Two Dimensional Unsteady Dam Breach Analysis using Fuse Plug Models

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Abstract

Failure of a dam besides causing massive damage to property is responsible for loss of lives. In the case of embankments, failure due to overtopping is apprehended to occur more commonly as compared to other causes of failure. Therefore, it is necessary to analyze the breaching of an embankment so that in the unfortunate eventuality of embankment breach, a definite evacuation plan could be formulated. For studying the breach behavior of an embankment, it is important to determine different breach parameters that include breach initiation time, breach width, time to breach and shape of breach. The breach phenomenon is strongly dependent upon the cohesive forces of the fill material and hydraulic characteristics of flow. Geotechnical factors and rate of erosion are also key factors in the breaching process. Present study describes the results of eight tests on varying proportions of fill material conducted in a small flume using two wooden fuse plug model.

Temporal variation of the breaching process, the water surface profiles and various breach characteristics were observed, compared and analyzed. By studying the water surface profiles of the breach phenomenon, three phases of breach development were observed. It was found that breach growth depends upon dimensions of fuse plug models, type of fill material and inflow intensity. Surface and headcut erosion were observed for cohesive and non-cohesive soils. Further, it was established that it is a small duration phenomenon strongly dependent on the cohesive properties of fill material. Purely cohesive soils tend to delay the overall breach process. The constant hydraulic conditions and limited width of the flume are some of the limitations of the study.

Keywords: Fuse plug, overtopping, temporal variation, water surface profile, headcut erosion.

Introduction

Earthen dams have been built across rivers since the beginning of modern civilization and today there are a large number of big and small earthen dams in the world. They are widely used for different purposes like water supply, irrigation and flood control all over the world. Apart from these benefits, the failure of such dams in the past has resulted not only loss of lives and massive damage to infrastructure but also in causing interruption of basic facilities and environment. The destructiveness and large scale geographic changes were recognized due to landslides, earthen dam failure.[8,12]

The occurrence of landslides is also contributing factor to climate change. But these are natural disasters. Besides due to natural disasters, embankment dam failures in the past have been reported on account of activated mechanisms such as overtopping, seepage, structural defects with other causes as differential settlements, foundation defects and rock slide.[13]

Previous studies[4] described that overtopping was the most common form of embankment failure that occurred in the past. The risk of overtopping for embankment dams can never be eliminated completely but can be reduced.[16] During the dam failure, the flooded water outflows through or over the dam to raise the discharge on downstream side of the dam. It was asserted that in case of a dam failure, the flow magnitude increases abruptly and evacuation time is very less than the precipitation- runoff floods.[5]

Hence, it becomes significant to understand the failure processes for damage assessment and developing early warning system for population at downstream. Presented in this study is a detailed breach process for cohesive and non-cohesive embankments using fuse plug model to understand breach behavior of earthen dams during overtopping of embankment dam models.

Review of Literature

The primary steps to analyze the dam breaching are to predict the breach characteristics and routing of the outflow hydrograph.[20] Understanding the breach mechanism is difficult as it requires determination of breach characteristics like formation time, breach initiation, development of breach, shape of breach etc. Also, there are other factors which influence the breach characteristics such as embankment material, geotechnical behavior and hydraulic flow through breach which can be determined experimentally.[21]

This is further increased by the element of uncertainty involved in the phenomenon. Different approaches were classified to analyze the breaching of dams as parametric and physically based simplified and detailed breach models.[24] Broadly, the different methods, which are available in literature may be categorized as parametric modeling[25], case studies[10,11], physical modeling[23] and experimental studies.[19]

Among the very recent studies are the works of different researchers.[1,9,11,19] Interestingly, out of these researchers, Latifi et al[11] studied the pore water pressure and settlement of Alborz earth dam and predicted the future planning. Alhasan et al[1] developed a one-dimensional mathematical model by using Ritter and Dressler solution for analysis but they studied experimentally the unsteady flow in smooth as well as in rough channels caused by failure of a dam.

But the experimental investigation of breaching of embankments was studied in a large flume[9] and in a small flume[19]. And both described the temporal variation of breach parameters. The development of breach for cohesive and non-cohesive embankments was studied by many researchers[3,6] and they described the whole process in different phases. Also the fuse plug models were used to study the embankment breaching.[15,19]

From the above review of literature, it is clear that none of the approaches is fully equipped in itself to provide a complete solution to the prediction of breach parameters of width, intensity, time etc. For the breach analysis, it is essential to conduct small scale or large scale tests which help to address many of the limitations identified in literature.[17] Further there should be correlation between laboratory tests and the realistic dam failures.

Material and Methods

Experimental Set up and Material Used: With the major objective of studying the breach mechanism, a study was planned and conducted in the hydraulics research laboratory of Civil Engineering Department at M.M. Engineering College, Mullana, Ambala (India). The study was conducted using two fuse plugs and in a glass walled water flume to understand and analyze the breach behavior of earthen embankments.

Fuse plug model and flume dimensions: Fuse plug, a temporary earth fill structure connected to the dam, washes out in a predictable mode without damaging the rest of the dam [2]. A fuse plug is designed by considering the water surface level of the reservoir. As shown in figure 1, it allows erosion of fill material in longitudinal as well as in vertical direction during overtopping and no erosion in lateral direction. It is an efficient alternative to provide additional discharge capacity under high flood conditions and acts as an auxiliary spillway. The dimensions of the models are presented in table 1.

The fuse plug models were made of wood and were painted before placing in the flume channel to avoid seepage during the tests as shown in figure 2. The flume had a square section of 0.57 m x 0.57 m and was 4.5 m long (Figure 3).

Experimental program: The position of the embankment models inside the flume for all tests was same. The coarse and fine grained soils of different proportion were utilized as fill material and the properties of embankment material were determined in the Soil Mechanics laboratory (Table 2).

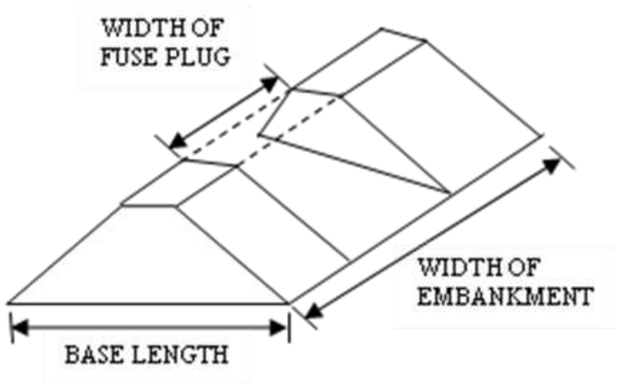

Fig. 1: Fuse plug model

Table 1
Dimensions of fuse plug models

Symbols	Values (cm)	
	Fuse plug 1 (FP 1)	Fuse plug 2 (FP 2)
Width of fuse plug, B_f	14.6	32.5
Top length, L_{ft}	20	20
Base length, L_{fb}	120	120
Height, H_f	25	25
Slope	1 V: 2 H	1 V: 2 H

The embankment material was mixed at optimum moisture content corresponding to maximum dry density and was placed in layers of 8 cm each. These layers were compacted with a hand operated compaction roller (Figure 4a). To reduce seepage, a layer of pure clay was placed on upstream side of embankment. After construction, the model was left as such in this position for 24-48 hours.

This would allow the material in the model to stabilize itself. After a suitable lay-off water was filled on upstream side of the dam upto the pre-determined level leaving a free board of 4 cm. After filling the water on upstream side of embankment, it was retained for about 20 hours for homogeneous saturation of embankment as shown in figure 4b.

The temporal variation of breach growth was observed with a high speed digital video camera (Fastec Imaging Inline Gigabyte Ethernet Camera) (Figure 5) along pointer gauges with rolling carriage.

Definition sketch and breach flow parameters: During overtopping of the embankment model, breach width and depth were observed at short intervals of time and breaching process was videotaped and instant photographs were taken. For both the fuse plugs the different time durations of breach such as breach initiation, breach formation and time to breach were observed during the overtopping process. Different breach parameters necessary to analyze the breaching process have been shown in figure 6.

Fig. 2: Fuse plug models FP-1 and FP-2

Table 2
Properties of soil used for different tests

Test no.	Coarse grained soil (%)	Fine grained soil (%)	MDD (gm/cc)
FP11, FP21	95	5	1.902
FP12, FP22	85	15	1.88
FP13, FP23	70	30	
FP14, FP24	55	45	1.925
FP15, FP25	40	60	1.86
FP16, FP26	30	70	1.87
FP17, FP27	20	80	1.85
FP18, FP28	10	90	1.925

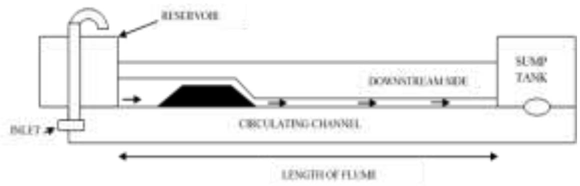

Fig. 3: Line diagram of flume

Fig. 4a: Hand operated roller

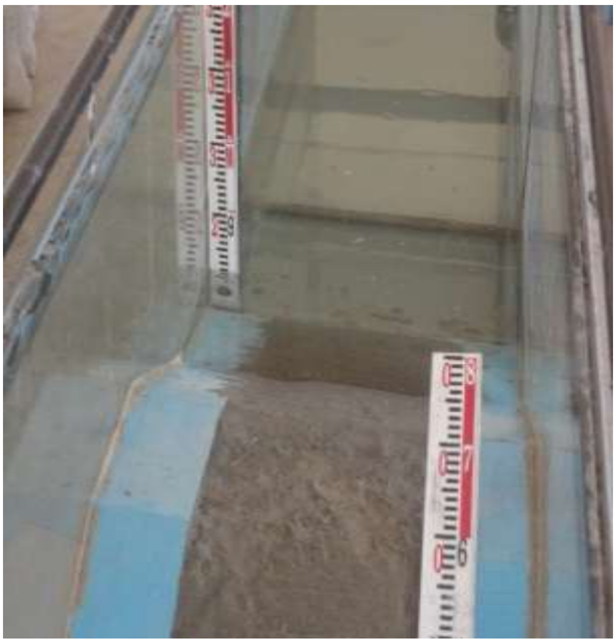

Fig. 4b: Saturation of embankment

Fig. 5: Experimental Set up

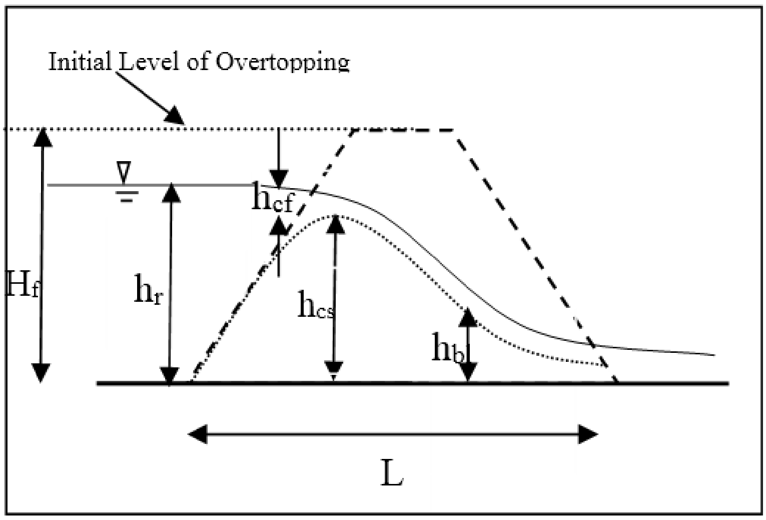

Fig. 6: Different flow parameters

Results and Discussion

The results of the experimental observations have been analyzed and discussed under the following subheadings:
a) Evolution of breach
b) Embankment profile and
c) Normalized Breach Hydrograph.

a) Evolution of breach: As the high flood level (HFL) becomes slightly higher the level of the top of the crest, the sheet of water moves to the downstream from over the dam. The dam is, thus, overtopped. The initial energy of the overtopping sheet of water for a few seconds is resisted by the compacted surface of the dam, after which it begins to erode at the downstream face of the crest. Researchers in the past[3,6] have described the breach phenomenon in different phases.

Accordingly, here it is being described in three phases. The breach growth for cohesive and non-cohesive embankments is described under 3 phases with some exceptions. On the basis of observations of different tests, these three phases are explained as

Phase of breach initiation: Both the categories of fuse plugs had same fill material in the analogous models. Accordingly, they exhibited similarities in the initiation of erosion. For models with predominantly non-cohesive material i.e. FP 1.1 to FP 1.4 and FP 2.1 to FP 2.4, the first signs of erosion were observed on the surface of the downstream face of the filling along the path of first stream of overtopping water (Figure 7a). The material on the surface was not able to resist the erosion and in a matter of about 10 sec the water had developed a narrow channel.

However, in the case of model with cohesive material, i.e. FP 1.5 to FP 1.8 and FP 2.5 to FP 2.8, the overtopping water failed to make any distinct mark on the crest or the downstream face for a considerable duration. The first visible sign of erosion commenced at the downstream toe of the fill material (Figure 7b) and progressed upward. It was very clear that whereas for the non-cohesive material it started from top to bottom, it started from bottom towards up in the predominantly cohesive material. However, for the same fill material, there was no basic difference in the two categories of fuse plugs in the initiation of erosion and correlates with the observations of Walder et al[22].

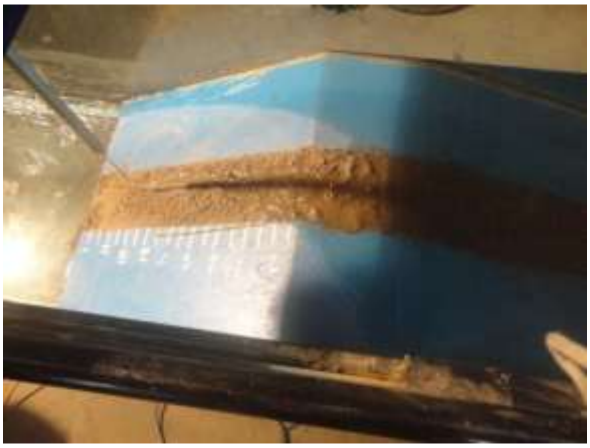

Fig. 7(a): Surface erosion on downstream side and over the crest

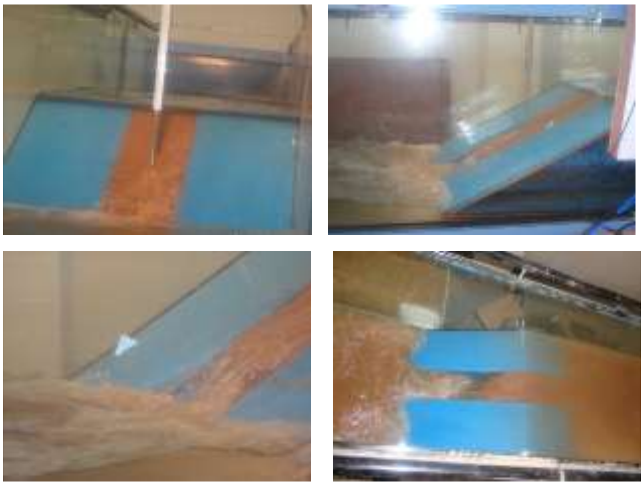

Fig 7(b): Erosion at downstream toe

Phase of breach progression: In this phase, the breach progresses due to continuous overtopping. The progression for pre dominantly non-cohesive fill material i.e. FP11 to FP 14 and FP 21 to FP 24, was interrupted due to caving in of sediments.

Also different irregular gradients on downstream face were observed which accelerated towards the upward direction. For cohesive fill material i.e. FP 15 to FP 18 and FP25 to FP28, the step migration of erosion occurred after 5-15 minutes from the phase of breach initiation. It was due to detachment of sediment in lumps with increased magnitude which caused the widening of the breach.

These experiments are useful to understand the erosion mechanisms of breach under cohesive and non-cohesive fill material because of the confinement of the side walls, the process, at best presents a 2-D breach analogy as shown in figure 8a. The experiments conducted by Schmocker and Hager[14] support these results. According to these authors, the morphodynamics of 2-D experiment, in which water spills over the entire embankment, was different as the water surface would be nearly parallel to the bed surface.

Phase of final breach: In this phase, the erosion of sediment advances further towards upstream of the model and due to increased discharge on account of breach of crest, the breach of channel becomes wide. For model with cohesive fill material i.e. FP15 to FP 18 and FP 25 to FP 28 of a headcut type erosion was observed along the entire length of crest. The same type of breach development was observed for non-cohesive fill material i.e. for FP 11 to FP 14 and FP 21 to FP 24.

But in the case of non-cohesive material for the remaining models, a sudden and complete washout of the fill material occurred in a few seconds (Figure 8b). Under similar conditions, the total breach time was less and the breach widening was more in case of FP 2. It was due to the larger crest length of FP2 which in turn had increased the infiltration process and also the time to breach.

b) Embankment profile: The temporal variation of different breach characteristics was observed and analyzed at different stages of the figure 9 (a and b) and figure 10 (a and b). It may be observed that in the case of clayey soil, the process of breach was gradual and the slopes at various stages were gentle in comparison to their counter-parts in the fill material which was purely non-cohesive. This could be better explained by the time required to breach at similar levels. It can be observed that the time required for complete washout was 182 minutes and 232 minutes in the case of clayey soil in comparison to 13.5 minutes and 24 minutes for the non-clayey soils.

However, when the two types of fuse plugs were compared within themselves for the same fill material, the time required for the clayey and non-clayey soils was opposite. This could be explained that for the clayey soil, the lumps required in FP-2, to be completely eroded were more and hence required more time. But in case of non clayey soil, the smaller width of FP-1 provided more confinement and thus resisted longer to be completely washed out. So for different type of fill material, the cohesion plays a vital role and affects the rate of erosion.

Fig. 8(a): Caveing in of sediment

Fig. 8(b): Widening of breach

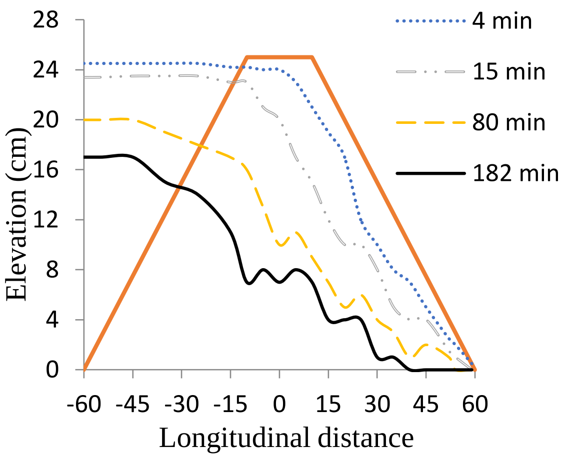

Fig. 9(a): Embankment profile for FP-1

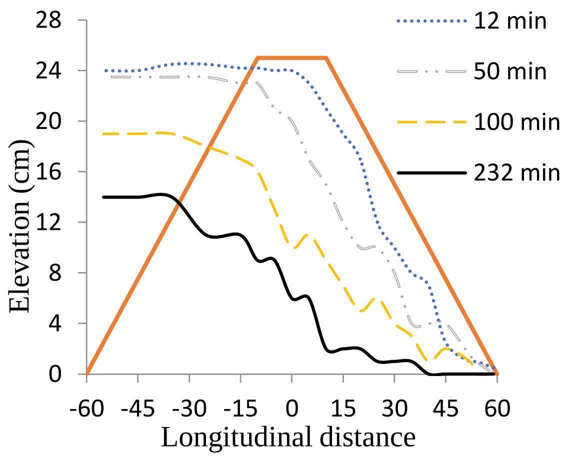

Fig. 9(b): Embankment profile for FP-2

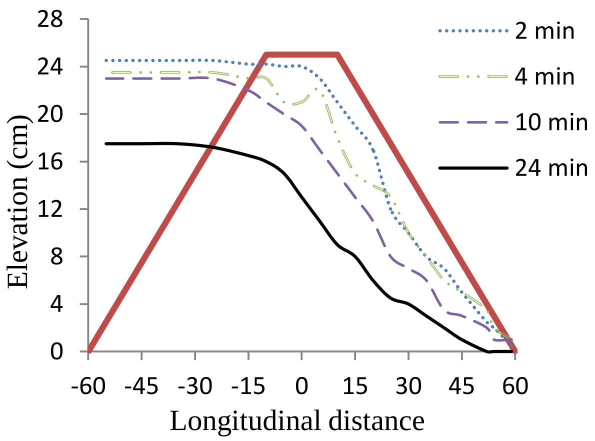

Fig. 10(a): Embankment profile for FP-1

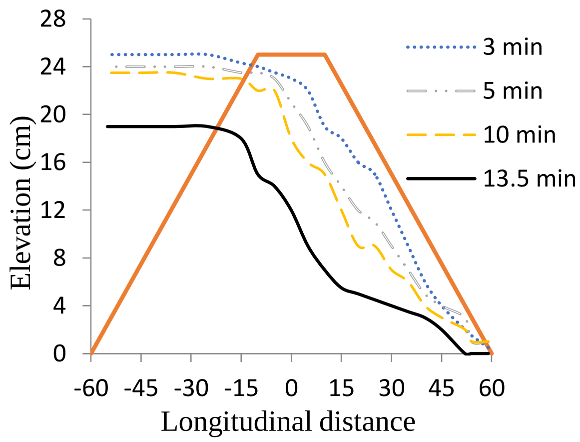

Fig. 10(b): Embankment profile for FP-2

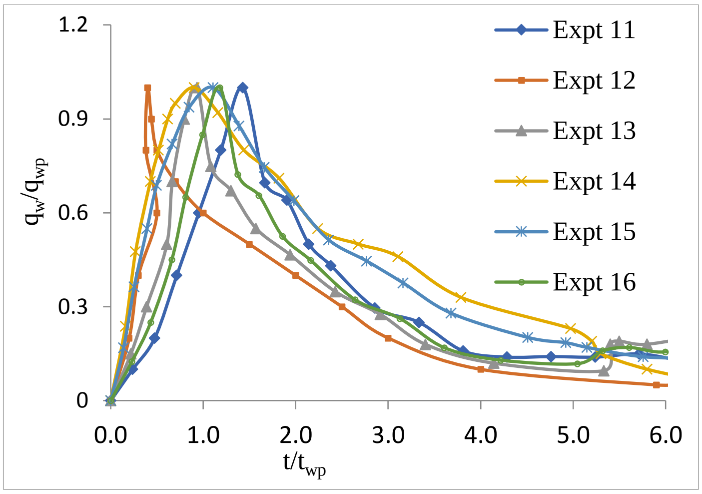

Fig. 11: Normalized breach flow hydrograph

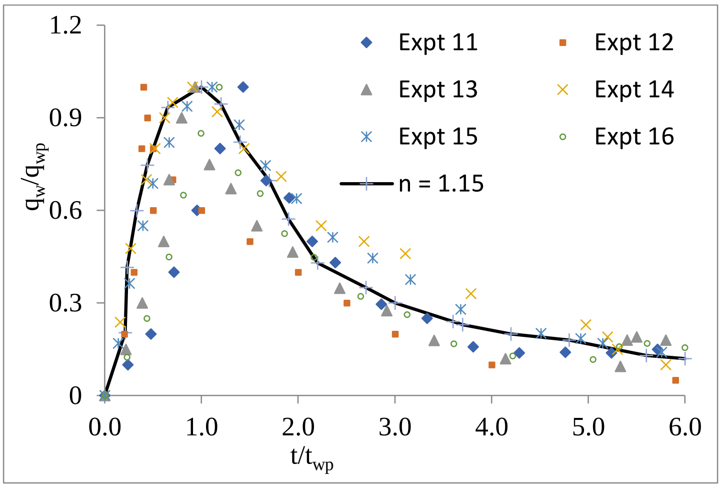

Fig. 12: Normalized breach flow hydrograph with exponent value of n as 1.15

c) Normalized Breach Hydrograph: Different hydrographic curves were plotted for all models using FP-2, except for 9 and 10. Normalized breach discharge (q_w/q_{wp}) and corresponding normalized time to breach (t/t_{wp}) are necessary to determine first. The maximum value of discharge intensity is denoted by q_{wp}. For calculating discharge intensity (q_w), the breach outflow discharge (Q_f) is divided by average breach width and measured in m3/s/m. Breach outflow discharge (Q_f) was determined using the equation of continuity of flow as:

$$Q_f - Q_{in} = A_s \frac{dh_r}{dt} \quad (1)$$

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

The normalized breach hydrograph has been plotted between q_w/q_{wp} (along y-axis) and t/t_{wp} (along x-axis) as shown in figure 11. Different curves show that initially there is a steep rising followed by diminishing ends which correlate with the results of Verma et al[19]. The values of t/twp vary within a range of 0.4 to 1.6 when q_w/q_{wp} is equal to 1. The following equation describes all the hydrographic curves of figure 11 with different values of exponent 'n'.

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

Equation (2) is similar to the equation used by Verma et al.[19] The value of exponent 'n' to express the best fit curve was estimated by trial and error method and its value is 1.15 (Figure 12) which correlates with the results given by Verma et al[19] as exponent value was 1.1. This equation has a coefficient of correlation (r^2) as 0.85 which indicates the excellent fit of the curve.

Conclusion

For the present study different tests were performed and analyzed for cohesive and non-cohesive earthen embankments using fuse plug models. It is concluded that breach characteristics depends upon geotechnical factors, geometry of fuse plug models and hydraulic conditions.

I. The type of embankment material influences the rate of erosion during overtopping of earthen dams. Water surface profiles of different tests indicate the type of erosion. For non-cohesive soil, the breaching occurs progressively but in case of cohesive soil, it arises in steps which is called headcutting.

II. The whole breaching process was critically described in three phases. The result concludes that initially a tapered channel was formed and with the passage of time the breach widens due to cave-in of sediment. The breach discharge increases rapidly with continuous overtopping and due to increased discharge, heavy sediments were eroded which widen the breach channel. Finally, the breach discharge decreases as the breach widens.

III. For cohesive soil, the cohesion plays a vital role and affects the rate of erosion. The total breach time (time to breach) increases due to cohesion. Steep erosion of embankment material with gentle slope occurs for non-cohesive soil.

IV. Breach width at the top is more than the bottom of embankment which concludes the rectangular and trapezoidal shape of the breach irrespective of soil composition of embankment. These results show a relationship with the literature.

V. The washout of fuse plug during overtopping of embankments occurs in controlled manner and it reduces the chances of damage of rest of the body of dam.

VI. Large size of fuse plug rises the infiltration process which in turn increases the duration of phase I. But under similar conditions, the total breach time is less and breach widening is more by increasing the crest length of fuse plug.

VII. The normalized breach hydrograph can be expressed by equation (2) with exponent 'n' equal to 1.15 and the value of coefficient of correlation, r^2, as 0.85 indicates best fit curve.

VIII. These two dimensional tests are greatly valuable for describing the breach behavior, erosion mechanics and help in developing early warning systems.

IX. Limitations of this study are small flume, limited soil type, limited discharge, two fuse plug models and constant hydraulic conditions. Further large scale tests are recommended to predict the long term behavior of breaching process.

Acknowledgement

The first author would like to acknowledge the help received from M. M. Engineering College, M. M. University (MMU), Mullana, Haryana and National Institute of Technology (NIT)), Kurukshetra, India.

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(Received 15th September 2020, accepted 21st November 2020)