# FRAMEWORK FOR THE ESTIMATION OF OVERALL PROBABILITY OF DAM FAILURE OF ANCIENT EARTH DAMS IN SRI LANKA

L. I. N. De Silva, Senior Lecturer (Email: nalinds@civil.mrt.ac.lk)
Premkumar. S, Postgraduate Student (Email: ananthwow@yahoo.com)

Department of Civil Engineering, University of Moratuwa

**Abstract:** Sri Lanka has a rich history of earth dam construction with over 300 large scale ancient earth dams in service. However, large number of ancient earth dams are suffering partial failures due to excessive seepage, piping and slope instability. The failure of an earth dam involves a number of modes. The quantitative risk analysis and assessment approach relate to the total probability of failure and therefore the individual probabilities estimated for different failure modes under various loading conditions need to be combined. The probability of failure for each mode involves engineering assessment of the particular failure mechanisms, and looking for solutions that can reduce the probability of those failure modes or minimise the consequences of a failure. No standard framework is adopted in Sri Lanka for the estimation of overall probability of dam failure. The objective of this paper is to develop a standard framework for the estimation of overall probability of dam failure to be included in the quantitative risk assessment process for ancient earth dams in Sri Lanka. Critical loading conditions which are relevant to Sri Lanka are considered in the present study.

**Keywords:** risk assessment, probability of failure, event tree, load state, failure mode

## 1. Introduction

A complete quantitative risk assessment seeks to enumerate the risks in terms of probability of failure and consequences, to the extent possible. Therefore estimating the probability of failure is the most important and critical part in quantitative risk assessment. With the move to a risk based approach to dam safety there has been a concomitant focus on estimating the probability of failure of dams.

The failure of a particular component of a dam under different loading conditions (e.g. Flood earthquake, and normal operating load) involves various failure modes. If we consider internal erosion and piping, it can be further divided into different path way and processes. So, each of these failure modes should be considered according to the conditions in estimating the probability of dam failure by internal erosion and piping. Historic performance and event tree are the two broad categories of methods in use for estimating probability of failure.

The majority of risk evaluation guidelines however relate to the overall probability of failure for the reservoir and therefore the individual probabilities estimated for different dam sections or components, failure modes and loading conditions need to be combined. In most cases one or more of several failure modes may come into play from the same causative event, therefore the events are not mutually exclusive and the failure probabilities cannot be added directly.

Here, in this paper the framework for the estimation of overall probability of dam failure is developed based on the condition of earth dams in Sri Lanka. The different methods available for estimating probabilities for given failure modes of a dam under different loading conditions are briefly summarised. In terms of combining the estimated probabilities of failure two broad methods are discussed.

## 2. Failure Mode Analysis

As a first step, the failure modes to be analysed should be identified. A failure mode is a sequence of system response events, triggered by an initiating event, which could culminate in dam failure. Procedures for failure mode identification vary, but in a typical approach, a small team of dam engineers, who have knowledge of historical dam failure mechanisms, would develop a list of failure modes [7]. Failure modes analysis can be undertake using systematic and comprehensive process such as FMEA (Failure Modes and Effects Analysis) or FMECA (Failure Modes, Effects and Criticality Analysis) [1]. In quantitative risk assessment, the usual process is FMEA; because the later parts of the risk assessment will define criticality. FEMA is a quantitative technique by which the effects of individual component failures are systematically identified.

An ANCOLD guideline divides the FMEA in to nine steps as [1];

- Establish the basic principle and corresponding documentation in performing the analysis
- Define the system which may be define at various levels
- Define the components of each sub-system
- Identify the causes of the failure modes and operating conditions under which the failure can occur
- identify the failure modes
- Identify the effects of the component failure on system considering local and global effects
- Identify the failure detection method,
- Identify compensating or mitigating provisions including isolation and redundancy
- Assign the severity classification.

Since this paper is aimed to develop a frame work for overall probability estimation, it is necessary to consider only up to fifth step of FMEA. Other steps will be considered in estimation of consequences.

Most important failure modes to be considered for embankment dams are embankment instability settlement and loss of free board, internal erosion and piping, embankment overtopping and slope instability.

Failure modes should be listed in sufficient detail to capture all of the significant failure scenarios [1]. For example, if we consider internal erosion and piping, based on the failure path we can sub divide as; internal erosion and piping through the embankment, through the foundation and from embankment to foundation. Furthermore piping through the embankment can be sub-divided into; internal erosion and piping through the dam and internal erosion and piping along or into conduit [4]. These failure scenarios can be further sub-divided into potential piping process such as; initiation, continuation, progression and breach mechanism in order to identify the causes of the failure modes [2].

## 3. Evaluation of Load States

ANCOLD guidelines on risk assessment [1] summarises that the obvious hazards are;

- The storage water is itself a hazard, given that the dam is an imperfect container (hence the need to consider failure modes under normal operating conditions)
- Floods;
- Earthquakes

Data on earthquakes felt in Sri Lanka suggest that earthquakes of magnitude 4 have not occurred in Sri Lanka during historical times for which records are available. However, the possibility of earthquakes of magnitude greater than 4 occurring at these dam sites cannot be ruled out [8]. In this paper, based on the studies and present status of ancient earth dams in Sri Lanka, earthquake loading is considered as less obvious.

Loading on the dam needs to be partitioned over the full range of possible loads. The amounts of partitioning of the load states should take account of the type of analysis and the system response to the loads. Preliminary studies will use less partitioning, or may not formally partition the loads.

Most of the Sri Lankan dams are interconnected and failure of an upstream dam may cause other dams failure. But, the failure of upstream dams should not be considered as loading conditions in a risk analysis [7]. The risk of multiple dam failures/incident are addressed by assigning the cause of failure to the most upstream dam failure and including the resulting dam failures as consequences for that dam [7].

### 3.1 Normal Operating Loads

A reservoir level-duration relationship is used to estimate the likelihood that normal operating loads will occur in a specified range [3]. This relationship should be based on a continuous record of water levels, and not peak water levels. It is important that this relationship be representative of operating conditions for the period of time for which the risk analysis is to be carried out.

If operating rules, inflow characteristics, or reservoir release patterns have changed over the life of the reservoir, the historical record should be adjusted, using reservoir simulation, to represent future conditions before the reservoir level-duration relationship is developed [3].

### 3.2 Flood Loads

ANCOLD guidelines on risk assessment divide the flood load evaluation in to three tasks as [1];

i. Production of event magnitude versus frequency/probability curves to define a loading domain.
ii. Partitioning of the loading domains into load states that will be used in the risk analysis.
iii. Identify the load scenarios. One or more load states define a load scenario.

The term loading domain is used to refer to the total range in magnitude of loads, together with their associated probability of occurrence, expressed as a continuous relationship – peak flood discharge versus annual exceedance probability (AEP).

Two approaches have been taken for portioning of the loading domain [1].

- Manual partitioning of the loading domain into a relatively few states – typically 3 to 10;
- Automated partitioning by use of available software to produce a large number of load states.

In manual approach, the load state covers a range of load values, represented by a single value representative load, usually the mean of the portion end point loads, which is the basis for assigning estimated conditional probability of failure [1].
An example of manual portioning of an inflow flood domain for quantitative analysis is given in Table 1.

Table 1: Manual portioning of inflow flood domain

| Partition Point Peak Inflow Discharge ($m^3/s$) | Partition Point Annual Exceedance Probability | Representative Inflow Discharge ($m^3/s$) | Annual Probability of Flood with Peak Inflow in Partition |
|---|---|---|---|
| 250 | 1 in 1 | | |
| | | 1725 | 9.980E-01 |
| 3200 | 1 in 500 | | |
| | | 4475 | 1.714E-03 |
| 5750 | 1 in 3500 | | |
| | | 7375 | 2.571E-04 |
| 9000 | 1 in 35000 | | |
| | | 10500 | 2.571E-05 |
| 12000 | 1 in 3500000 | | |
| | | 12750 | 1.857E-06 |
| 13500 | 1 in 1000000 | | |
| | | 13500 | 1.000E-06 |
| Total | | | 0.9999993 |

In the above table, the two right hand columns define the load states for use in risk analysis.

## 4. Estimation of Probabilities

There are two broad categories of methods for estimating probabilities of failure:

a) Historic performance methods
These methods use the historic performance of dams similar to the dam being analysed to assess a historic failure frequency, and assumes that the future performance of such dams will be similar. These methods do not directly account for the reservoir loading, nor do they allow for the detailed characteristics of the dam or for particular intervention. Generally speaking, these methods are only applicable for screening and preliminary level portfolio risk assessments, and for checking more detailed event tree methods, and should not be used alone for detailed assessments.

b) Event tree method
Event tree methods have the advantage that the mechanics of the failure, from initiation to breach can be modelled; the details of the dam and its foundation and the ability to intervene to prevent breaching.

### 4.1 Internal Erosion and Piping

The probability of failure of internal erosion and piping can be estimated using historic performance method or event tree method. The method of estimating the probability of failure of embankment dams by piping, have been summarized by Foster et al (2000) [5].

The event tree method involves the decomposition of the failure process into a sequence of events, starting from initiating events through to breaching. Conditional probabilities are assigned to each branch of the event tree, often by a panel of "experts". These are generally judgmental probabilities and are based on the expert's experience, review of information on the design, construction, and performance of the dam, and the reading of selected dam incident and performance case histories from the literature [4].

In this paper the event tree for internal erosion and piping through embankment and foundation is developed based on Foster et al (1999) [4] and Rabin Fell and Chi Fai Wan (2005) [2]. The event tree for internal erosion and piping is given in Figure 1. The branches of event tree for internal erosion and piping through the embankment are;

i. Initiation;
   A – In dam/ along or into conduit
   B1 - Concentrated leak or suffusion
   B2 - No leak
ii. Continuation;
   C1 - No erosion
   C2 - Some erosion
   C3 - Continuing erosion
iii. Progression;
   D1 - Support a roof
   D2 - Not support a roof
   E1 - Ability to limit flow
   E2 - Inability to limit flow
   F1 - Non erodible soil
   F2 - Erodible soil
iv. Early intervention;
   G1 - Successful
   G2 - Unsuccessful
v. Breach mechanism;
   H1 - Breach initiate
   H2 - Breach not initiates

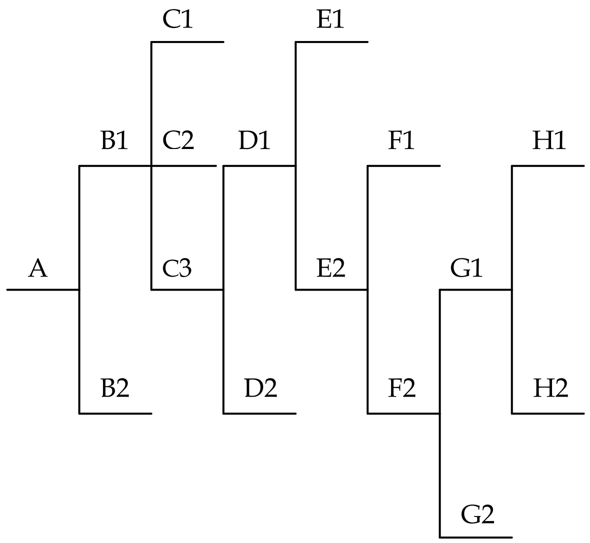


Figure 1: Event tree for internal erosion and piping through the embankment

Similarly in the event tree for internal erosion and piping through foundation, branches are almost same as for internal erosion and piping through the embankment. The limitation of flows is less influential for limiting the enlargement of the pipe in piping through the foundation compared to piping through the embankment [4]. But the factors influences the limitation flow are contribute by restricting erosion [4]. So flow limitation and soil erodibility are combined in to one branch as "flow restriction".

Factors influencing on the likelihood of each branches of an event tree are slightly different for piping through embankment and piping through foundation depending on the material type and filter conditions. The probability of each branches in the event tree of internal erosion and piping can be calculated by engineering judgement using "verbal descriptors" scheme given in Barneich et al (1996) [2].

## 4.2 Slope Instability

Probability of slope failure can be estimated using historical data, mathematical modelling and quantification of expert judgement. In this paper we have discussed about the method based on quantification of expert judgement.

Figure 2 present the relationships between factor of safety and annual probability of failure based on actual engineering projects and developed through quantified expert judgment [6]. This plot is an updated version of the one originally presented by Lambe (1985) and Baecher and Christian (2003) [6]. Figure 2 classifies earth structures into four categories, based on the level of engineering, ranges from best Category (I) to poor Category (IV). We establish the level of engineering by examining the practices followed for design, investigation, testing, analyses and documentation, construction, and operation and monitoring. The four categories correspond to the following types of facilities [6]:

i. Category I—facilities designed, built, and operated with state-of-the-practice engineering. Generally these facilities have high failure consequences;
ii. Category II—facilities designed, built, and operated using standard engineering practice. Many ordinary facilities fall into this category;
iii. Category III—facilities without site-specific design and substandard construction or operation. Temporary facilities and those with low failure consequences often fall into this category;
iv. Category IV—facilities with little or no engineering.

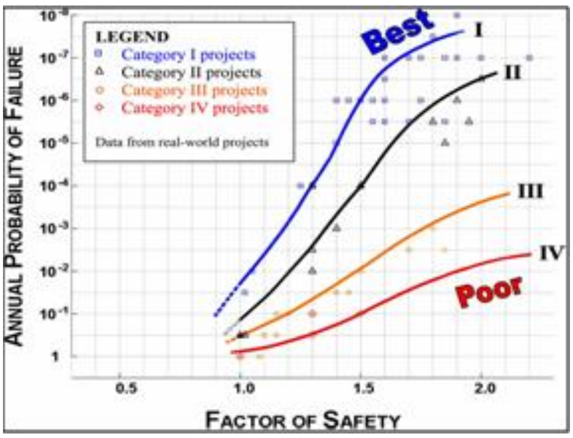


Figure 2: Factor of safety versus annual probability of failure [6]

### 4.3 Embankment Overtopping

The probability of failure is calculated from the reservoir level AEP, and a system response curve, that is, probability of failure versus depth of water over the dam crest, which is developed for that dam. Selection of the response relationship is subjective, with factors such as material type, compaction and inherent susceptibility to erosion influencing the choice.

Most studies seem to accept that the probability of failure approaches 1.0 when the depth of overtopping is between 0.5m and 1m for a modern compacted rockfill dam or a well-grasses cohesive earthfill dam, but near zero for poorly compacted erodible earthfill [1].

## 5. Combining the Probabilities

In quantitative analysis, annual probability of failure should be estimated from the estimation of probabilities previously made.

ANCOLD guidelines on risk assessment summarise the different methods of combining the probabilities as [1]:

- The estimated overall total probability of failure per annum over all components of the dam, overall load states/scenarios and over all failure modes
- The estimated total probability of failure per annum for each component of the dam (for example, concrete gravity section, main embankment or saddle embankment);
- The estimate total probability of failure per annum by load state/scenario;
- The estimated total probability of failure per annum by failure mode.

### 5.1 Common Cause of Failures

Common cause failure modes are failure modes that can occur simultaneously at a single dam section due to a single initiating event, and failure modes that can occur simultaneously at multiple sections of a dam due to a single initiating event. The total probability of dam failure is some combination of the probabilities of dam failure that are associated with each of the possible modes. For this case, there is no practicable way of computing the estimated overall probability of failure, given the several individual mode conditional probabilities of failure. Following the theory of uni-modal bounds the bounds can be determined [1].

### 5.2 Uni-Model Bound Theorem

The conditional probabilities for the failure modes that are not mutually exclusive can be adjusted for common cause occurrence by using the uni-modal bounds theorem. The uni-modal bounds theorem (Ang and Tang, 1984) states that for k positively correlated failure modes, with conditional branch failure probabilities (system response probabilities, or SRPs), pi, the system (total) branch failure probability, lies between the following upper (u) and lower (l) bounds:

The upper bound is the union of the events, the several failure modes. From de Morgan's rule, the estimated upper bound conditional probability is [1];

$$P_{UB} = 1- (1-P_1).\ (1-P_2)\ldots\ldots\ (1-P_n) \qquad (1)$$

Where,

$P_{UB}$ = the estimated upper bound conditional probability of failure

$P_1$ to $P_n$ = the estimates of the several individual mode conditional probabilities of failure.

This computation must be made on the estimated conditional probabilities of failure before multiplying by the annual probability of the loading scenario [1].

The lower bound estimate is the maximum individual conditional probability

### 5.3 Combining Probabilities of Failure modes Initiated by Flood

The annual likelihood or probability of occurrence of the load state or scenario needs to be multiplied by the estimated conditional probability of failure, in order to find the annual likelihood of failure for each failure mode [1]. If likelihood of failure is to be aggregated over several failure modes that are not mutually exclusive, it is necessary to apply de Morgan's rule to compute the estimated upper bound conditional probability before multiplying by the annual likelihood of the load state or scenario.

### 5.3 Combining Probabilities of Failure modes Initiated by Normal operating Load

For normal operating conditions, it is the reservoir level state that contributes the load state. For normal operating load, the annual probability of failure, found by multiplying the annual probability of initiation and the conditional probability of failure, are weighted by the dimensionless proportion of time that the reservoir is in each level state [1]. Here the conditional probabilities are influenced by level state. Since the reservoir level states are mutually exclusive, and exhaustive of the total reservoir level domain, proportion of time that the reservoir is in each level state should sum to 1.0.

### 5.4 Overall Probability of Dam Failure

The overall probability of dam failure is the addition of total overall annual probability of failure for every loading condition (e.g. Flood and normal operating load).

## 6. Conclusions

In this paper, the framework for the estimation of overall probability of dam failure is developed based on the condition of earth dams in Sri Lanka. Here we have discussed the methods that are applicable to earth dams with available data and proper investigation.

Here, the earthquake loading is considered as less obvious, based on the Sri Lanka's earthquake history records. Since the embankment instability and loss of free board is mainly occurs under earthquake loading, it has been omitted from discussion. In future there may be a possibility to occur high magnitude of earthquake and in that case earthquake loading should be considered under risk analysis.

When using the "verbal descriptors" to estimate the probabilities, engineering judgement should be taken with care. Otherwise it would result in over estimation or under estimation of the probabilities. Here, the internal erosion and piping from embankment to foundation is not discussed, since it less likely to occur in earth dam.

For screening level studies, the conservative assumption that the reservoir is always full under normal operating conditions analysis may be reasonable in some cases, but this position should not be taken without consideration of how representative it is of the annual operating cycle for the reservoir.

The Uni-Modal Bounds Theorem provides a method for adjusting conditional probabilities for the failure modes that are not mutually exclusive. This adjustment should be made simultaneously over all sections of a multi-section dam. It should be calculated and applied separately in each probability interval for a loading type.

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