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An Overview of Breach Modeling of Earthen Embankment Dams

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ABSTRACT

Embankment dams are some of most significant and beneficial structures. These are constructed for retention of water for irrigation and supply of water for domestic and industrial purposes. Failure of any embankment results in loss of lives as well as loss of structures. To develop evacuation plans (early warning system) for embankment failure, prediction of breach outflow hydrograph becomes important. The existing models can simulate the failure of different embankments, by overtopping or piping by considering embankment condition and soil parameters. This paper compares these models on the basis of components involved like use standard principles of hydraulics, sediment transport and soil mechanics etc. It also describes the necessity of development of a new model the failure of an embankment that can simulate breach formation, and hence consequent risks, more reliably than existing models.

Keywords: Embankment Dam, Overtopping, Breaching, Peak outflow, Fuse Plug, Physical Model, Empirical model.

1. INTRODUCTION

Dams are the important hydraulic structures built across the rivers for various purposes. Embankment dams are constructed for retention of water for irrigation and supply of water for domestic and industrial purposes. Middlebrooks (1953) presented a brief history of earthen and rockfill dams and summarized the causes of inadequacies of earth dams since 1914. The duration of earth dam breaches can vary from 15 minutes to more than 5 hours (Singh and Snorrason. 1982).

2. DETAILS OF EXISTING MODELS

There are numerous methods for predicting the breach outflow and these may be based on case studies, physically based methods, comparative analysis or process based methods. Pioneer Cristofano (1965) proposed the first physically based dam breach model which relates erosion of breach channel

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with rate of water flow through breach by assuming a trapezoidal breach of constant bottom width. Major contributions during the early times are described in Table 1.

From 1965 to 1990, various regression and mathematical models were developed, but none of these routing models have specifically attempted to integrate a detailed simulation of the erosion processes that lead to dam breach. Detailed simulation of the breach process has required the use of separate models specifically focused on erosion processes that provide output of breach geometry development over time. NWS BREACH model (Fread, 1988) was one of the well known models.

In the next decade, the researchers developed the models by considering the erosion processes as described in Table 2.

Table 1: Models Developed in the duration 1965 – 1990

Authors	Model description
Harris Wanger (1967)	mathematical model
Johnson and Illes (1976)	published a classification of breach shapes
Kirpatrick (1977)	presented best fit relation for peak discharge as a function of depth of water behind dam at the time of failure
Fread (1977)	DAMBRK model
Brown and Rogers (1977)	BRDAM model
Knauss (1979)	considered various factors which affect the instability of dams, degree of compaction and grain size diameter
SCS (1981)	related peak outflow as a function of depth of water behind dam at the time of failure
Lou (1981) and Ponce and Tsivoglou(1981)	developed a mathematical model
Simmmler and Samet (1982)	studied the process of overtopping perimentally and concluded that as the erosion progresses, triangular shape change into trapezoidal
Singh and Snorrason (1982, 1984)	provided the first quantitative guidance on breach width by plotting breach width vs dam height graph for 20 dam failures.
MacDonald and Langride-MonoPiolis (1984)	relationship, using 42 data failures, for the Breach Formation Factor defined as product of volume of breach outflow and depth of water above breach.
Costa (1985)	presented a comprehensive summary of flood discharges resulting from all types of dams
Pugh (1985)	fuse plug embankments for lateral erosion
Froehlich (1987)	developed non-dimensional equations for estimating breach parameters.
Fread (1984)	developed BREACH model
Singh and Scarlatos (1988)	developed BEED model
USBR (1988)	provided the guidance for selecting breach width and time of failure in studies using DAMBRK

The regression equations and mathematical models were developed in 1970's and 1980's and refined in 1990's , to relate breach parameters to dam and reservoir characteristics. During 1990's several researchers compiled database and developed numerical models for predictive equations for breach parameters and breach peak outflow.

Table 2: Models Developed in the decade 1990 - 2000

Researcher	Model description
Von Thun and Gillette (1990)	Proposed 2 methods for estimating breach formation time
Fread (1993)	NWS-FLDWAV
Robinson and Hanson (1993,1994, 1996)	Tested on different soils for Head cut Erosion and then developed a computer model
Froehlich (1995a,b)	Developed new predictive equation for average width and time of failure.

So in this decade a number of initiatives around the world had helped to understand breaching processes, and feeding into improved numerical models for the prediction of breach growth. After 20th centuary, the detailed physical models as described in Table 3.

Table 3: Models Developed in Present Century

Researcher	Model description
Cheng (2000)	used 3 non-dimensional numbers to explored *peak outflow changes of a dam breach section*
Mohamed (2002)	HR BREACH model
Wang and Kahawita(2002,2006)	FIREBIRD BREACH
Temple *et al*. (2005)	SIMBA model
Macchione (2008)	a dam breach model simple but physically based model
Froehlich (2008)	mathematical expressions for expected values of *final width and side slope of a trapezoidal breach*.
Xu and Zhang (2009)	new regression equations for breach parameters

All the above methods and models are classified under different categories as described in the literature (Reclamation, 1988), the different models are classified as shown in the Figure 1.

3. CLASSIFICATION OF EXISTING MODELS

The existing models may be classified on the basis of techniques or methods used for establishing these models. As shown in Figure 1, the models may be classified as follows.

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3.1 Empirical Models

Predicting Peak Outflows from Case Study Data: Historical failures provide useful data for dam breach modeling. The peak outflows and the time to reach the peak are the crucial parameters of breach outflow hydrograph. From the various case study data, many researchers developed different empirical formulae, based on dam characteristics to determine the peak outflows directly.

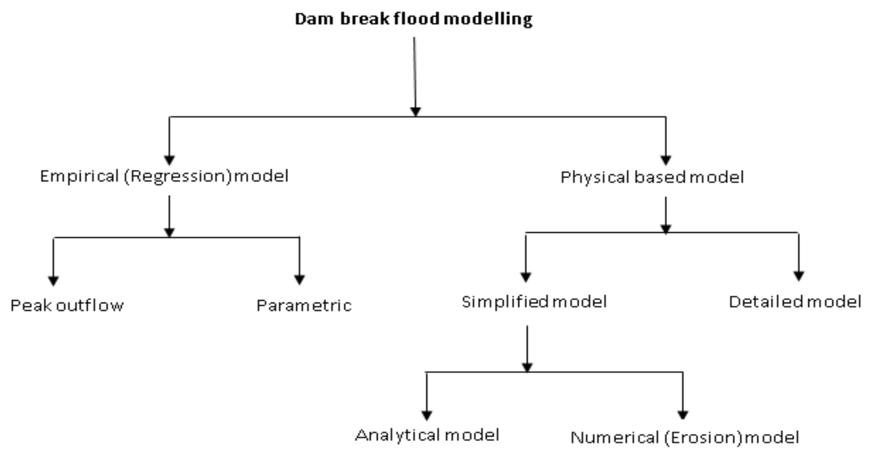

Figure 1: Classification of Existing Models

3.1.1 Regression models or Equations from breach parameter

There are different parameters which describe a breach. These may by dependent (breach depth, breach width, time to failure, side slope etc.) and independent parameters (dam dimensions, type of dam, initial water level, volume of reservoir etc.). In this approach, breach formation process was determined by using statistically regression equations and the flow through the breach is analyzed separately. As in previous method, the regression equations, used to determine breach parameters, were based on dam failure case studies. Wu (2011) reviewed and stated that only few researchers considered the effect of embankment erodibility in the breach modeling.

There are significant uncertainties in estimating the breach parameters and peak outflows Wahl (2004) which is the disadvantage of this approach. Also the predicting breach characteristics and processes were considered to contain the greatest uncertainty (Singh 1996; Morris 2000 Froehlich 2008). The accuracy of regression models depends on the number of case studies and the accuracy of these databases. In general, there are a number of factors on which peak outflow depends like ersion process, hydraulic conditions, geotechnical factors etc. It may be concluded that up to last decades, regression equations were widely used for estimating breach parameter as well as peak outflow, but these did not correlate the erosion processes as the material erodibility was not considered in these equations. Also warning time was not defined before the release of peak outflow.

3.2 Physical Models

During 1980's, many physical models, analytical and numerical, were developed. These models were base on principles of hydraulics, physics of breach erosion, sediment transport and geomechanics. Also different flow equations, derived from regression analysis, were used to estimate breach outflow hydrograph with some assumption. In the literature, the physically-based models were divided in different groups based upon the degree of use of empirical relationships within the model versus theoretical processes (Kahawita, 2007). These models are classified as simplified and detailed physical models.

3.2.1 Simplified physically based breach models

Simplified models with significant simplifications were developed in last few decades on the basis of analytical and numerical solutions. In these models the breach cross section was assumed as rectangular, triangular of trapezoidal. The weir formula was also used to determine breach flow.

Analytical models: For analytical models, significant simplifications were made and different equations like reservoir water-mass depletion equation, broad crested weir hydraulics, and breach erosion relation were used to develop more reliable breach models. Fread (1981, 1984) developed an analytical equation to predict peak outflow from a breached dam. The equation described the simultaneous lowering of reservoir elevation as the breach forms. Singh & Scarltos (1988) developed analytical models for the simulation of earth dam breach erosion by assuming trapezoidal breach shape and assuming simplified reservoir storage curve. To estimate the flow over the breach they used broad-crested weir hydraulics and a breach-erosion relation. Singh and Quiroga (1988) and Macchione (1989) also derived the analytical solutions for breach outflow hydrograph. Walder and O'Connor (1997) presented a mathematical model of dam breach formation and used it to relate dimensionless peak outflow. Macchione (2008) assumed a critical flow through the breach and proposed a dam breach model with cross section simplifications. He considered the geometry of the embankment, the shape of the reservoir, and the hydraulic characteristics of the flow through the breach and its erosive capacity, and the shape of the breach. After that this model was compared by Macchione and Rino (2008) and found that this model was easy to use equations to predict peak discharge as well as whole outflow hydrograph. The simplified physical models have the limited applicability as many simplifications were made.

Numerical (Erosion) models: The numerical models were still simplified models but have accurate approximations as compared to analytical models. These models used the geomechanics, flow regimes, hydrodynamics and instability processes. According to many researchers (Wan and Fell (2004), Jang et al. (2011), Hanson et al. (2011)), embankment erodibility plays an important role in embankment breaching. Cristofano (1965) was the first to have simulated gradual dam breach erosion. He gave a relation between rate of erosion of the breach and discharge through the breach by taking the effect of shear strength of soil particles and the force of the flowing water. The overflow section was assumed trapezoidal in shape and the bottom width remained constant for all timeOne-dimensional mathematical model was presented by Nogueira (1984) for progressive earth dam failure by considering the equations of unsteady flow and derived geometric relationships for breach channel. In the late 1990s, some research groups developed more comprehensive simplified physical models. Till 1990's there was no any model which can integrate a detailed simulation of erosion process for dam breach modeling (Wahl, 2010). From 1998 to 2001, a research project was undertaken and HR BREACH model was developed at HR Wallingford (Mohamed, 2002).

Recently Hanson et al. (2011) developed the soil parameters for dam breach. Wu (2013) presented a comprehensive simplified physically based breach model, which was able to simulate the breaching processes of non-cohesive and cohesive, homogeneous and composite embankments owing to overtopping and piping. The model considered a flat broad-crested weir with a trapezoidal cross section for estimating the breach due to overtopping. He simulated the cohesive embankment breach erosion processes in the form of headcut migration and the breaching of composite embankment with clay core and cover. The model covers the dam breaching by applying different algorithms to determine the headwater and tail water levels and allowing embankment base erosion. A simple one dimensional mathematical model was developed by Alhasan et. al. (2015) and a computer code was compiled. The model was calibrated using the field data compiled from 4 failures of small embankment dams breached during 2002 in the Czech Republic. He proposed a numerical procedure, including conceptual, mathematical and numerical models and a comparison of calculated dam break parameters with site data. NWS-BREACH model was probably the most famous physical model.

3.2.2 ***Detailed Physical Based Breach Models***

Uncertainties in predicted breach parameters and the flood hydrograph exist because of significant model simplifications (Mohamed et al. 2002). One, two and three dimensional numerical dam break models are currently being developed by many authors worldwide. Recently many researches (Mohamed et al. 2002; Wang et al. 2006; Wahl et al. 2008; Morris et al. 2009a; Wu et al. 2009) had developed more comprehensive physically based embankment breach models which are able to simulate the breaching processes of cohesive and noncohesive, homogeneous, and composite embankments. The breach descriptions were used as input to these models, which calculate the breach outflow analytically by assuming the occurrence of erosion. Tingsanchali and Chinnarasri (2001) developed a one-dimensional numerical model to simulate the dam surface erosion and slope sliding failure with time for dam failure due to flow overtopping. They used explicit finite difference scheme to solve one-dimensional equations of continuity and momentum for unsteady varied flow over steep bed slopes. Only a few recent models have considered the breach formation by headcut erosion (Hanson et al. 2005; Zhu et al. 2006; D'Eliso 2007). These detailed breach models encounter difficulties owing to a lack of understanding of sediment transport under embankment breach flow conditions. The application of the models has been hindered by an inability to quantify the erodibility of cohesive embankment materials (Wahl et al. 2008). The key objectives of these tests have been to observe embankment failure processes, understanding of the erosion processes. Another objective of these tests was to provide realistic information to improve and verify dam failure computer models.

Wu (2011) described the multi-dimensional physical based dam breach models developed recently. He concluded that breaching of embankments due to overtopping involve mixed flow regimes with overfalls, lateral erosion with huge mass failure. The embankment erodibility plays an important role in breach analysis of embankments (Wan and Fen, 2004, Hanson et. al. 2011).

4. EXPERIMENTAL MODELS

Most of the approaches, as described in previous sections, were based on regression equations physically based numerical or analytical models and the mechanism of breach erosion. For realistic study of dam breach, experimental study is necessary which help to overcome the shortcomings identified in other methods. In the last 30-40 years, relevant experimental studies have been made to understand embankment breaching processes and collect reliable data to develop embankment breach models, with significant contributions such as laboratory tests and field experiments (Coleman et al. 2002; Rozov 2003). Zhu et al, (2004) stated that various experiments were conducted on the breaching of embankments during last several decades and they classified these experiments as large-scale test (field test) and small-scale tests (laboratory tests).

4.1.1 Laboratory Experimental Model

In the past, the researchers' had conducted numerous lab experiments with and without fuse plug. Fuse plug is, a temporary earthfill structure, which is designed by considering the water surface of the reservoir behind it and wash out in a predictable and controlled manner (Verma etal., 2014). It acts as a safety valve for embankments and during floods and provides a safe passage without damaging the body of dam (CWC, 1989). In laboratory, different experiments were conducted using fuse plug and without fuse plug.

Initially the lab experiments using fuse plug were carried out by Tinney and Hsu (1961), Chee (1984), Pugh (1985), Pan et al. (1993), Sahu et. al. (2013), Verma etal., (2014). Sahu et. al. (2013) stated that the experimental study in the laboratory environment using fuse plug is necessary to establish the relationships among breach hydraulic, breach geometry and transport of erodible soil.

The small-scale tests without fuse plug conducted by many researchers in laboratory to understand for breaching processes of embankments Powledge and Dodge (1985), Visser (1998), Tingsanchali and Chinnarasi (2001), Coleman et al. (2002), Rozov (2003) and Mohamed et al. (2004). Wahl (2007) summarized the laboratory experiments conducted by many invetigators and Wu (2011) updated the list given by Wahl. The selected laboratory test with and without fuse plug is summarized in Table4a and 4b.

4.2.2 Field Experimental models

The researchers includes, Pan and Loukola (1993), Visser et al. (1991 and 1996), Meadowcroft et al. (1996), Hahn et al. (2000) and Höeg et al. (2004) conducted the tests in field. The first significant field experiments were done by Simmmler and Samet (1982) and studied the process of overtopping experimentally. Recently various researchers conducted large scale experiments in the field like European IMPACT project (Morris and Hassan 2005), USDAARS research project (Hanson and Hunt, 2005), and Zhang et al. (2009).

Table 4a: Laboratory Experimentation Using Fuse Plug (Updated from Wahl, 2007 and Wu, 2011)

Reference	**Experiment detail**	**Organization**	**Number of tests**
Tinney and Hsu (1961),	Lab and field scale-overtopping	Washington State University, U.S.	13
Chee (1984),	Lab scale- overtopping	University of Windsor, Canada	-
Pugh (1985),	Laboratory scale	Bureau of Reclamation, U.S.	8
Pan et al. (1993).	Field scale- overtopping	China	>50
Schmocker et al. (2013),	Lab scale- two fuse plugs	Laboratory of Hydraulics, Hydrology, and Glaciology, Zurich	10
Sahu et. al. (2013)	Lab scale- overtopping	India	4
(Verma etal., 2014)	Lab scale- overtopping	M.M. University, India	5

Table 4b: Laboratory Experimentation (Updated from Wahl, 2007 and Wu, 2011)

Reference	Experiment detail	Organization	Number of tests
Powledge and Dodge (1985)	Embankment erosion-overtopping	University of Colorado, U.S.	3
Visser (1998)	Sand dikes- overtopping	Delft university of technology, Netherland	5
Tingsanchali and Chinnarasi (2001)	Overtopping-Non-cohesive embankment breach partial/full breach	Asian Institute of Technology, Thailand	16
Coleman et al. (2002)	Overtopping- non cohesive	University of Auckland, New Zealand	9
Rozov (2003) and	Overtopping- non cohesive	St. Petersburg state Technical University, Russia	4
(Morris *et al.*, 2005)	Overtopping and piping	*HR Wallingford, UK*	22
Zhu et. al. (2006)	Laboratory- head cut erosion		5

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(Morris *et al.*, 2007)	IMPACT project	*HR Wallingford Ltd, Howbery Park, Wallingford,*	22
Al-Riffai et al. (2009)	Homogeneous- side slope instability	University of Ottawa, Ottawa	8
Orendorff et al. (2010)	Small and large flume- variation in compaction	University of Ottawa, Canada	
Zhu et. al. (2011)	Laboratory scale- head cut erosion	Delft university of technology, Netherlands	5

The field tests of large scale tests was one of the important steps required to understand the complex natural phenomena and validate embankment breach models. From laboratory experiments and field tests, it may be concluded that in case of overtopping failure the erosion process was different for different type of soil. According to Pugh 1985; Ralston 1987; Powledge et al. 1989; Singh 1996; Visser 1998; Hanson et al. 2005) for non-cohesive, earth embankments, surface erosion occurs where for cohesive embankments head cut erosion occurs.

5. CONCLUSION

Embankment breaching processes are very complex and involve strong vertical and lateral erosion, discrete mass failure, and headcut migration. The failure mode and mechanism are affected by upstream and downstream water conditions, embankment configurations and soil properties. A number of parametric, empirical, erosion and physically-based embankment breach models have been established in the past decades, but prediction with these models involves significant uncertainties. The biggest limitation of the existing breach models is quantifying erosion rates or erodibility of cohesive soils under embankment breaching flows. Great progress has been made to investigate embankment breaching processes through laboratory and field experiments and real-world case studies. However, most laboratory experiments were for small scale homogeneous embankments, only a few outdoor experiments were conducted at large scales. It is important to conduct more large-scale laboratory experiments and field case studies to improve existing embankment breach models or develop new ones. Also for future calibration of earthen dam breaching more reliable data is required which may be obtained from past experiments or sets of historical events.

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