflow and duration as a function of the time of year)

Event 8. The probability of the occurrence of event 8 "end of construction," is P_{E_8}. The end of construction condition is important because of the buildup of pore pressures within the embankment. The value of P_{E_8} is the probability that excessive pore pressures will develop within the embankment during and immediately following construction. The factors which affect pore pressure within the embankment are:

1. Type of embankment material

2. Rate of construction

3. Water content of embankment material

4. Physical characteristics of embankment

P_{E_8} can be estimated using judgment based on the factors listed above as well as available empirical information (e.g. case histories).

Event 9. The probability of the occurrence of event 9 "steady state seepage," P_{E_9}, depends largely upon dam usage. For example, if the reservoir is used mostly for recreational purposes or other uses which would require a relatively stable pool level, the value of P_{E_9} would be close to one. In this case, however, there is a period of time after the reservoir has been filled before the steady state seepage condition can be reached. Other conditions, which cause regular fluctuations in the pool level of the reservoir (e.g. agricultural use), would probably seldom allow the steady state seepage to occur. For these conditions the value of P_{E_9} would be low.

Event 10. The probability of the occurrence of event 10 "inadequate quality control," is $P_{E_{10}}$. Some of the factors which contribute to inadequate quality control include:

1. Human error on the part of the inspector and/or contractor

2. Incompetent inspector and/or contractor

3. Intentional carelessness (one example: inspector "pads" reports to please contractor)

4. Insufficient scope of the quality control program

It is assumed here that all the responsibility with respect to quality control falls on the inspector and the contractor. The contractor

includes all of the workers. Based on past experience with inspectors and contractors as well as other available empirical information, P_{E10} would be estimated using judgment.

Event 11. The probability of the occurrence of event 11 "design error," is P_{E11}. A design error is a design which is not correct with respect to the state-of-the-art design procedures. The major uncertainty which would need to be dealt with here is the frequency of human error among design engineers. Studies involving the design of nuclear power plants would be very useful in estimating the value of P_{E11}.

Event 12. The probability of the occurrence of event 12 "improper evaluation of soil properties," is P_{E12}. Some of the factors which con tribute to improper evaluation of soil properties are:

1. Inadequate field studies (site, foundations, borrow area investigations, etc.)

2. Incompetent engineers and/or technicians

3. Soil samples that are not representative

4. Testing errors

5. Human errors

P_{E12} would be estimated using statistical data on soil parameters as well as judgment.

Event 13. The probability of the occurrence of event 13 "earthquake (ground shaking at the damsite)," is P_{E13}. Based on studies which have been done by Haley and Hunt (1974), Schnabel and Seed (1972), Algermissen and Perkins (1973), and Seed, Idriss, and Kiefer (1969) an exceedance probability vs. bedrock acceleration curve can be developed for a given damsite. Therefore, values of P_{E13} can be obtained for specific design lives for each expected bedrock

acceleration. This enables the designer to predict the ground shaking which will occur at the damsite.

Event 14. The probability of the occurrence of event 14 "burrowing animals," is $P_{E_{14}}$. The biggest uncertainty associated with this probability is the type of animals which are found at or near the damsite. If the types of animals which burrow are found at or near the damsite the probability that the event "burrowing animals" will occur will be relatively high. A value for $P_{E_{14}}$ will need to be estimated based on these types of circumstances.

Event 15. The probability of the occurrence of event 15 "sabotage and vandalism," is $P_{E_{15}}$. The best possible source of information available to assist in determining the value of $P_{E_{15}}$ would be empirical in nature (e.g. case histories). $P_{E_{15}}$ would be estimated using judgment and would be based on the number and frequency of situations in the past where sabotage and vandalism of earth dams has occurred.

Probability of correlated joint events

Six different joint event combinations were determined to be correlated. As explained in Chapter III, the probability of a correlated joint event P_{CE_i} is the probabilities of the intersection of the two events which in this case are not independent. Therefore, the probability of the correlated joint events is less than or equal to the probability of either of the separate joint events. In the case of the correlated joint event of "landslide into reservoir" and "flood:"

$$P_{CE_1} = P(E_1 \cap E_2) \text{ and } \begin{matrix} P_{CE_1} \leq P_{E_1} \\ P_{CE_2} \leq P_{E_2} \end{matrix}$$

where

P_{CE_1} = Probability of correlated event 1 (landslide

into reservoir and flood)

P_{E_1} = Probability of event 1 (landslide into reservoir)

P_{E_2} = Probability of event 2 (flood)

The value of P_{CE_i} will be estimated by a judgment decision in which the extent to which each of the events are believed to be correlated.

Probabilities of system response

In order to obtain a probability of system response (P_{SR}) resulting from various event and/or correlated event probabilities, transition procedures must be performed for each of the linkages between the events and the system responses. A transition probability matrix has been developed in Figure 7 which illustrates each of the linkages and indicates the procedure to determine the partial probability corresponding to each linkage. The linkages will be identified using matrix notation (x,y) where the x values are the system responses and the y values are the events of Figure 7. Descriptions of the procedures which could be used to obtain the partial probabilities for each linkage in the matrix (Figure 7) will be covered in this section.

Linkage (1,1). The event is "landslide into reservoir." The system response is "rise in pool level." Since landslides can take on various forms (i.e. fall, rotational slide, translational slide, and flow), the major uncertainty associated with this linkage is the mass volume which is released into the reservoir. This is very important because the rise in pool level is proportional to the water displaced by the landslide mass. A rigorous approach to this problem is not

SYSTEM RESPONSE / EVENT	RISE IN POOL LEVEL	SLOPE STABILITY FAILURE	FOUNDATION SPREADING	CORE CRACKING	PIPING	STRUCTURAL FAILURE OF APPERTENANCES	DIFFERENTIAL SETTLEMENT
LANDSLIDE INTO RESERVOIR	Reservoir Operation Model						
FLOOD	INFLOW DESIGN FLOOD ANALYSIS						
HYDRAULIC SYSTEMS FAILURE	Judgment (testing and case history)						
IMPROPER DAM OPERATION	Judgment (case history(					Judgment (testing and case history)	
CONSTRUCTION DELAYS	Judgment (case history)						
UPSTREAM DAM FAILURE	Flood Routing Analysis						
RAPID DRAWDOWN		Probabilistic Slope Stability Analysis					
END OF CONSTRUCTION		Probabilistic Slope Stability Analysis	Probabilistic Slope Stability Analysis	Judgment			Static Settlement Analysis
STEADY STATE SEEPAGE		Probabilistic Slope Stability Analysis	Probabilistic Slope Stability Analysis	Judgment	Judgment		Static Settlement Analysis
INADEQUATE QUALITY CONTROL	Judgment (case history)	Probabilistic Slope Stability Analysis	Probabilistic Slope Stability Analysis	Judgment	Judgment	Judgment (case history)	Judgment (case history)
STATE OF THE ART DESIGN ERROR	Judgment (human studies)	Probabilistic Slope Stability Analysis	Probabilistic Slope Stability Analysis	Judgment (human studies)	Judgment (human studies)	Judgment (human studies)	Judgment (human studies)
IMPROPER EVALUATION OF SOIL PROPERTIES		Probabilistic Slope Stability Analysis	Probabilistic Slope Stability Analysis	Judgment	Judgment		Judgment
EARTHQUAKE (GROUND SHAKING AT DAMSITE)	Judgment (case history)	Probabilistic Seismic Stability Analysis	Probabilisitc Seismic Stability Analysis	Judgment			Judgment (testing and case history)
BURROWING ANIMALS					Judgment		
SABOTAGE AND VANDALISM						Judgment (case history)	

Figure 7. Matrix of available and proposed methods for estimating transition probabilities of system response given an event occurs.

possible at this time. Therefore, slope stability analysis combined
with judgment would be used to estimate the transition probability
of system response (P_{PL_1}).

Linkage (1,2). The event is "flood." The system response
is "rise in pool level." Flood routing techniques would be used
to evaluate the pool level characterisitics resulting from a flood.
Linsley and Franzini (1972) present methods for flood routing through
controlled reservoirs. Special considerations would be required
while evaluating the shape of the critical hydrograph for a given
flood. Moderate inflow sustained over a long time interval could
have a much greater affect on the total volume increase of the
water in the reservoir than high inflows over a relatively short
time interval. The transition probability (P_{PL_2}) would be estimated
based on the results of various flood routing configurations which
show potential for a noticeable rise in pool level.

Linkage (1,3). The event is "hydraulic systems failure." The
system response is "rise in pool level." The major uncertainty
associated with this linkage is the net inflow at the time of failure.
For this procedure it will be assumed that hydraulic systems failure
means that no water is allowed to pass through the outlet works.
Therefore, the inflow at the time of failure will essentially be the
streamflow if direct precipitation and groundwater are neglected
during the critical period. Since the events are independent the
relationship for this transition probability is:

$$P_{PL_3} = (P_{PL_2})(P_{E_3})$$

where

P_{PL_2} = the probability of the flood which causes a noticeable rise in pool level occurring

P_{E_3} = the probability that the event, hydraulic systems failure, will occur

Linkage (1,4). The event is "improper dam operation." The system response is "rise in pool level." It will also be assumed here that improper dam operation means that no water will pass through the dam's outlet works. Therefore, the relationship is as before:

$$P_{PL_4} = (P_{PL_2})(P_{E_4})$$

where

P_{E_4} = the probability that the event, improper dam operation, will occur.

Linkage (6,4). The event is "improper dam operation." The system response is "structural failure of the apertenances." There may be cases in which the apertenant structures are not operated correctly and stresses which are not normally induced on the apertenant structures take place. High stresses could result from abnormal pressures produced by a phenomenon such as a "water hammer." To evaluate the probability that the apertenances would fail under these types of adverse conditions, empirical information in the form of either case histories or manufacturer's estimates of apertenance structural performance would be used to estimate the transition probability, (P_{SF_1}).

Linkage (1,5). The event is "construction delays." The system response is "rise in pool level." Since the dam is still under

construction, in this case the only outlet for the water is through the diversion tunnel. The relationship will still be the same:

$$P_{PL_5} = (P_{PL_2})(P_{E_5})$$

where

P_{E_5} = the probability that the event, construction delays, will occur

It should be noted here that the value of P_{PL_2} will be different than before, since the flood magnitude which would cause a noticeable rise in pool level would be different than for the full reservoir.

Linkage (1,6). The event is "failure of upstream dam." The system response is "rise in pool level." This linkage would be analyzed using state-of-the-art flood routing techniques. The failure of the upstream dam would be assumed to be an instantaneous, complete release of its impounded water. Some of the factors that would affect the probability of the rise in pool level would be:

1. Volume of the upstream reservoir

2. Distance between the reservoirs

3. Characteristics of the river channel between the reservoirs (e.g. narrow, deep, winding, etc.)

A good approximation for the transition probability of a rise in pool level due to failure of an upstream dam is:

$$P_{PL_6} = P_{E_6}$$

where

P_{E_6} = the probability that the event, failure of upstream dam, will occur

It would not be a good approximation, however, if the factors listed above caused the flood wave to dissipate. This indicates the necessity

of the flood routing analysis in order to determine how the flood wave

is affected by those factors.

Linkage (2,7). The event is "rapid drawdown." The system

response is "slope stability failure." The uncertainties which need

to be considered with regard to a slope stability failure resulting from

rapid drawdown are:

1. Variability of the soil properties as a function of their

location in the embankment

2. Drawdown characteristics (rate, magnitude, etc.)

3. Existing condition of the dam as a result of the drawdown

(stresses, pore pressures, etc.)

The embankment should be analyzed using a probabilistic slope stability

analysis developed by Sharp et al. (1980). This computer program will

provide an estimate of the probability of failure for several failure

surfaces based on the static conditions imposed by the rapid drawdown

condition. To perform the analysis on existing embankments, a

field testing program would be required to determine the in situ

soil properties. Laboratory testing facilities would also be needed

for the analysis. This transition probability of slope stability

failure (P_{SS_1}) can be expressed as:

$$P_{SS_1} = (P_{E_7}) \, P_{F_{rd}}$$

where

P_{E_7} = probability that the event "rapid drawdown" will occur

$P_{F_{rd}}$ = greatest probability of failure obtained from the

probabilistic slope stability analysis based on the

rapid drawdown condition

Linkages (2,8 and 9). The events are "end of construction" and "steady state seepage." The system response is "slope stability failure." The uncertainties which should be considered with regard to these events are:

1. The variability of the soil properties as a function of location in the embankment

2. The existing condition of the dam resulting from the event (stresses, pool level, etc.)

The static loading conditions resulting from the event in question would be estimated and used in the probabilistic slope stability analysis. The soil properties of the embankment obtained from the testing program would also be used in the program. These transition probabilities of slope stability failure (P_{SS_2} and P_{SS_3}) can be expressed as:

$$P_{SS_2} = (P_{E_8}) \, P_{S_{ec}}$$

where

P_{E_8} = probability that the event "end of construction" will occur

$P_{S_{ec}}$ = greatest probability of failure obtained from the probabilistic slope stability analysis of the slope based on the end of construction condition

$$P_{SS_3} = (P_{E_9}) \, P_{S_{ss}}$$

where

P_{E_9} = probability that the event "steady state seepage" will occur

$P_{S_{ss}}$ = greatest probability of failure obtained from the probabilistic slope stability analysis of the slope based on the steady state seepage condition

Linkages (3,8 and 9). The events are "end of construction" and "steady state seepage." The system response is "foundation spreading." The uncertainties as well as the analysis of these transition probabilities are identical to those of linkages (3,8) and (3,9) with the exception that they would also apply to the foundation as well as the embankment. The expressions are:

$$P_{FS_1} = (P_{E_8}) \, P_{F_{ec}}$$

where

$P_{F_{ec}}$ = greatest probability of failure obtained from the probabilistic slope stability analysis of the foundation based on the end of construction condition

$$P_{FS_2} = (P_{E_9}) \, P_{F_{ss}}$$

where

$P_{F_{ss}}$ = greatest probability of failure obtained from the probabilistic slope stability analysis of the foundation based on the steady state seepage condition

Linkage (4,8 and 9). The events are "end of construction" and "steady state seepage." The system response is "core cracking." The uncertainty to be considered in addition to those mentioned for the transition slope stability probabilities is the behavior of the core and shell materials relative to each other. These transition probabilities of core cracking (P_{CC_1} and P_{CC_2}) can be estimated from estimates of the relative settlement between core and shell zones. Investigation of embankment and foundation would be required to predict such settlement. Loading conditions would depend on which event was being considered. Settlement would be predicted based on

two main conditions. Usually the core and the shell material have different stiffnesses. Hydraulic fracturing could occur in the core if it settled relative to the shell. However, if the shell settled relative to the stiff core, plastic yielding or brittle cracking could occur. Other factors such as compaction methods could have an affect on the probability estimations (e.g. compacting wet or dry of optimum).

Linkage (5,9). The event is "steady state seepage." The system response is "piping." Since there are essentially no deterministic methods available at this time to analyze piping in soil structures, the transition probability of piping (P_{P_1}) will be estimated using a judgment decision approach. The estimate would be based on factors such as:

1. Zoned or homogenous dam

2. Materials in embankment (how do materials vary from zone to zone, if zoned dam)

3. Filter characteristics, if any

4. Foundation characteristics (fractured, grouted, etc.)

5. Pool level

Case histories in which dams have failed due to piping would be valuable in estimating the probability.

Linkages (7,8 and 9). The events are "end of construction" and "steady state seepage." The system response is "differential settle-ment." Once again, the transition probabilities of differential settlement (P_{DS_1} and P_{DS_2}) would need to be estimated based on results of static settlement analyses. Using appropriate static loading conditions according to the event in question, a static

settlement analysis would be performed at selected locations on the embankment. Dunn, Anderson, and Kiefer (1980) describe current available methods such as Bonsennesq or Westergaard which could be used for granular soils, as well as Terzaghi's method which could be used for cohesive soils. A probabilistic settlement analysis could be developed. This would involve a probabilistic characterization of the foundation soil profile using the method suggested by Vanmarcke (1977).

Linkages (1-7, 10). The event is "inadequate quality control." The system responses are all responses. The major uncertainty here is the extent to which the quality control is inadequate and the affect this degree of inadequacy has on each system response. For this study it will be assumed that the transition probability for each system response is equal to the probability of the event "inadequate quality control." This assumption is based on the consideration that if the event takes place, it will cause each appropriate system response to take place as well. Therefore, the probability of the event becomes the transition probability of the system response. This is a conservative approach, but appropriate for this stage of development of the risk analysis procedure. Therefore they can be expressed as:

$$P_{E_{10}} = P_{PL_7} = P_{SS_4} = P_{FS_3} = P_{CC_3} = P_{P_2} = P_{SF_2} = P_{DS_3}$$

Linkages (1-7, 11). The event is "design error." The system responses are all responses. The consideration of these transition probabilities would be handled much the same as they were for the event "inadequate quality control." Again, the main uncertainties would be the number of design errors and the significance they would have on the system responses. The transition probabilities of each

system response can be estimated as before as being equal to the probability of the event "design error." They can be expressed as:

$$P_{E_{11}} = P_{PL_8} = P_{SS_5} = P_{FS_4} = P_{CC_4} = P_{P_3} = P_{SF_3} = P_{DS_4}$$

Linkages (2-4 and 6, 12). The event is "improper evaluation of soil properties." The system responses are all applicable responses. The evaluation of the transition probabilities as well as the uncertainties to be considered would be similar to linkages (1-7,10) and linkages (1-7,11). The transition probabilities can therefore be expressed as:

$$P_{E_{12}} = P_{SS_6} = P_{FS_5} = P_{CC_5} = P_{P_4} = P_{DS_5}$$

Linkage (1,13). The event is "earthquake (ground shaking at damsite." The system response is "rise in pool level." As explained earlier, relationships of exceedance probability vs. bedrock acceleration can be obtained. Therefore, the main uncertainty is the bedrock acceleration required to cause a noticeable rise in pool level (wave of water in reservoir). The estimation of this transition probability for rise in pool level (P_{PL_9}) would be a judgment decision aided by case histories, a theoretical analysis of water waves induced by tectonic displacements and the seismic history at or near the damsite.

Linkage (2,13). The event is "earthquake (ground shaking at damsite." The system response is "slope stability failure." The transition probability of slope stability failure (P_{SS_7}) can be found using a probabilistic seismic stability analysis such as the one outlined by A-Grivas, Howland, and Toleser (1979). This model accounts for the following uncertainties:

1. Variability of material strength parameters

2. Exact location of potential failure surfaces

3. Value of the maximum ground acceleration during an earthquake

In the analysis, the material comprising the slope is assumed to be statistically homogeneous and potential failure surfaces are taken to be of an exponential shape (log-spiral). The maximum acceleration during the earthquake is the seismic load, and its probability of occurrence can be estimated using the method proposed by Algermissen and Perkins (1973) and by Haley and Hunt (1974). A-Grivas, Howland, and Toleser (1979) assume that the slope is rigid and, therefore, the maximum ground acceleration is equal to that of the slope. Using attenuation relationships for the region, curves can be developed for "probability of failure" vs. "distance between source and site" (point source), "distance between fault and site" (fault source) or "radius of area source" (area source) such as those shown in Figure 8. Hence, for a given earthquake magnitude or maximum acceleration, probabilities of failure can readily be found for the appropriate sources. Therefore, for a given earthquake magnitude, the transition probability can be expressed as:

$$P_{SS_7} = (P_{E_{13}})(P_{SA})$$

where

P_{SA} = probability of failure calculated from the probabilistic seismic stability analysis.

Linkage (3, 13). The event is "earthquake (ground shaking at damsite)." The system response is "foundation spreading." This would be analyzed in a manner similar to linkage number (2,13) with one exception. More attention and consideration should be made in terms
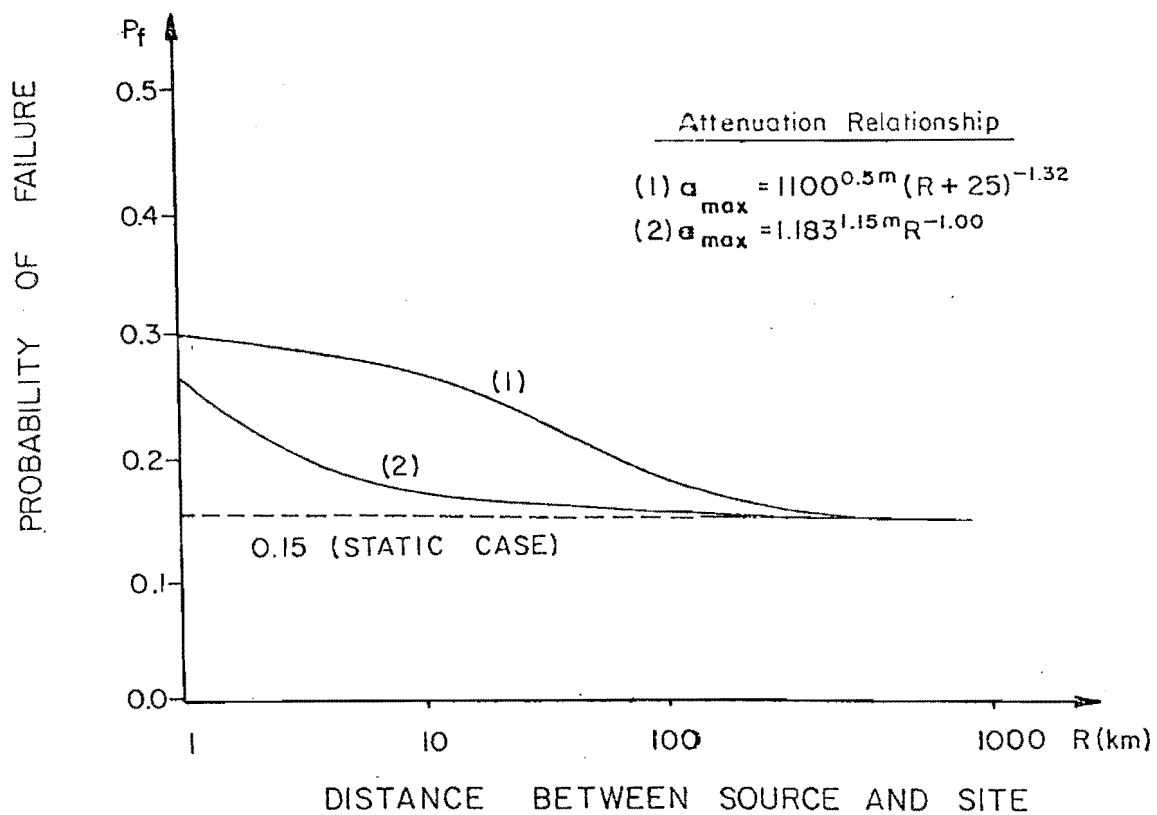
Figure 8a. Probability of failure vs. distance from point source,
after A-Grivas (1980).
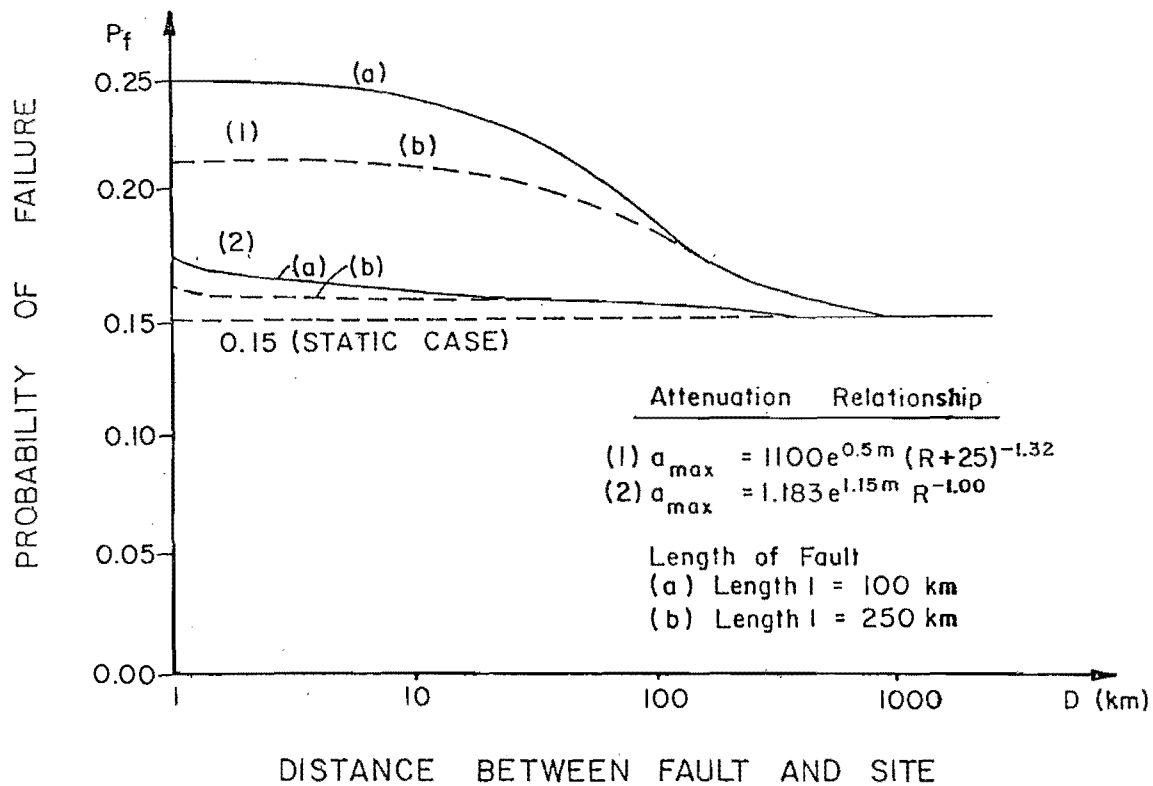
Figure 8b. Probability of failure vs. distance between fault and
slope ($\theta = 45^\circ$), after A-Grivas (1980).

P_f

PROBABILITY OF FAILURE

Attenuation Relationship

(1) $a_{max} = 1100 e^{0.5m} (R + 25)^{-1.32}$

(2) $a_{max} = 1.183 e^{1.15m} R^{-1.00}$

Depth of Area Source

(a) Depth = 0 km
(b) Depth = 20 km

0.5

0.4

0.3 — (a)
(b) — (1)

0.2 — (a)
(b) — (2)

0.15 (STATIC CASE)

0.1

0.0

1   10   100   1000   1 (km)

RADIUS OF AREA SOURCE
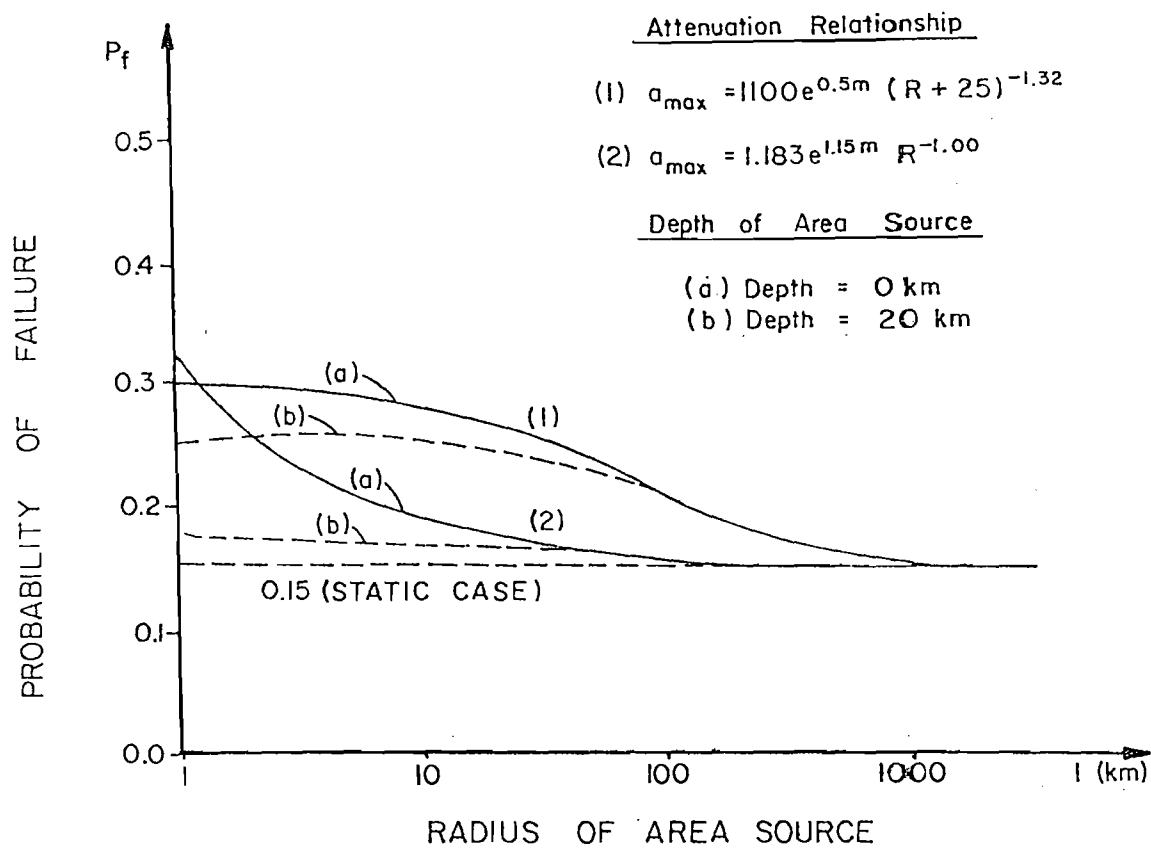
Figure 8c.   Probability of failure vs. radius of area source, after A-Grivas (1980).

of the existing foundation conditions. The wide variability in the types of foundations which could be encountered (from bedrock to soft, deep unconsolidated material) in damsites could have a significant affect on the potential for foundation spreading during dynamic loading conditions.

Linkage (4, 13). The event is "earthquake (ground shaking at damsite)." The system response is "core cracking." Predications can be made for ground acceleration characteristics based on earthquake magnitudes. Since the development of a deterministic method for analyzing the cracking of the core material in an earth dam is still in its infant stages, a judgment decision would be used to estimate the transition probability of core cracking (P_{CC_6}). Knowing the strength characteristics of the core and shell materials would be valuable in this estimate. Testing programs involving both static and cyclic shear tests would be desirable.

Linkage (7, 13). The event is "earthquake (ground shaking at damsite)." The system response is "differential settlement." The value of the transition probability of differential settlement (P_{DS_6}) would again be estimated in this case. Case histories involving settlement during an earthquake of materials similar to those found in a dam embankment or foundation would be helpful in estimating the probability of differential settlement (P_{DS_6}). Also, multidirectional shaking tests such as those performed by Pyke, et al. (1974) could be done on representative models.

Linkage (5, 14). The event is "burrowing animals." The system response is "piping." The value of the transition probability of piping

(P_{P_4}) will depend very much on the circumstances which surround the dam. Since most animals which burrow do not burrow very deep, the size of the dam can be an important factor. The only animals which tend to burrow quite deep are ground squirrels but they will stop once they encounter seeping water or moist soil. Therefore, for a large dam with a stable pool level, the value of P_{P_4} would be almost zero.

Linkage (6, 15). The event is "sabotage and vandalism." The system response is "structure failure of the apertenances. The major uncertainties here are:

1. The degree to which vandalism can contribute to the structural failure of the apertenances

2. The motives for such events which are peculiar to a particular dam or damsite

Since the motive of sabotage is destruction, it will be assumed that the probability of sabotage alone is equal to the probability of structural failure of the apertenances due to loads induced on the structure resulting from sabotage. This probability will not be the same as for other loading conditions. The degree of structural failure of the apertenances resulting from vandalism will depend on the following:

1. Characteristics of the act

2. Extent of the act

3. Number of unnoticed repetitions

Case histories will be the best tool in estimating the transition probability of structural failure of the apertenances (P_{SF_4}). Con-

siderations involving those factors listed above will also be valuable in the judgment decision.

Probabilities of outcome

Once the probabilities for each system response have been determined by taking the summation of its own partial probabilities, the outcome probabilities can be found in a similar manner. To obtain the outcome probability P_O resulting from various system response probabilities, transition procedures must be performed for each linkage between the system responses and the outcomes. Another transition probability matrix has been developed in Figure 9 which shows the procedure used to determine the partial probability corresponding to each linkage. Descriptions of these procedures will be covered in this section. As has been done previously, matrix notation (x,y) will be used to label the linkages in this section. These linkages, however, will correspond to Figure 9. The "x" values will represent the outcomes and the "y" values will represent the system responses.

Linkages (1-3, 1). The system response is "rise in pool level." The outcomes consist of all appropriate outcomes. Major uncertainties associated with these linkages would be:

1. Existing freeboard at the time the rise begins

2. Rate of pool level rise (most likely not constant)

3. Duration of the rise

The freeboard would vary depending on uses such as irrigation, municipal, wildlife, etc. From a general standpoint, the freeboard would probably be a function of the time of year. Based on model studies and case histories, probability distribution curves could be developed

OUTCOME SYSTEM RESPONSE	NO FAILURE	PARTIAL FAILURE	COMPLETE FAILURE (Breaching/ Over-topping)
RISE IN POOL LEVEL	JUDGMENT (model studies and case history)	JUDGMENT (Model studies and case history)	JUDGMENT (Model studies and case history)
SLOPE STABILITY FAILURE		ESTIMATION BASED ON PROBABILISTIC SLOPE AND SEISMIC ANALYSIS RESULTS	ESTIMATION BASED ON PROBABILISTIC SLOPE AND SEISMIC ANALYSIS RESULTS
FOUNDATION SPREADING		ESTIMATION BASED ON PROBABILISTIC SLOPE AND SEISMIC ANALYSIS RESULTS	ESTIMATION BASED ON PROBABILISTIC SLOPE AND SEISMIC ANALYSIS RESULTS
CORE CRACKING	JUDGMENT	JUDGMENT	JUDGMENT
PIPING		JUDGMENT	JUDGMENT
STRUCTURAL FAILURE OF APURTENANCES		JUDGMENT (Testing and case history)	JUDGMENT (Testing and case history)
DIFFERENTIAL SETTLEMENT	ESTIMATION BASED ON SETTLEMENT ANALYSIS AND TESTING RESULTS	ESTIMATION BASED ON SETTLEMENT ANALYSIS AND TESTING RESULTS	ESTIMATION BASED ON SETTLEMENT ANALYSIS AND TESTING RESULTS

Figure 9. Matrix of available and proposed methods for estimating transition probabilities of outcomes given a system response occurs.

for different cases involving "rate of rise" and "rise duration" (see Figure 10). This would provide ranges of values for the probabilities of each outcome condition for a given initial freeboard. This would be valuable in making the estimations for each transition probability $(P_{NF_1}, P_{PF_1}, P_{CF_1})$.

Linkages (2 and 3, 2). The system response is "slope stability failure." The outcomes are "partial failure" and "complete failure." Probably the biggest factor which would determine the outcome of the dam from a slope stability failure, is the location of the slip surface. The depth of failure, for example, can determine whether or not the crest is affected and whether the dam is breached. Both the probabilistic slope stability analysis and the seismic analysis provide this information as well as the probability of failure. Therefore, based on case histories and model studies, probability distributions could be developed (see Figure 11) as an aid in estimating these two transition outcome probabilities (P_{PF_2}, P_{CF_2}).

Linkages (2 and 3, 3). The system response is "foundation spreading." The outcomes are "partial failure" and "complete failure." An identical procedure could be used to estimate P_{PF_3} and P_{CF_3}. However, the considerations would now apply to the foundation as well as the embankment. Care must be taken to consider the variable nature of the foundation conditions.

Linkage (1-3, 4). The system response is "core cracking." The outcomes consist of all appropriate outcomes. The uncertainty which would probably have the biggest effect on the outcome will be the characteristics of the crack:

Key: PO_1 = area under curve over any failure condition range

NF = no failure condition

PF = partial failure condition

CF = complete failure condition
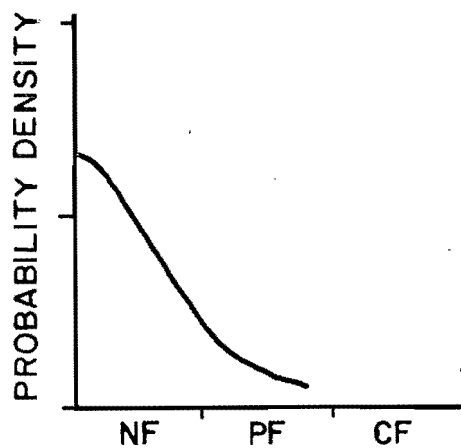
a) RATE OF RISE : LOW
RISE DURATION : LOW
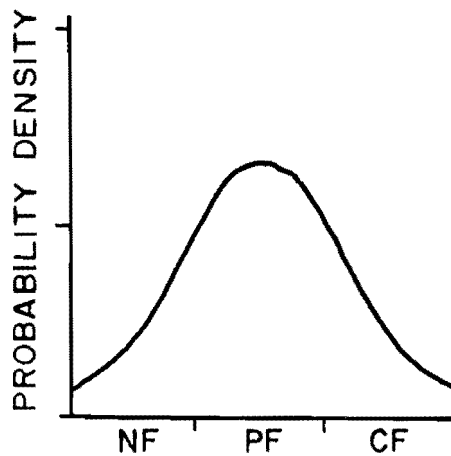
b) RATE OF RISE : LOW   HIGH
or
RISE DURATION : HIGH   LOW
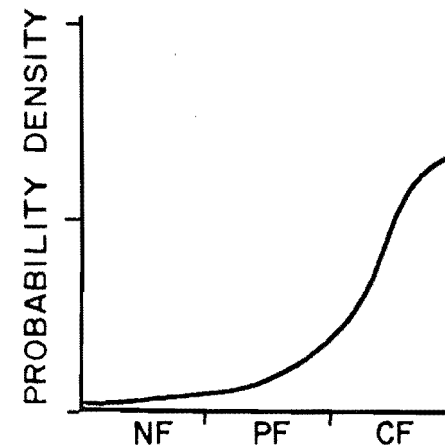
c) RATE OF RISE : HIGH
RISE DURATION : HIGH

Figure 10. Possible probability densities to determine partial outcome probabilities from system response: rise in pool level (hypothetical).

Key: P_{PF_2} and P_{CF_2} = area under curve over any failure condition range

PF = partial failure condition

CF = complete failure condition

a) Pss : LOW
   FAILURE : SHALLOW

b) Pss : LOW   HIGH
         or
   FAILURE : DEEP   SHALLOW

c) Pss : HIGH
   FAILURE : DEEP
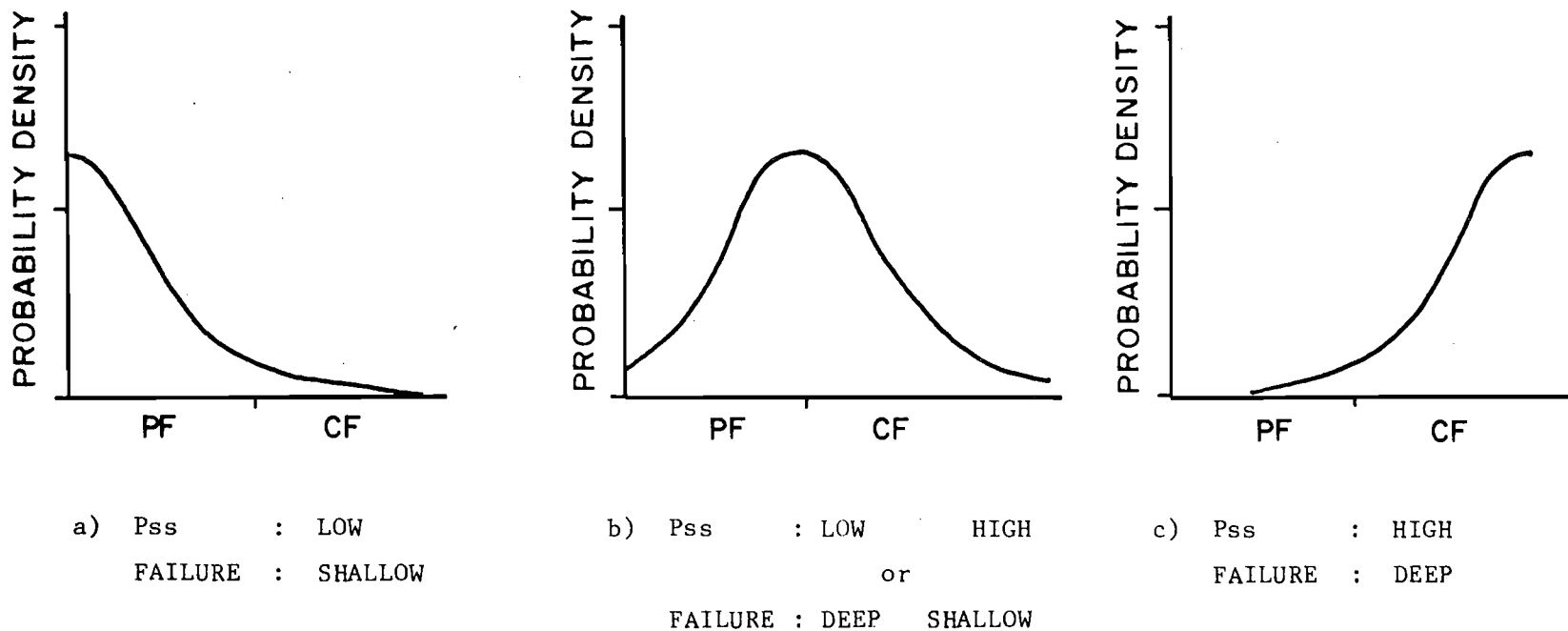
Figure 11. Possible probability densities to determine partial outcome probabilities from system response: slope stability failure (hypothetical).

1. Length

2. Location in the embankment

3. Direction (longitudinal, transverse, etc.)

4. Size of opening

5. Others

Since there is no deterministic method at this time to predict the
physical characteristics of cracks in soil structures, probabilities
would be estimated using a judgment decision approach. Case studies
as well as the amount of confidence placed in precautions (e.g. com-
pacting core material wet of optimum) would be the most valuable aids
in making such an estimation.

Linkages (2 and 3, 5). The system response is "piping." The
outcomes are "partial failure" and "complete failure." The extent to
which piping will occur is an uncertainty which will have a great
effect on the outcome of the dam. Some of the factors involved would
be:

1. Amount of fines removed

2. Characteristics of void

3. Location of void

4. Others

Like core cracking, there are no deterministic methods available at
this time for piping failures. If and when the piping was discovered
would also have a significant impact on the outcome. Due to the
nature of piping failures, it is very likely that the vast majority of
such failures would result in complete failure, unless it had been
discovered in its early stages. Based on these types of factors,
estimations for P_{PF_5} and P_{CF_5} can be made.

Linkages (2 and 3, 6). The system response is "structural failure of the apertenances." The outcomes are "partial failure" and "complete failure." The extent of failure of the apertenances would have a large impact on the outcome. Some of the factors would be:

1. Number of structures that failed

2. Whether or not structures are permanently damaged

3. Expected repair time, if repairs are possible

4. Others

Since the greatest concern with respect to an apertenance failure is the uncontrolled filling or expelling of reservoir water, possible repair of the structures as well as repair time would be important factors in the outcome. The pool level at the time of failure would also need to be considered. Based on these as well as other pertinent factors unique to a particular dam, estimations for P_{PF_6} and P_{CF_6} can be made.

Linkages (1-3, 7). The system response is "differential settlement." The outcomes consist of all appropriate outcomes. The uncertainties which can cause concern with respect to differential settlement in earth dams are:

1. Degree of relative movement within the embankment resulting from the settlement

2. Amount of freeboard loss due to settlement

3. Others

The concern which exists about relative movement is due to the potential of significantly large cracks occurring in the embankment. Many times the configuration of the abutments and foundation will determine the

type of cracking that will occur. With regard to freeboard loss, it
is highly unlikely that a complete failure could occur due to a free-
board loss resulting from differential settlement. The settlements are
not large enough. Estimations for P_{NF_3}, P_{PF_7}, and P_{CF_7} can then be
made based on careful consideration of the conditions presented above.

<div align="center">Estimation of Consequences</div>

Exposure factors

Once the probabilities for each of the outcome conditions (P_{NF},
P_{PF}, P_{CF}) are known, the magnitude of the consequences can be esti-
mated on the basis of various exposure factors including·

1. Time of year

2. Dam location

3. Flood warning time

Time of year. This exposure factor affects two main conditions:

1. Pool level (i.e. volume of impounded water)

2. Number of people in potential flood area

Potential impounded water usage predictions used in conjunction with
hydrological studies of the area would be valuable in predicting
net flow (whether it be outflow or inflow) as a function of the time
of year. Relationships could then be developed for the volume of
impounded water as a function of the time of year.

Present and projected future land use of the area would allow
predictions of populations in potential flood zones downstream of the
dam. Since the land use around or near a reservoir is very often of a
recreational nature populations vs. time of the year relationships

would need to be developed from available local information. Although these predications would be unique to each dam considered, they could be developed by using case histories of dams with similar characteristics (i.e. recreation, irrigation, and other needs which have shaped the surrounding population growth).

Dam location. This exposure factor affects land use downstream which in turn affects the following:

1. Number of people downstream

2. Amount of property downstream (structures, agriculture, etc.)

3. Aunt of aesthetically pleasing land downstream

The recreation potential and climate also can have a large affect on the land use downstream. Present and predicted future quantities of people, property and aesthetically valuable land in the potential flood zones, would need to be done as a function of the life of the earth dam structure. Zoning maps as well as case histories of similarly located dams would facilitate these predications.

Flood warning time. This exposure factor is not considered in estimating consequences resulting from a partial failure since no flood is involved. This exposure factor affects the following:

1. Steps which can be taken to save people

2. Steps which can be taken to save property

3. Steps which can be taken to save natural aesthetics

Definitions of potential flood zones will be beneficial in describing the affect of flood warning time. Similar to a recommended procedure of the Water Resources Council (1980) the flood zones are the following:

1. Primary flood zone, the area which is in the direct path of
   the flood water currents

2. Secondary flood zone, the area which is subject to rising
   flood waters, but is not in its direct path

Based on either actual trial runs or case histories of evacuations
which have occurred in the past, estimates could be made on how many
people could be evacuated per unit of time. Flood warning time would
probably have little effect on damages occurring in the primary flood
zone. However, with sufficient warning, steps could be taken to save
a good portion of the property and natural aesthetics damage in the
secondary flood zone.

Procedures for estimating consequences

Using the exposure factors listed above, estimates of consequences
can be made. The procedures for these consequences are explained below.

Repairable structural damage to dam. This would depend almost
totally on the type of system response or combination of responses
that caused the partial failure. Estimates of dollar damages would be
made by using average repair costs per unit time multiplied by the
estimated time of repair. The estimated time of repair would be a
direct result of the type and extent of damage incurred on the earth
dam structure. As presented in Chapter III, the repair cost estimate
in dollars is multiplied by the probability of partial failure to equal
the expected costs of the structural damage due to a partial failure.

Loss of revenue. Revenue refers to the regular income from the
existence of the dam. Revenue is obtained based on the following
factors:

1. Power generation

2. Irrigation (water rights, taxation, etc.)

3. Flood control

4. Recreation

5. Navigation

6. Others

Not all of these factors apply to every dam. Based on these factors, a study would be required to estimate the revenue in dollars per year which would be lost if the dam was no longer operable. Since loss of revenue can result from either a partial or complete failure outcome, estimations of revenue loss would be done separately as explained in Chapter III.

Irreparable structural damage to dam. This type of damage can be estimated in terms of dollars. It is the estimated cost of the earth dam project.

Loss of lives, property and natural aesthetics. To estimate losses of lives, property and natural aesthetics, a method such as the one proposed by the Water Resources Council (1980) could be used. There are basically four main steps in this method:

1. Delineate the affected zones

   a. primary flood zone

   b. secondary flood zone

2. Determine characteristics of affected zones (descriptions of the existing and projected characteristics of the potential flood zones)

3. Projections of activities and land use of potential flood zones

4. Collection of land market values of potential flood zones and

   related data

Using flood routing techniques, the primary and secondary flood zones
could be delineated on maps of the area of the damsite. The data
obtained from the four steps listed above is then used to estimate the
property damage in dollars, the lives lost and the loss of natural
aesthetics in terms of acres inundated.

CHAPTER V

POTENTIAL APPLICATIONS OF THE

RISK ANALYSIS PROCEDURE

Discussion

It should be emphasized at this point that the risk analysis

should not be used as the "final word" for risk assessment of the dam

at this time. It is, however, a very valuable source of information

for the engineer in making engineering decisions pertaining to earth

dam planning, design, construction, and operation.

Decisions involving cost and safety trade-offs

Many decisions must be made during the planning, design, construc-

tion, and operation of earth dams. Many of these decisions involve

trade-offs between increasing costs and increasing safety. An example

which involves an economic criterion for defining an acceptable level

of risk consists of three curves as shown in Figure 12. Curve a) re-

presents the plot of cost vs. dam embankment base width. Curve b) re-

presents the relationship between expected cost due to damages resulting

from dam failure vs. dam embankment base width. Curve c) represents

the summation of curves a) and b) and reveals the embankment base

width at which the combined costs are at a minimum (indicated by

point x in the figure). However, current design practices might

require a minimum embankment base width of the value, point y. In

this case the dam would have to be built according to accepted practice
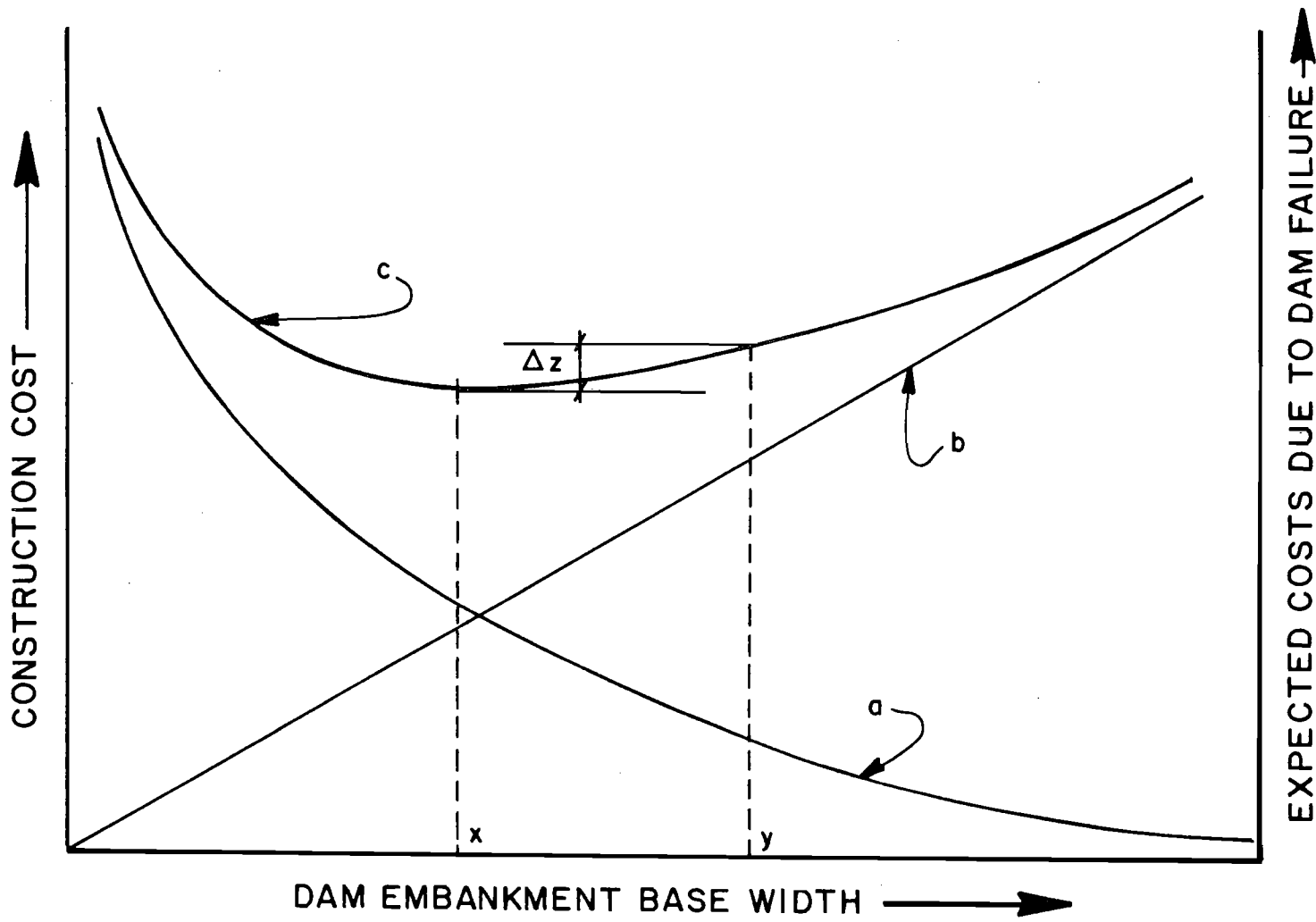
Figure 12. Use of an economic criterion for developing an acceptable level of risk.

at an increased cost of Δz ($). This emphasizes the point that
although the minimum cost can be found for various economic consider-
ations of the dam project, that minimum cost may not be at an accept-
able level of risk.

Decisions based on risk analysis results

The expected values of the consequences of an earth dam failure
obtained from the risk analysis procedure can be very valuable in
terms of making these decisions which include the following items:

1. Site selection

2. Selection of design parameters

3. Materials selection

4. Embankment cross-sectional geometry and apertenant struc-
    tural design

5. Quality control

6. Operating rules

There are potentially many other items in which risk analysis could
lead to a more rational basis for decision making under uncertainty.
However, the discussion below will be limited to the use of risk
analysis procedures in decision making with respect to the items
listed above.

Site selection. Many factors are taken into account with respect
to the selection of a particular damsite. Obviously, the amount of
material which is going to be required to construct an earth dam is
going to depend largely on the width of the structure. There are many
other things to consider, however. The geologic characteristics
of the foundation and/or abutments could jeopardize the site in terms

of the potential safety of the dam. A risk analysis procedure could prove very valuable in making decisions which would provide a balance between economy and safety of a particular damsite. After several potential sites have been considered and the list had been narrowed down to two or three, the risk analysis could be performed on the potential sites. Although the data base at this point would be very small, an assessment of the risk could be made for the damsites based on case histories of failures of similar dams. Outcome and final consequence estimations could then be used, in conjunction with other pertinent factors, to make a final decision as to which damsite would be the best in terms of safety, economy, and all other applicable considerations.

Selection of design parameters. If the risk analysis procedure revealed, for example, that the potential rise in pool level was the major contributor in the potential failure and ultimate consequences associated with a particular dam, this information could lead to a decision to enlarge the emergency spillway. Other decisions may be with regard to slope stability considerations in which decisions may be made, for example, to flatten the embankment slopes. In any case, the risk analysis can facilitate decision making during any part of the design stage.

Materials selection. The variability of the soil properties of the embankment materials is an important factor in determining the expected value of the consequences of dam failure. It is analyzed by means of the probabilistic slope stability analysis to determine the probability of a slope stability failure in the risk analysis procedure.

In general, the more variable the soil strength properties are. the higher the probability of failure becomes. When attempting to select a borrow area, for example, some areas may contain soils with more variable soil properties than others. Hence, even though one borrow area may be closer to the site and therefore cheaper to haul, it may not be the best choice if it is highly variable with regard to its soil strength properties. If variability in the material is excessive, a decision may have to be made to import material from more distant borrow areas which could lead to rejection of the site if hauling costs for borrow areas with lower variability soils are too high.

Quality control. As discussed in the materials selection topic, soil variability plays an important part in the embankment safety. Quality control is a means of reducing the variability of every aspect of a dam project as well as the soil strength properties. The risk analysis procedure provides a means for establishing the level of quality control to be used by trading off the increases in construction costs associated with higher levels of quality control against the reduction in the expected consequences of dam failure. If it is determined that the high degree of quality control significantly enhances the safety of the earth dam, a decision could be made to increase the quality control and use a more economical materials source.

Operating rules. Since one of the major factors associated with the operation of the dam is the control of the impounded water, an important consideration is the influence of the operating rules on the safety of the dam. This consideration could be handled by

performing a risk analysis on a few extreme cases and comparing the results. If effects are not too great, for example, operating rules may not need to be very rigid. Other aspects regarding the dam operation may also be tried and decisions made accordingly.

Case Study of Growing Data Base

In cooperation with the Water and Power Resources Service, the Soldier Creek Dam of Utah was selected for a case study of the proposed risk analysis procedure. Due to the limited research development funds available at this time, it was not possible to perform analytical work on Soldier Creek Dam. The feasibility study of this earth dam, which is part of the Central Utah Project, was commenced in 1948 and was completed in approximately 1974. A study performed by W. A. Wahler and Associates was presented in June 1977 and recommended that the reservoir filling process be delayed. Data and information on the Soldier Creek Dam was supplied by the Engineering and Research Center office, Denver, Colorado. A chronological list of the documents supplied is shown in Table 3. The material has been compiled in Table 2 to illustrate the "growing data and information base" for Soldier Creek Dam. As shown in this table, the various reports, tests, and analyses are categorized by activity types and located on a time scale. A detailed project activity sequence summary has been compiled (see Table 4 in the appendix) and contains a brief description of activities in their time sequence.

With the available data on Soldier Creek Dam and with extra data available from WPRS, it will be possible to test the risk analysis

Table 2. Soldier Creek Dam growing data base.

Activity	48	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Hydrology					Inflow Flood Study																	Bank Storage & Seepage	Reservoir Capability	Flood Summary	Inspection		
Geology	Reconnaissance											Report									Construction Engineering Geology Report						
Seismicity																		Seismic Monitoring						Earth Quake Evaluation			
Slope Stability														Stability Calculations										Embankment and Foundation Inspection			
Soil Properties								Report		Lab Tests	Exploration Report					Construction Materials Test Data	Earth Work Tests										
Foundation																Exploration					Grouting			Abutment Drilling			
Hydraulics																Spillway & Outlet Summary										Seepage Inspection of Abutments	
Project Activity Sequence*	1				2			3			4	5		6	7	8	9		10	11	12		13	14	15		

*See project activity description to decode numbers (Table 4 in the appendix)

procedure. Since the Soldier Creek Dam is complete, the next phase of the case study will explore the differences in risk analysis results obtained at different stages in the project's life. It would also indicate which of the proposed methods for estimating transition probabilities can be used and which need to be modified. An indication of what kinds of data are more useful than others in performing the risk analysis procedure will also be obtained. This indication will be valuable in recommendations for the types of data which should be obtained from sampling and testing.

Advantages and Limitations of the Risk Analysis Procedure

Advantages

1. A design with a higher factor of safety does not necessarily lead to a safer structure

2. The designer is required to explicitly consider all of the failure mechanisms

3. Quantitative estimates of the transition probabilities are required and this enables the designer to identify the most likely modes of failure

4. The procedure is adaptable to the "growing data base" of a dam

Limitations

1. Uncertainties associated with the probabilities which are estimated using judgment and empirical data

2. Considerable weight in the analysis is placed on transition probabilities estimated by judgment

3. The framework may not be complete because some events and/or linkages may have been overlooked

4. All the information needed to perform the analysis may not be readily available

5. A considerable amount of time and effort would be required to perform the entire analysis

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A framework for risk analysis of an earth dam has been presented
with suggested procedures for estimating transition probabilities.
The general framework is also applicable to other types of civil
engineering structures.

1. Before the probabilistic models, empirical and judgment pro-
    cedures can be applied in practice, the risk analysis procedure
    needs to be further developed. In addition, procedures for
    utilizing the knowledge of engineers to make the subjective
    probability estimates need to be developed.

2. The value of the continuation of future development of a practical
    comprehensive risk analysis procedure for earth dams cannot be
    over emphasized based on the advantages listed in Chapter V.

3. The confidence which can be placed in the results of the risk
    analysis procedure may be reduced due to certain limitations of
    the procedure such as those listed in Chapter V.

4. A possible means for handling the subjective probability estimates
    is to lump these transition probabilities together and use histori-
    cal values to estimate the lumped probabilities. Baecher, et al.
    (1980) proposed a similar procedure in which they presented the
    possibility that the observed rate of failure of 10^{-4} represents
    the frequency of unexpected causes.

Recommendations

1. To provide a practical test of the proposed risk analysis procedure
    and to give opportunity for refining the techniques for estimating
    the transition probabilities, a detailed case study of Soldier
    Creek Dam should be performed. Phases of the project in which data
    were either not available or insufficient to make adequate judgment
    estimations, could be estimated by using lumped probabilities as
    described above.

2. Future studies should be performed to develop empirical and prob-
    abilistic methods for those phases of the risk analysis procedure
    which now depend on judgment decisions. Some examples of the most
    promising areas for study are:

    a. Probabilistic methods involving differential settlement

    b. Methods for evaluating core cracking and piping in dam
        embankments

    c. Human behavioral studies dealing with human error.

3. During future research studies, those elements of the risk analysis
    procedure which are determined to be significant with regard to
    their potential contribution to the probability of failure and
    ultimate consequences, should be omitted from the procedure. A
    possible criterion for deciding whether or not elements can be
    ignored by comparing their probability of occurrence with the
    probability of occurrence of natural phenomena.

4. After further research and development work has been successfully
    completed, the risk analysis procedure should be made accessible
    to the practicing engineer by incorporating the entire procedure

into an user-oriented interactive computer program. The program would require the user to select the method for estimating the transition probabilities and these estimates would be made in subroutines to the main program using user-supplied input.

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APPENDIX

Table 3. Soldier Creek Dam – chronological listing of information
collected from WRPS in December 1979.

DATE		TITLE
Feb.	1948	Reconnaissance Geological Report
June 3,	1958	Inflow Design Flood Study
June 3,	1958	Memo: Design Storms for Soldier Creek Dam
Aug. 14,	1958	Memo: Review of Inflow Design Flood
Sep. 11,	1958	Memo: Inflow Design Flood Study for Soldier Creek Dam
Sep.	1961	Lab Report: Earth Mtls. Investigation Lab Test Results
Aug.	1964	Definite Plan Report
Dec. 2,	1964	Lab. Tests on Proposed Embankment Mtls. for Final Design
Jan.	1965	Geology Report No. G-210
Jan.	1965	Preconstruction Earth Mtls. Exploration Report GM-81
July	1965	Information Requested for Preparation of Specification Designs and Estimates, D & E No. 171
1967 –	1968	Embankment Stability Calculations (Fellinius – May Solutions)
Apr. 15,	1968	Memo: Discussion of Machine Control Parameters for Stability Analysis by F. M. Method Using CDC-6400
May 2,	1968	Memo: Foundation Exploration
Mar. 25,	1969	Spillway and Outlet Works, Design Summary
	1969	Specifications/Computations
June 3,	1970	Construction Materials Test Data Spec. No. DC-6854

Table 3. Continued.

DATE	TITLE
July 1970	Design Consideration
Dec. 22, 1972	Memo: Seismic Monitoring of Soldier Creek Reservoir
1972	Earthwork Field & Lab Testing with Summaries
Mar. 1973	Record of Foundation and Tunnel Grouting
Aug. 12, 1974	Memo: Riprap Report
Aug. 1974	Construction Engineering Geology Report Rpt. # G-295
Approx. 1974	Final Construction Report
June 10, 1975	Project Accretion Flow Studies (Feature: Bank Storage & Seepage)
June 29, 1976	Reservoir Water-Holding Capability
Apr. 4, 1977	Flood Hydrology Summary
May 10, 1977	Memo: Inspection of Earth Embankment and Foundation
June 1, 1977	Memo: Earthquake Evaluation
June 1977	Wahler Report
July 6, 1977	Memo: Riprap Repair
Dec. 3, 1977	Faxogram: Subject: Technical Paragraph for Abutment Drilling
May 4, 1978	Inspection Report
May 10, 1978	Inspection Report
Dec. 7, 1978	Memo: Water Samples
1978	Placement of Riprap
July 18, 1979	Memo: Water Samples
NO DATE	Standing Operating Procedures

Table 4. Soldier Creek Dam - project activity sequence description.

1. Reconnaissance Geology Report (1948)
          Preliminary Report:
    No exploration has been done for construction at this point.
    Material that seemed to be available by inspection was looked at.
    Conclusions:
          Foundation materials seemed to be adequate.
          Further investigation will be needed for materials.

2. Inflow Design Flood Study (1958)
          Relatively detailed study was conducted with virtually all
          contributing factors being taken into account. (i.e. aqueduct,
          frequency study, diversion requirements).
    Conclusions:
          Agree with a preliminary design flood study which was
          conducted July 16, 1948.
          Two alternative inflow design floods were presented:
                a) Maximum probable snowmelt and moderate frequency
                   rain.
                b) Record snowmelt and maximum probable rain.

3. Earth Materials Laboratory Report (1961)
          This report still seemed reconnaissance oriented. Location and
          description of borrow areas A-E was given. Descriptions and
          results of borrow material tests were supplied.
    Summary and Conclusions:
          Required material volume estimates were given.
          Availability estimates such as the type of materials
          pervious or impervious) for each borrow area were given.
          There were also some groundwater descriptions given.

4. Laboratory Tests on Materials Proposed for "Final Design" (1964)
          This involved a relatively detailed testing program
                (gradation, Atterberg limits, compaction, placement,
                consolidation, shear values, etc.).
          Pre-construction test results were also shown.

5. Summary of All Earth Materials Investigation Between 1948-65
          Concluded that 3 million cubic yards of earth material would
          be required.
          Eleven borrow areas were investigated in detail:
                Investigation outlined "sufficient" materials for the
                construction of the dam.
          Location and availability of the following was evaluated:
                Concrete aggregates, riprap, lumber and mine timbers,
                gravel road materials.
          Geology Report No. G-210 (1965)

Table 4. Continued.

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5.   Relatively detailed report which investigated:
(cont.)   Regional geology, damsite geology, construction materials.
            Site conditions and earth materials investigations were
            conducted using many borings.

       Summary and Conclusions:
            Soldier Creek Damsite is one of the best sites, if not the
            best, left for water storage in Utah.
            This conclusion is based on the geology, nearby avail-
            ability of construction materials and overall design
            requirements as a result of the site conditions.

6. Stability Calculations: (1967-68)
    Calculations were performed using the Fellenius-May solution on
    the following maximum section:
            5 zones (middle zone was core with toe drain)
            2 foundation layers.

7. Stability Calculations were still being made
    Memo from Chief Engineer concerning foundation exploration: (1968)
        Location and depth of 8 drill holes were requested to
        facilitate additional exploration for foundation.
        Locations of 2 exploration lines (A and B) were requested for
        profiles and geologic descriptions.

8. Design Summary of Spillway and Outlet Works (1969)
    Recommendations as a result of this study were:
            a) Adopt single stage construction
            b) Adopt two level outlet works without spillway
               (initially approved December 12, 1967)
            c) Adopt flip bucket with a limited stilling capacity.
            d) Remove alluvial fan in mouth of side drainage draw to
               expose sound rock but do not provide excavated channel
               for side drainage. This assumes adoption of recommen-
               dation c).
            e) Gate aeration is recommended only if design can be model
               tested to establish satifactory performance. (Branch
               Chief rejected proposed test at $10,000)
    Addendum (April 1970)
        Provisions for selective level withdrawals for protection of
        game fish. (Estimated cost increase $200,000).
        Selective level provisions with modified vertical shaft intake
        was recommended.

9. Construction Materials Test Data (1970)
        No specific summaries were given.
        Test results were given on:
            Concrete aggregate, riprap, soil test data (Denver Lab..
            Field Lab., Borrow Areas A-G).

Table 4. Continued.

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10. Earthwork Field and Lab. Testing with Summaries (1972)
    Construction has begun
    Embankment testing and monitoring of in-place soil properties
    is included with references to the locations of each sample
    on the embankment with reference to its borrow origin.
    Memo Dealing with Seismic Monitoring of Soldier Creek Reservoir
    1972)
    This memo was an attempt to negotiate a program to monitor the
    earthquake potential with respect to the filling of Soldier
    Creek Reservoir. It still seemed to be pending due to funding
    complications although the Bureau seemed to be much in favor.

11. Record of Foundation and Tunnel Grouting (1973)
    Location and extent of grouting was indicated.
    Quantity, quality, and pressure of applied grout was also given
    here.

12. Construction Engineering Geology Report (1974)
    The following information was given with respect to the
    construction of Solider Creek Dam as related to:
        Damsite, grouting, outlet works, access shaft, and
        stilling basin, construction embankment materials.

13. Bank Storage and Seepage
    Reservoir Water - Holding Capability (1976)

14. Flood Hydrology Summary (1977)
    Summaries were included in the areas of:
        Flood types, design storm, unit hydrographs, moderate
        snowflood, maximum snowflood, combined design floods,
        diversion frequency study, and historical floods.
    Memo regarding earthquake evaluation was submitted: (1977)
    Relatively detailed report for the purpose of evaluating
    operating basic earthquake, design basic earthquake, maximum
    credible earthquake, and the recurrence interval for two
    seismotectonic provinces they called Basin and Range and Rocky
    Mountain - Colorado Plateau.
    Memo Regarding Inspection of Earth Embankment and Foundation
    (1977).
    Tables were compiled showing the following information for a
    given day:
        Elevation reservoir, time and amount (gpm) for the right
        and left abutments, seepage respectively.
    Memo regarding the drilling of observation holes in the abutments.
    Information as to the requested well depth, location, and
    nearest drill hole number were given.

Table 4. Continued.

15. Seepage Inspection of Abutments (1978)
        Regular readings have been taken at certain intervals and it
        seems they will continue to be taken in future.
    Water Samples (1978)
        Information of water samples taken also at a regular basis.