LARGE SCALE PHYSICAL MODELING OF EMBANKMENT DAMS BREACH

By

Muhammad Ashraf Elsayed Muhammad

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Irrigation and Hydraulics Engineering

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Title of Thesis:

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Key Words:
Embankment; breach parameters; overtopping; physical modeling

Summary:
Embankment dams are the most common type of dams built across the world and they are especially susceptible to failure by overtopping, which is the most common mode of failure of dams worldwide. Understanding the failure mechanisms in embankment dams and levees can lead to better design of flood mitigation, flood mapping, and flood warning systems. Many embankment breach experiments were reported in the literature but they are usually conducted on small scale non-cohesive embankments. A database of 123 events of embankment failure due to overtopping was collected and analyzed using nonlinear regression analysis to provide new equations for calculating several parameters describing the breach process. Moreover, this study uses a large scale physical model constructed on the premises of the Hydraulic Research Institute to model the failure of large scale cohesive and non-cohesive soil embankments. Instantaneous photos, grid of wires, and graded steel rods were used to capture the morphological changes in the embankment during the experiments. A 3D representation of the embankment failure was produced and the stages of the breach process were analyzed. The study showed the great extent to which soil properties affects the failure of embankments due the variation in breach process for embankments with same dimensions but different soil compositions. Finally, the derived breach parameter equations were assessed using the results from the physical model and yielded good agreement for the non-cohesive embankments.

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Nomenclature

1-D	One-Dimensional
2-D	Two-Dimensional
3-D	Three-Dimensional
ASCE	American Society of Civil Engineers
cm	Centimeters
D/S	Downstream
ESRI	Environmental System Research Institute
HRI	Hydraulics Research Institute
hrs	Hours
km	Kilometers
km^2	Squared Kilometer
LS^{-1}	Litres per Second
m	Meters
m^2	Squared Meter
m^3s^{-1}	Cubic meters per second
MAPE	Mean Absolute Percentage Error
Matlab	Matrix Laboratory (software)
MCM	Million Cubic Meters
R^2	Coefficient of determination
RMSE	Root Mean Squared Error
U/S	Upstream
USA	United States of America

Abstract

Failure of dams and levees can have catastrophic impacts on the downstream regions as it leads to huge loss of life, death of livestock, destruction of buildings and infrastructure. Dams and levees are expected to be under greater threat from more frequent and more severe floods due to climate change. Embankment dams are the most common type of dams built across the world and they are especially susceptible to failure by overtopping, which is the most common mode of failure of dams and levees worldwide. Understanding the failure mechanisms in embankment dams and levees can lead to better design of flood mitigation, flood mapping, and flood warning systems. Many studies concluded from analyzing historical dam failure incidents that adequate warning time can lead to a significant saving of lives from the population at risk.

However, there are many complex and interacting hydrodynamic and morphological processes involved in the failure event that are not fully understood yet. That places a big limitation on the ability to model the failure processes especially using numerical models. Moreover, predicting the outcome of the breach failure event by statistical analysis of historical dam failure events produces equations that must be used with cautious outside the data range used to derive the equations. Physical modeling of the breach process can represent a challenge as well. Although, many embankment breach experiments were reported in the literature, they are usually conducted on small scale non-cohesive embankments. The breach process differs significantly from cohesive and non-cohesive embankments, and scaling down of experiments can cause issues related to scaling of material particles.

In this study, the state of the art equations for determining the breach parameters were assessed and were updated by using a database of 123 events of embankment failure due to overtopping. Regression analysis using the multiple linear regression analysis tool in Microsoft excel or the nonlinear regression analysis tool in Matlab to provide new equations for calculating the breach height, average width of the breach opening, the peak discharge from the breach event, and the time for breach formation.

This study uses a large scale physical model constructed on the premises of the Hydraulic Research Institute in Egypt to model the failure of large scale cohesive soil and non-cohesive embankment. The embankments failure was tested due to overtopping by filling a 400 m^2 reservoir upstream the embankment. Special care was taken regarding proper construction and compaction of soil in the embankment body. Instantaneous photos, grid of wires, and graded steel rods were used to capture the morphological changes in the embankment during the experiments.

The stages of the breach process were thoroughly analyzed, and a Matlab script followed by photo editing was used to produce a 3D representation of the embankment failure. The study showed the great extent to which soil properties affects the failure of embankments due the variation in breach process for embankments with same dimensions but different soil compositions., which showed that the increased percentage of clay in the soil mixture significantly increased the resistance of the embankments to erosion. Finally, the breach parameter equations were assessed using physical model results and yielded good agreement for the non-cohesive embankments.

Chapter 1 : Introduction

1.1. Problem definition

Failure in dams and levees can have destructive impacts on the downstream regions. There are three main failure modes of dams and levees: 1) Overtopping, 2) Pipping (or internal erosion) and 3) Structural failure. Different statistics vary on the percentage of occurrence of these modes of failure. However, according to data collected by Foster et al. (1998) and Costa (1985); overtopping is the primary mode of failure for dams as shown in Table 1.1.

Table 1.1: Occurrences of different modes of dam failure

Mode of Failure	Foster et al.	Costa
	Percentage of occurrence (%)	
Overtopping	48	34
Pipping	46	28
Structural	5	30
Others	1	8

Moreover, throughout the world many dams are constructed as earth-fill or rockfill embankments. For example, statistics released by the US Committee on large dams (1975) indicated that about 80% of the large dams in the United States are constructed using erodible soil material, which makes them especially susceptible to failure by overtopping. Overtopping occurs when an extreme event exceeds the safety evaluation flood of the structure. Once water flow on the downstream side of the dam, a breach process initiates in the body of the dam. The form of the breach process is crucial in determining certain factors such as time till failure, temporal variation in opening dimensions in dam body and the outflow hydrograph from the breached dam (El-Ghorab et al., 2013).

Usually earth-fill dams and levees are constructed from local soil located at the dam site. The soil properties have direct effect on the structure's resistance to failure due to breaching (Orendorff, 2009). Though numerous breaching tests were reported in the literature, two main shortcomings can be noted about them. First, most of these tests were conducted on non-cohesive soils. However, breaching failure in cohesive and non-cohesive soils follows different mechanisms (Orendorff, 2009). Moreover, most of them were conducted on small scale models. Small scale models might not accurately simulate the complex processes involved in levee breach mainly due to material scaling problems (Heller, 2011). For example, ASCE (2011) reported more than 725 test runs on earth-fill dams and levees conduced since the 1960s with breach overtopping as the failure mechanism. However, most of these tests were conducted on small scale with non-cohesive embankment material.

Investigating the breach failure of dams through analyzing historical incidents of dam failures is an alternative approach to evade the challenges associated with constructing and running embankment failure tests. Regression analysis was widely used in deriving equations estimating parameters that describe the breach process (ASCE 2011). Main shortcomings in these equations is combining data form two or more dam failure causes in the derivation of these equations, and the lack of sufficient number of data points used in the regression analysis.

1.2. Objectives

The objectives of this study are as follow:

- Analyze state of the art breach parameters estimation equations, and then use nonlinear regression analysis to derive an updated set of equations.
- Conduct large scale experiments on breach of cohesive and non-cohesive soil embankment.
- Study the breach temporal evolution and the corresponding outflow hydrograph from breached embankments.
- Assess the effects of embankment soil composition on the failure process.
- Use the results from the physical model to investigate the performance of the newly derived breach parameter equations.

1.3. Methodology

Research conducted in this study is composed of two parts: First, the derivation of breach parameters equations, second, physical modeling of embankment breaching. There is a large number of reported dam failure incidents. This historical information can provide a wealth of data compared to the limited number (and sizes) of physical model tests. Consequently, the approach of this study is to derive equations from statistical analysis of historical dam failures then evaluate these equations using the results from physical modelling.

The main objective of the first part of the study is to derive equations used for estimating parameters characterizing the breach process. These parameters are derived using regression analysis by using dam dimensions and properties as the independent variables in the analysis. To carry out this task, data for historical cases of dam failures were collected from various sources. Only data for embankment failures due to overtopping were considered in this study.

Once sufficient data was collected, nonlinear regression analysis was conducted using Matlab scripting to derive the breach parameters estimation equations. These equations were compared to other equations reported in the literature. Finally, the uncertainty in the proposed equations was investigated by resampling from the original set of data to derive different equations and assess the deviations of these equations from the derived equations before resampling.

The second part of the study involves the construction and running of large scale tests of embankment breaching. The selected embankments dimensions represent near life scale of typical emergency levees (ASCE, 1987). The experiments involved embankments from both cohesive and non-cohesive soil compositions. The embankments will be compacted using the standard compaction procedure for small dam. An important requirement will be maintaining a close to constant water surface level upstream the embankment head during the breach process. A constant head during tests near the embankment can be maintained by a large reservoir volume, and adjusting the inflow rate. The breach will be initiated by carving a small pilot channel at the middle