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Experimental Study of Breaching of an Earthen Dam using a Fuse Plug Model

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ABSTRACT

Failure of dams due to overtopping is among the most frequent forms of embankment failures. Owing to massive and wide spread damage to structures and loss of lives associated with a dam failure, the subject has drawn the attention of scientists. The study also becomes essential for damage assessment and for development of early warning system of people downstream of the embankment. The rate of breaching of earthen embankments due to overtopping depends upon the soil and flow characteristics alike. Different input parameters that help in understanding the phenomenon are the temporal variation of initiation of the breach, breach width, breach depth, intensity of discharge and its time-to-peak. Present paper gives the results of laboratory investigation conducted using a wooden fuse plug and five different soils. The hydraulic conditions were kept same for all the experiments. It was observed that cohesiveness and degree of compaction were key factors in the erosion process. While for pure non-cohesive soils, surface erosion occurred gradually, but for the cohesive soils, headcut erosion was observed. The behaviour of breach depends upon dimensions of fuse plug, type of fill material, reservoir capacity and inflow. A common equation has been fitted to the series of normalized breach flow hydrographs of different soils. The equation has a coefficient of correlation R^2 equal to 0.8 indicating a good fit. Limited space of storage reservoir on the upstream of the embankment, and width of the flume are the limitations of the study.

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NOMENCLATURE

w_{opt}	Optimun moisture content (%)	ρ_s	Dry density (gm/cc)
d_{50}	Median particle size (mm)	W	Water content (%)
Q_{in}	Inflow discharge (m^3/s)	Q_f	Outflow discharge (m^3/s)
h_r	Water level in reservoir (cm)	U	Velocity of flow (cm/s)
q_w	Discharge intensity ($m^3/s/m$)	q_{wp}	Peak discharge intensity ($m^3/s/m$)
t_{wp}	Time corresponding to peak discharge intensity (sec)	u_c	Velocity corresponding to initiation of sediment motion (cm/s)
h_{cf}	Water level above crest of fuse plug (cm)	**Subscripts**	
h_{cs}	Height of crest of sediment (cm)	Opt	Optimum moisture content
A_s	Reservoir water surface area (cm^2)	50	50 percent finer than a particle size

1. INTRODUCTION

Dams are significant hydraulic structures built across rivers for various purposes. From ancient times, embankment dams have been built and used throughout the world [1]. Water stored on the upstream of a dam is used for irrigation, flood control, hydro electric power generation, water supply, etc. However, the failure of an embankment dam results in massive and wide spread damage to structures and loss of lives. In the past, embankment dam failures, besides natural disasters have been reported on account of seepage, overtopping, piping and structural defects. From previous studies, it

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may be concluded that about one third of dam failures were caused by overtopping [2]. The risk of overtopping for embankment dams can never be eliminated completely but can be reduced [3]. Thus, it becomes necessary to analyse the behaviour of a dam before and during the process of overtopping. As warning time and subsequent time to evacuate directly affect the property and life losses due to failure of the dam, so it becomes more important to determine different parameters of dam failure to develop these systems [4]. The different parameters like breach initiation, breach formation etc., can be determined by obtaining the influence of soil material and rate of erosion on the process of breaching during the failure of dam due to overtopping [5]. The factors responsible for breaching of an embankment are properties of material used for embankment, geotechnical behaviour and the hydraulic flow through the breach [6]. It is not possible to determine these parameters practically in the field [7].

In the past many researchers collected the data from different dam failures and analyzed the breaching of dams. MacDonald and Langride-Monopiolis [8] analysed the breaching shap and concluded that it may be triangular or trapezoidal. The mathematical expressions were developed to determine the final width and slope of breach [9]. Hassanzadeh [10] studied the unsteady flow in smooth and rough channels caused by failure of a dam both experimentally and theoretically. The author made use of the Ritter and Dressler solution for analysis of the experimental observation. He concluded that for nearly smooth channel, the Ritter solution was confirmed, while for rough channel, Dressler solution could be confirmed satisfactorily by the experimental data.

Many more researchers developed multi parameter regression models based on case study data [2, 11-13] and analytical models based on equations derived from breach erosion and hydraulics [14]. Using these erosion based models, breach parameters were determined which were further used as input data for flood routing models [14]. The different equations, methods and models of embankment dam breaching based on case studies were critically reviewed by Wahl [4]. Recent methods, models and equations based on case studies and database for dam breach modelling cannot completely and accurately describe the process of breaching due to overtopping as these approaches rely on the results of case study data from past dam failures or on the physics of dam breach erosion. But these models and equations describe the flood routing in a better way. A large number of laboratory and field investigations on the breaching of embankments were carried out in the past decades [15] and these were summarized by Wahl [12].These field tests were based on erosion mechanics and the conducted experiments give a general idea for passing of design flood, without damaging the dam under controlled conditions. Wang and Bowles [16] concluded that the location of breach and shape of reservoir directly affects the peak discharge as well as outflow hydrograph shape. Among the very recent studies are the works of references [17-19]. Interestingly, out of these three literature reportes, one [17] is a case study and author studied the pore water pressure and settlement of Alborz earth dam and predicted the future planning, the other [18] is an experimental investigation in a large flume and another [19] is a one-dimensional mathematical model study, indicating that all three forms of studies have drawn the interest of researchers. For the dam breach analysis, it is essential to conduct small scale or large scale tests which help to address many of the shortcomings identified in the literature [20]. Further there should be correlation between laboratory tests and the realistic dam failures. In the present paper the results of an experimental study of progressive breaching of embankment dams due to overtopping have been presented using a fuse plug model.

2. FUSE PLUG

Fuse plug is a temporary earthfill structure, which is designed by considering the water surface of the reservoir behind it and it washes out in a predictable and controlled manner [1]. It acts as a safety valve for embankments (auxiliary spillway); and during floods it provides a safe passage without damaging the body of the dam [21]. As shown in Figure 1, the fuse plug allows the erosion of earthfill in longitudinal as well as in vertical direction. Since there is no erosion in the lateral direction, a two dimensional phenomenon of washout process occurs in the fuse plug.

3. EXPERIMENTAL PROGRAMME

Tests for studying the breaching of an embankment using a fuse plug were conducted in a recirculating water flume in the Hydraulics research laboratory of Civil Engineering Department at M.M. Engineering College, Mullana, Ambala (India).

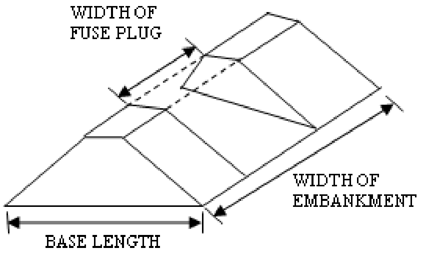

Figure 1. Schematic of fuse plug (cast out of wood)

3. 1. Experimental Set up

The experimental set up comprised of a glass water flume, a wooden fuse plug, five different soils, a roller for compaction and other standard laboratory devices. The flume dimensions were 4.5 m x 0.57 m x 0.57 m (Figure 2). For storage of water, a rectangular tank of dimensions 1.00 m x 1.00 m x 0.85 m was used and another tank of same dimensions was used as a sump tank. For water circulation, a channel of dimensions 4.85 m long, 0.57 m wide and 0.85 m deep, was used which was attached to sump tank.

To circulate the water, a motorized pump connected to water circulation channel at one end, was used. At the other end of the pump, a 100 mm diameter pipe was attached to fill the reservoir at a constant rate. To measure the rate of inflow, a piezometer was attached to the reservoir tank. The walls and bottom of flume were made of glass to allow lateral observation of the model during the tests. To obtain water elevations and temporal variation of longitudinal and cross-sections of embankment as the tests proceeded, a pointer gauge with a rolling carriage, placed on the side walls of the flume, was employed. For constructing the embankment models, different proportions of sand, silt and clay were used. The soil properties were determined in the Soil Mechanics laboratory before the construction of embankment.

3. 2. Soil Properties

Soil properties of embankment material were determined in the Soil Mechanics laboratory. The optimum moisture content, dry density and water content for each soil were determined and the results are shown in Table 1.

Figure 2. A photographic view of the complete set up of experimentation

TABLE 1. Properties of fill material

Soil type	w_{opt} (%)	ρ_s (gm/cc)	d_{50} (mm)	w (%)
Soil A	16	1.63	0.55	18
Soil B	13.5	1.88	0.23	16.6
Soil C	14	1.93	0.06	16
Soil D	12.5	1.91	0.065	18
Soil E		1.94	0.07	15.4

Particle size analysis was carried out and used for plotting the particle size distribution curve and determining the mean sizes of different soils (Figure 3).

3. 3. Experimental procedure

The fuse plug model was made up of wooden material and placed inside the flume. The dimensions of the model used in the present study are presented in Figure 4 and Table 2. The height and width of the model were restricted as per dimensions of the flume. For the construction of embankments in the flume, the soil was placed in loose layers of about 5 cm thick in the fuse plug. To compact each loose layer at its OMC, a hand-held roller and wooden rammer were used [22]. Different embankment models were made with mixes of locally available soils in different proportions.

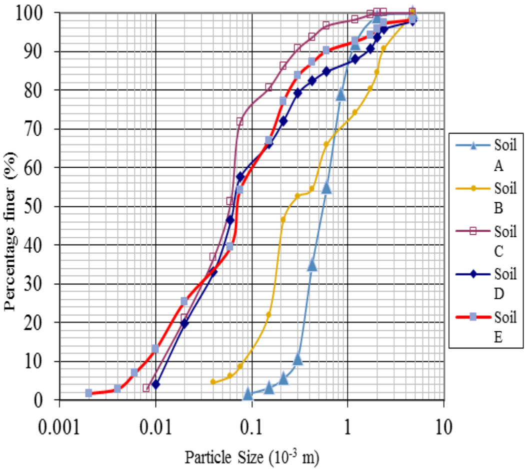

Figure 3. Sieve analysis of different soils

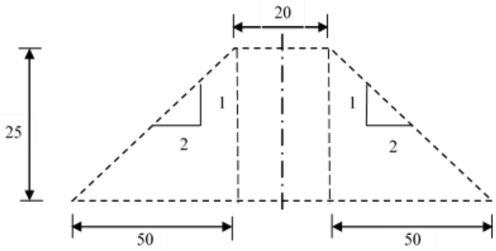

Figure 4. L-section of fuse plug model

TABLE 2. Cross section of fuse plug model

Dimensions of fuse plug model		Values (cm)
Width of model (B_f)		14.6
Longitudinal length of model, L	Top length (Crest) (L_{ft})	20
	Base length(L_{fb})	120
Height (H_f)		25
Slope		1 V: 2 H

After constructing the embankment, for uniformity of embankment material, an extension time of 48 hours was provided. Before starting the experiment, the sump tank as well as water circulation channel were filled up to specified level so that circulation of water could be maintained through the reservoir tank and flume. Then the water was filled in the reservoir and upstream side of embankment. During the filling of water in reservoir tank, the inflow was controlled by the head regulator attached to the inflow pipe. The inflow discharge was also measured with the help of a piezometer. The depth of water on the upstream of the fuse plug was measured at regular intervals of time by a pointer gauge mounted on a rolling carriage. To maintain uniformity for all the tests, the water on upstream side was filled upto a height of 20 cm. After filling the water on upstream side of embankment, a retention time of 15-20 hours was provided for homogeneous saturation of embankment. Thereafter, the level of water on the upstream was increased and overtopping occurred. The temporal variation of embankment breach width (b_w) and depth (b_d) were observed during the experiment at short intervals using point gauges. The process of breach growth was videotaped with a high speed digital video camera (Fastec Imaging Inline Gigabyte Ethernet Camera). Also photographs at different instants of time were taken with digital cameras. To facilitate oservations of the development of breach, a grid of horizontal and vertical line was drawn on the glass sidewalls of the flume. The above experimental procedure was repeated for different models and different proportions of sand-silt-clay.

3. 4. Breach Flow Hydrograph Breach flow hydrograph is important for downstream reservoir pathway. For a fuse plug, it depends upon the geometry of fuse plug, properties of fill material of fuse plug, capacity of reservoir and the incoming flow to the reservoir [23]. Different parameters which were essential for determining the wash out process of the fuse plug model are shown in Figure 5. The water level above the crest of fuse plug (h_{cf}) was determined by taking the difference between water level in the reservoir (h_r) and height of crest of sediment (h_{cs}).

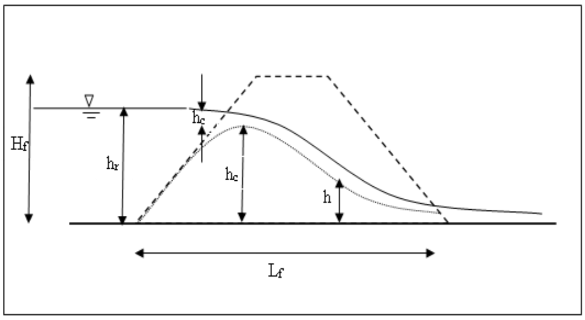

Figure 5. Sketch showing different flow parameters during the test

The discharge during the breach was determined using the equation of continuity of flow as:

$$Q_f - Q_{in} = A_s \frac{dh_r}{dt} \tag{1}$$

where Q_{in} = inflow discharge, A_s = reservoir water surface area.

The inflow discharge (Q_{in}) and the water surface area (A_s) of reservoir were constant throught the test. The rate of change of water level in the reservoir (dh_r/dt) was obtained by determining the temporal variation of water level in reservoir.

4. RESULTS AND DISCUSSIONS

Observations made during the breach process were tabulated and analysed for breach behaviour, breach initiation, time to breach for cohesive and non-cohesive soils.

4. 1. Surface and Headcut Erosion Figures 6 (a) and (b) present the lateral distance of breach in centimeter on the x-axis versus height of breach in centimeter on the y-axis for both the non-cohesive and cohesive soils, respectively. Figure 6 (a) is the result of two non-cohesive soils while Figure 6 (b) presents three cohesive soils. It may be observed that in both cases for large heights (smaller erosion) of breach, the lateral distance of breach is small.

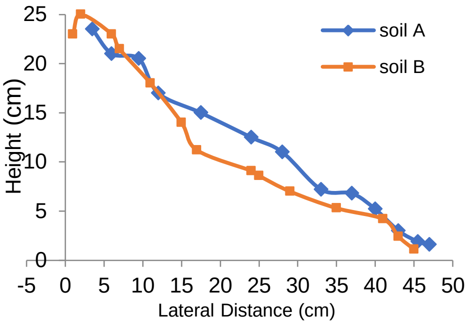

Figure 6(a). Progress of breach for non-cohesive soil

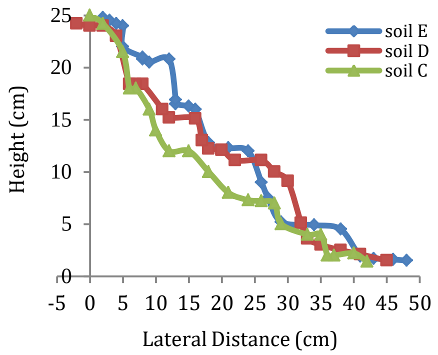

Figure 6(b). Progress of breach for cohesive soil

As the height decreases (with increase in erosion) the lateral distance of the breach increases. Figures explain the erosion of soil due to flow from a broad crested weir [23]. Further while for the non-cohesive soil gradual surface erosion occurs, but for the cohesive soil it is headcut erosion. The observation matches well with the observation of Zhu et al. [24] who described that the headcut erosion has a vital role in the process of breach growth for the cohesive embankments. Sahu et al. [25] described that the erosion of soil occurs in the process of overtopping and the eroded surface behaves like a broad crest weir. Also the longitudinal profile goes on changing with the passage of time. For non-cohesive soils, the soil particles start to move when the velocity of flow, becomes more than the threshold value ($u/u_c \geq 1$) and sand grains behave independently where u = velocity of flow and u_c = velocity corresponding to initiation of sediment motion. As the flow velocities are very high in case of breaching of embankment, the failure is instantaneous.

4. 2. Temporal Variation and Duration of Test

Many investigators assumed the breach cross sectional shape as triangular or trapezoidal for the analysis [3]. In different experiments of the present study it was observed that the breach is widest at the downstream toe and smallest at the crest level of the embankment. To determine the changes in embankment profile with time, the temporal variations of breach vs embankment depth were plotted for non-cohesive and cohesive soils as shown in Figures 6 (a and b). The duration of different tests was compared and it was observed that under similar hydraulic conditions and for same embankment profile, the duration of tests for sandy soil was very less as compared to embankments of silt clay mixtures. The amount of compaction slows down the erosion process for sand-silt-clay mixtures. The water content and optimum moisture content also affect the duration of breaching of embankment.

When the water content is higher than the optimum moisture content, it is not easy to compact the soil and maximum dry density could not be achieved as it is clear by comparing soil C and soil D. For soil C, it was easy to achieve high dry density with less number of passes of compacting roller as compared to soil D.

The tests conducted for all the soils show that cohesiveness of soil plays a vital role in assesing the duration of breach failure. The cohesive soils because of inter-particle bondage slow down the erosion process and subsequently increase the duration of breaching.

4. 3. Normalised Breach Flow Hydrograph

From the observations, a series of hydrographic curves (Figure 7) for both the cohesive and non- cohesive soils have been plotted between normalised breach discharge intensity (q_w/q_{wp}) on the y-axis and normalised time-to-breach (t/t_{wp}) on the x axis.

Here, q_w is the discharge intensity in $m^3/s/m$ and is equal to Q_f /average breach width.

It may be observed that the shape of all the curves is similar with a single steep rising peak followed by a gradual diminishing end. For all $q_w/q_{wp} = 1$, the t/t_{wp} varies between 0.5 to 1.5. It was also observed that cohesive soils tend to attain a $q_w/q_{wp} = 1$ at smaller t/t_{wp} values. The curves can be described in the form of Equation (2):

$$\frac{q_w}{q_{wp}} = \left(\frac{t}{t_{wp}}\right)^n exp\left[1 - \left(\frac{t}{t_{wp}}\right)^n\right] \tag{2}$$

This equation is similar to the equation given in the literature [23] with different values of 'n'. The exponent 'n' for different soils describing various curves is given in Table 3. The trend of 'n' may be attributed to the mass density. In the present work, the exponent 'n' for best fit curve was determined by trial and error method and is equal to 1.1. The best fit curve has been shown in Figure 8. The equation has a coefficient of correlation, R^2, as 0.8 which is indicative of a good fit.

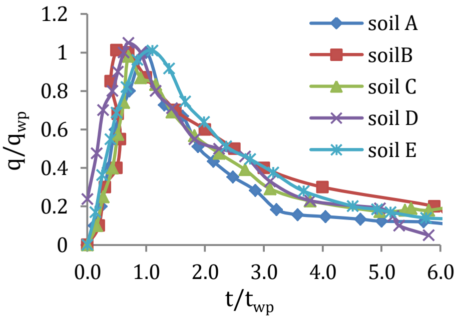

Figure 7. Normalised breach flow hydrograph

TABLE 3. Values of n for different fill materials

Soil type	n	ρ_s (g/ml)	d_{50} (mm)
Soil A	0.92	1.63	0.55
Soil B	1	1.88	0.23
Soil C	1.1	1.93	0.06
Soil D	1.18	1.91	0.065
Soil E	1.1	1.94	0.07

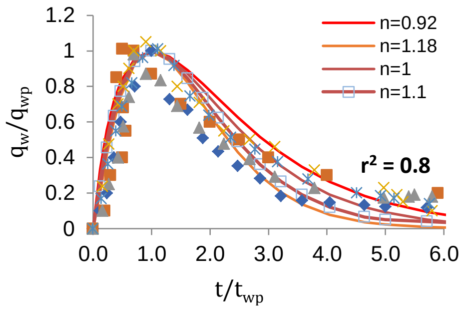

Figure 8. Normalised breach flow hydrograph with exponent value of n

5. CONCLUSIONS AND RECOMMENDATIONS

The present study describes the results of an experimental work conducted for earthen embankment breach using a fuse plug model. The conclusions of the study are:

i) The cohesiveness of soil has a remarkable impact on the process of breaching of an earthen embankment caused by overtopping.
ii) Degree of compaction and type of soil directly affects the rate of erosion on downstream side during overtopping of embankment.
iii) In all tests, except the test on sandy soil, the process of head cut erosion occurs during the breaching of embankment.
iv) During overtopping, the breach discharge increases abruptly and as the breach widens, it decreases gradually.
v) The normalised breach hydrograph can be expressed by Equation (2) with exponent 'n' equals to 1.1.
vi) The constant incoming discharge, limited width of flume and use of limited type of soils for experiments are some limitations of this study.

The results of the study are likely to be useful in the design of earthen embankments. The results will also be helpful in planning the evacuation and zoning of areas on the downstream of a dam.

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چکیده

شکست سد با توجه به سرریز شدن آب یکی از شایع ترین اشکال شکست خاکریزی است. با توجه به آسیب گسترده به سازه ها و از دست رفتن جان در ارتباط با شکست سد، این موضوع مورد توجه محققین قرار گرفته است. این مطالعه همچنین برای ارزیابی خسارت و برای توسعه سیستم هشدار دهنده به مردمی که در پایین دست خاکریز هستند ضروری است. نرخ شکست سدهای خاکی با توجه به سرریز شدن بستگی به خاک و ویژگی جریان دارد. پارامترهای ورودی مختلف که به درک این پدیده کمک می‌کنند عبارتند از تنوع زمانی شروع شکست، عرض شکست ، عمق شکست ، شدت جریان و زمان رسیدن به اوج. مقاله حاضر نتایج تحقیقات آزمایشگاهی انجام شده با استفاده از یک فیوز پلاگین چوبی و پنج خاک متفاوت ارائه می‌دهد. شرایط هیدرولیکی برای همه آزمایشها یکسان نگه داشته شدند. مشاهده شد که انسجام و درجه تراکم پذیری از عوامل کلیدی در فرایند فرسایش بودند. در حالی که برای خاک غیر چسبنده خالص، فرسایش سطحی به تدریج رخ داد ، برای خاکهای چسبنده، فرسایش خندقی مشاهده شد. رفتار شکست بستگی به ابعاد فیوز پلاگین، نوع ماده پرکن، ظرفیت مخزن و جریان دارد. یک معادله متداول برای فیت کردن مجموعه ای از هیدروگرافهای جریان شکست نرمال خاکهای مختلف استفاه شد. معادله دارای ضریب همبستگی برابر با ۰/۸بود که مناسب بودن آن را نشان می‌دهد. فضای محدود مخزن ذخیره در بالادست خاکریز، و عرض قنات محدودیت های مطالعه هستند.

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