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BREACH BEHAVIOR OF EMBANKMENTS USING TWO FUSE PLUG MODELS

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ABSTRACT

The failure of a dam, besides causing massive damage to the structure entails huge loss of lives. In case of embankment dams, the most commonly occurring failure is on account of overtopping as compared to other causes of failure. Therefore, it is necessary to analyse the breaching of embankments to develop disaster management plans like early warning systems and emergency action plan. To understand the breaching process, the essential breach parameters include breach initiation time, breach width, time to breach, shape of breach etc. These parameters are dependent on a multitude of factors like, the soil characteristics, degree of compaction, upstream discharge and geometry of the fill material. In the present study, a total of fifteen tests were conducted in a small water flume using two wooden fuse plug models of different dimensions. The temporal variations of breaching process, water surface profiles and different breach characteristics were observed and described in different phases. It was analysed that breach behaviour mainly depends upon the soil composition and upstream discharge. The constant hydraulic conditions and the limited width of the flume are some limitations of the study.

Keywords: *Fuse plug, dam breach, breach characteristics, temporal variation, headcut erosion, embankment profile.*

INTRODUCTION

A dam is a hydraulic structure constructed across a river to store water on its upstream sides with essential benefits like water supply, irrigation, hydro-power and flood control, to the society. Earthen embankment dams have been built since early days of development and used throughout the world (Verma et al., 2014). Now, there exist a lot of earthen dams small or large in the world. Along with their benefits, many dam failures have occurred in the past which results in not only loss of lives but also cause massive damage to environment and property. O'Connor and Bee (2009) recognised that there was not only destructiveness but also large scale geographic change due to earthen dam failures.

REVIEW OF LITERATURE

In the past, embankment dam failures, besides due to natural disasters have been reported on account of seepage, overtopping, piping and structural defects. Dam failure may be occurred due to many reasons like differential settlements, seepage, overtopping rock slide or poor construction (Rico et al., 2008 a). During the dam failure, the flooded water outflows through or over the dam to raise the discharge on downstream side of the dam. Fread, 1988 described that in case of dam failures, the magnitude of flow increases abruptly and the time required for evacuation is very less as compared to precipitation-runoff floods. According to Costa, 1985, approximately 34 % of dam failures are caused due to overtopping. The risk of overtopping for embankment dams can never be eliminated completely but can be reduced (Singh, 1996). Therefore, it is necessary to develop reliable methods to model the dam breach mechanism to analyse the dam failure. There are different approaches in the literature, to analyse the breaching of dams which include, parametric modelling (Xu and Zhang, 2009), case studies (Khassaf, 2011; Latif et al., 2013), physical modelling (Weiming, 2013) and experimental studies (Verma et al. 2014).

Prediction of breach parameters is quite complex because it is difficult to determined various breach characteristics (breach width, formation time, shape of breach) simultaneously. Wahl (2007) described the uncertainties in the prediction of embankment dam breach parameters. 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 (Johnson et al., 2011). Wu (2011) reviewed the different breach modelling methods and concluded that only a few researchers considered the effect of embankment erodibility in the breach modelling. The factors responsible for breaching of an embankment are properties of material used for embankment, geotechnical behaviour and the hydraulic flow through the breach (Wahl, 2011). Also it is not possible to determine these parameters practically in the field (Ponce and Tsivoglou, 1981).

Among the very recent studies are the works of Latifi et al. (2013), Alhasan (2015), Jhao (2014) and Verma et al. (2014). Interestingly, out of these three, Latifi et al. (2013) is a case study wherein the authors studied the pore water pressure and settlement of Alborz earth dam and predicted the future planning. Alhasan, 2015 is a one-dimensional mathematical model study. The works by Verma et al. (2014) and Jhao (2014) are experimental investigations conducted in a small and a large flume, respectively. Verma et al. (2014) studied the erodibility process using a fuse plug model in a small flume. 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 literature (Stephen et al., 2002). 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 two fuse plug models.

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DESCRIPTION OF FUSE PLUG

Fuse plug is an integral part of embankment dam and it acts as a safety valve. It is a temporary earthfill structure which is provided usually at the centre of the dam. By considering the water surface level of the reservoir, fuse plug is designed. During the high flood conditions, the fuse plug provides safe passage of water and washes out in a controlled manner without damaging the rest of the dam (CWC, 1989) and so behaves like an auxiliary spillway. As shown in Fig.1, it allows erosion of fill material in longitudinal as well as in vertical direction during overtopping and the erosion in lateral direction is limited to the vertical walls of the fuse plug. Therefore, washout process occurs two dimensionally. A few researchers studied and analysed breach modelling using fuse plug. Recently Verma et al. (2014) and Sahu et al. (2013) studied the breaching of embankment using a fuse plug.

EXPERIMENTAL PROGRAMME

Fifteen Tests on two fuse plug models were conducted in a recirculating water flume (in 2012) (Fig.2) for studying the breaching of an earth embankment, in the Hydraulics research laboratory of Civil Engineering Department at M.M. Engineering College, Mullana, Ambala (India).

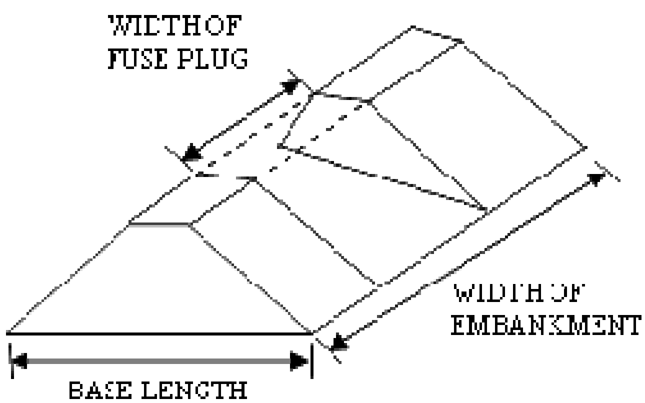

Fig. 1: Fuse Plug model

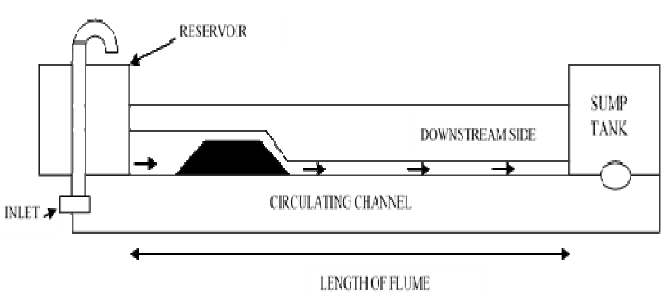

Fig. 2: Line diagram of the flume

Experimental set up

The different tests were conducted using a glass water flume, two wooden fuse plugs of different dimensions, soil of different composition, a compaction roller and other essential standard laboratory devices. The flume dimensions were 4.5 m x 0.57 m x 0.57 m. A reservoir of dimensions 1.00 m x 1.00 m x 0.85 m was used as water reservoir and another tank of same dimensions was used as a sump tank. A water circulating channel was used of dimensions 4.85 m long, 0.57 m wide and 0.85 m deep which were attached with sump tank (Fig. 2). The walls and bottom of flume were made of glass to allow lateral observation of the model during the tests. The soil properties were determined in the Soil Mechanics laboratory before the construction of embankment. The two digital cameras were used to record the process of 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.

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 have been shown in Table 1.

EXPERIMENTAL PROCEDURE

The wooden material was used for fabricating the fuse plug models and painted to avid seepage. For different tests the location of models inside the flume was same for all tests. The dimensions of the model used in the present study are presented in Fig. 3 and Table 2.

Fig. 3 (a): Fuse plug model (FP-1)

Table 1: Properties of soil use for different tests

Test no.	1,9	2,10	3,11	4,12	5,13	6,14	7,15	8
Coarse grained soil (% age)	38	89	85	95	93	80	76	72
Fine grained soil (%age)	62	11	15	5	7	20	24	28
Maximum dry density (gm/cc)	1.625		1.925	1.902	1.88	1.86	1.87	1.85

Fig. 3 (b): Fuse plug model (FP-2)

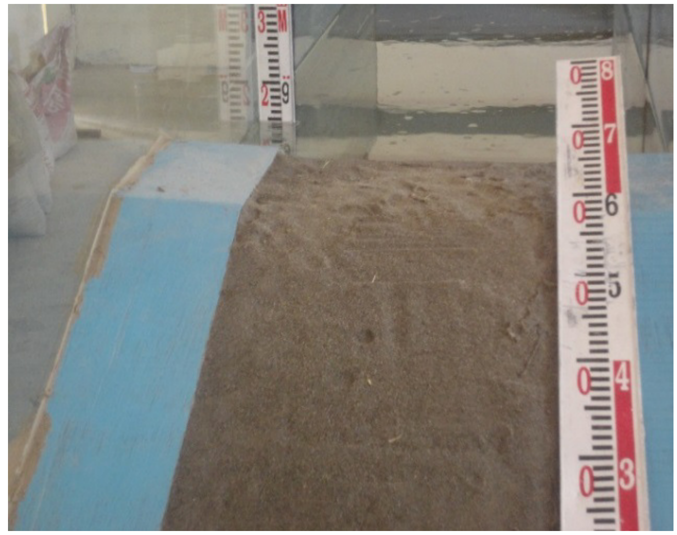

Fig. 4 (a): Storage of water

Table 2: Dimensions of fuse plug models

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

Embankment construction

The height and width of the fuse plug were restricted as per the dimensions of the model and flume. To reduce the seepage, a layer of pure clay was used at the toe on upstream side the model. The material was filled in 5 layers in the fuse plug model. The soil mixed with optimum moisture content filled in the flume and then the soil is compacted with hand operated roller. Different embankment models were made with mixes of locally available soils in different proportions. After constructing the embankment, an extension time of 24 - 48 hours was provided for uniformity of material. To facilitate observations of the development of breach, a grid of horizontal and vertical line was drawn on the glass sidewalls of the flume. During the filling of water in reservoir tank, the inflow was controlled by the head regulator attached to the inflow pipe and rate of inflow was 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 up to a height of 22 cm. After filling the water on upstream side of embankment, it was retained about 20 hours for homogeneous saturation of embankment as shown in Figure 4 (a) and (b). Thereafter, the level of water on the upstream was increased and overtopping occurred.

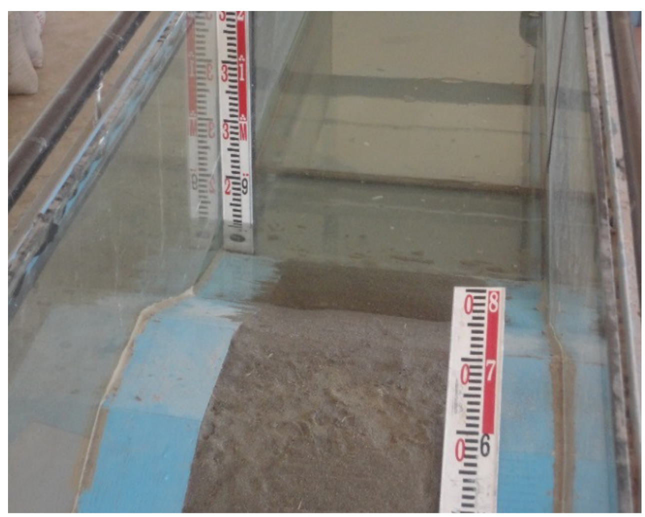

Fig. 4 (b): Saturation of embankment

Different breach parameters of embankment as breach width (b_w) and depth (b_d) were observed during the experiment at short intervals of time using point gauges. The breaching process of breach growth was videotaped with a high speed digital video camera (Fastec Imaging Inline Gigabyte Ethernet Camera) (Figure 5). The instant photographs were taken with two digital cameras. The procedure was repeated for different proportion of sand-silt-clay using two different fuse plug models.

Breach flow characteristics

Breach flow characteristics as breach initiation, breach formation, time to breach are important for downstream reservoir pathway. For a fuse plug, these characteristics depend upon the incoming flow to the reservoir, properties of fill material of fuse plug, geometry of fuse plug and capacity of reservoir. Different parameters which were essential for determining the wash out process of the fuse plug model is shown in Fig. 6.

side. The overtopping begins as the water starts to outflow from the reservoir. As the overtopping occurs, a small amount of erosion observed across the crest of dam like a notch (Figure 7 a). With the passage of time it forms a narrow channel which advances headwards along with almost vertical banks and channel develops steep or gentle gradient for non-cohesive soil as shown in Figure 7 (b) which were described as erosional cyclic steps (Walder and Godt, 2015). For cohesive soil, no erosion occurs in this phase (Figure 7 c), but detachment of downstream toe was observed (Fig.7 d).

Fig. 5: Experimental Set up

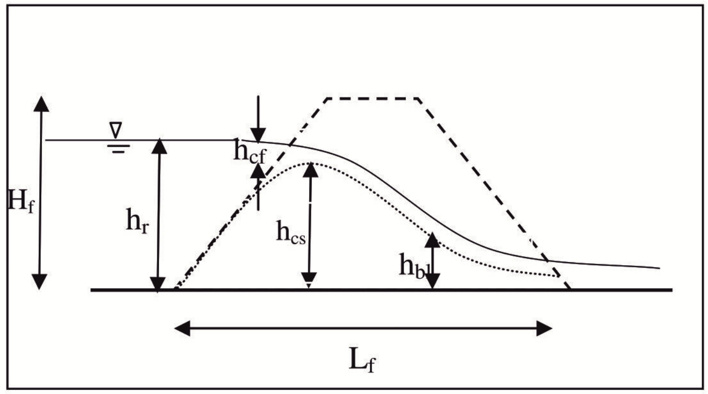

Fig. 6: Different flow parameters

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}). The temporal variation of embankment profile and breach characteristics was observed during the overtopping for all tests. Table 3 and Table 4 described the different breach characteristics using FP-1 and FP-2 respectively. Breach initiation time and breach final time are the time durations from the start of overflow.

Phase II: In this phase, the zones of alternating gradients increase in amplitude and migrate in upward direction with head-cutting. The process may be interrupted due to caving in of sediment from the banks of the breach channel, (Figure 8 a).

Phase III: Due to continuous outflow, the headcut migrates along the entire length of downstream side. It progressively increased towardsupstream and downward, with increasing discharge. Also, the breach channel widens as the sediment from the banks are passages by the flow of water and heavy sediments are progressively eroded (Figure 8 b). With the abrupt cutting of banks, the lengthening of breach crest may be dislocated. For cohesive soil, the instead of progressive erosion as in case of non-cohesive soil, head-cutting was observed which advances longitudinally (Figure 9 a, b). In case of FP-2, the embankment is broad, so there are more chances for infiltration of inflow which in turn increased the duration of phase I. as the downstream face is broad, so

Table 3: Different breach characteristics using FP-1

Test no.		1	2	3	4	5	6	7	8	
Breach initiation time (sec)		242	7	4	2	8	16	33	29	29
Breach final time (min)		182	6	14	3	5	10	24	38	38
Breach width (cm)	Top	14.1	14.6	14.6	14.6	14.6	14	13.6	13.4	
	Bottom	14.6	14.6	14.6	14.6	14.6	14.2	14.1	14	

Table 4: Different breach characteristics using FP-2

Test no.		9	10	11	12	13	14	15
Breach initiation time (sec)		1020	11	20	15	16	29	34
Breach final time (min)		232	8.5	6.2	5.5	6	12	13.5
Breach width (cm)	Top	32.5	32.5	32.5	32	32	31.4	30.2
	Bottom	30	31	30.2	30.8	30	30.2	30.3

Breach evolution

The development of breach was described for both cohesive and non-cohesive soils, as described by many investigators (Coleman et al., 2002, Hunt et al., 2005; Hanson et al., 2005). Here the breaching process is explained in 3 phases.

Phase I: Initially as the embankment is not fully saturated event an extension time of 15 – 20 hours was provided after filling the upstream side of the embankment, so infiltration occurs and the load of sediment increased on downstream

Fig. 7 (a): A notch over the crest of dam

Fig. 7 (b): Narrow channel on d/s side.

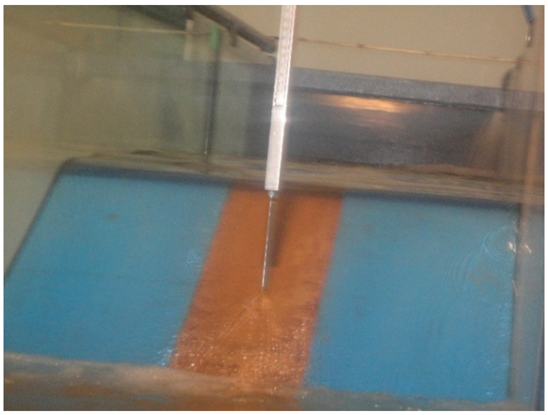

Fig. 7 (c): No erosion (initially)

Fig. 7 (d): Detachment of toe

Fig. 8 (a): Caveing in of sediment

Fig.8 (b): Widening of breach

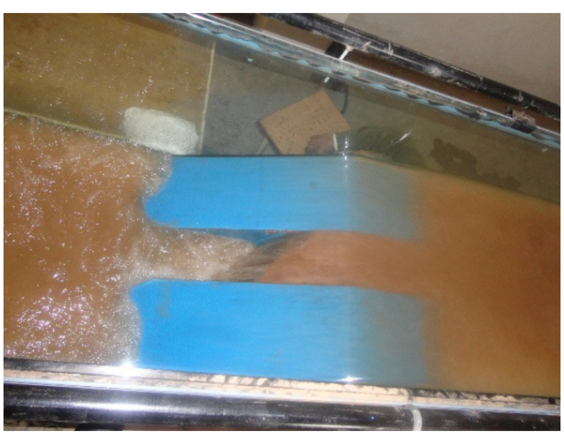

Fig. 9 (a): head-cutting in progress

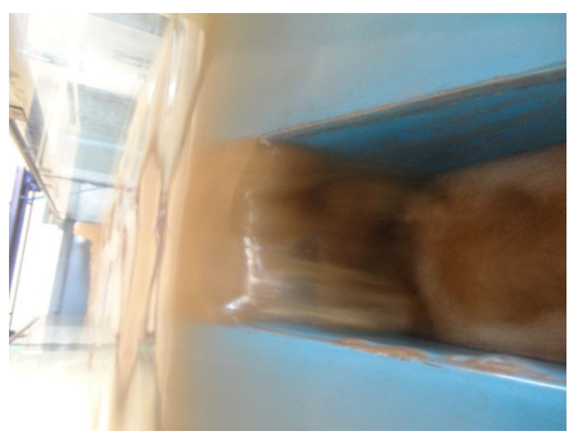

Fig. 9 (b): complete wash out of d/s

increased amplitude distributed laterally along with longitudinal direction. For FP-2, when other onditions remained constant, the time to failure is less as compared to FP-1 (Table 1) and the breach is more widened in phase III.

Breach development is a 3-dimensional process. This is highlighted in the paper by Schmocker et. al. (2013), Zhu et. al. (2011). However, in the case of a fuse plug, the sides are firm and vertical which cannot be eroded by the flow of running water. The walls thus form the limiting shape of the breach. Thus the fuse plug does not allow lateral erosion and the breach process during the experiments was 2-dimensional. The morphodynamics of 2D tests is distinctly different (Schmocker and Hager, 2009), so these tests are highly useful for describing the erosion mechanics but cannot define the process of breach widening.

Embankment profile evolution

The results of 4 tests (2 each for FP-1 and FP-2) are taken for describing water surface profile through channel. Test 1 and & 7, with same soil composition using FP-1 and test 9 & 15, with same soil composition using FP-2 were considered here. In all 4 tests, the time period starting from breach initiation to breach formation. Water surface profiles for different time intervals were described in Figure 10 and 11.

For non-cohesive soil as shown in Figure 11 (a) and (b), the slope of water surface remains almost constant and gentle with the steep erosion of downstream face. So,the slope of eroding headcut is constant throughout the test and from the literature the slope is equal to static friction angle. With the advances of breaching, the discharge overtopping the embankment goes on increasing. However in the case of laboratory experiments, since the size of reservoir and the discharge is limited, therefore, initially for some time the discharge increases with an increase in breach but after that due to a decrease in the head of water in the reservoir, the velocity and corresponding discharge decreases.

SUMMARY AND CONCLUSIONS

In this study, the results of an experimental work conducted in a small flume using twodifferent fuse plug models were described. Fifteen tests, eight using FP-1 and 7 using FP-2 are analysed for overtopping failure of embankments. For non-cohesive soil, the progressive erosion occurs in three phases. The results indicates that with the passage of time the breach discharge increses abruptly and decreases as the breach widens. For all the tests using FP-1, breach width at bottom and top is almost same except for test 6,7 and 8, which indicates the rectangular shape of btreach. For FP-2, the

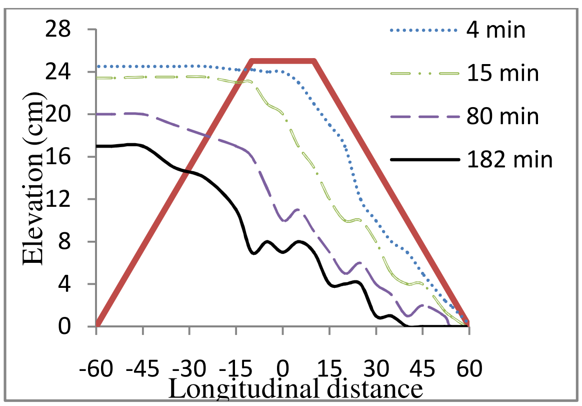

Fig. 10 (a): Embankment profile for test 1

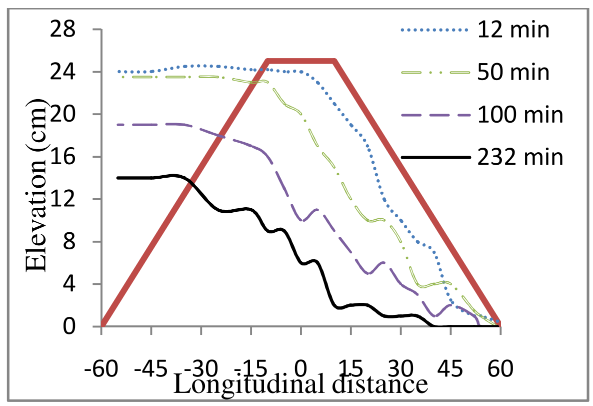

Fig.10 (b): Embankment profile for test 9

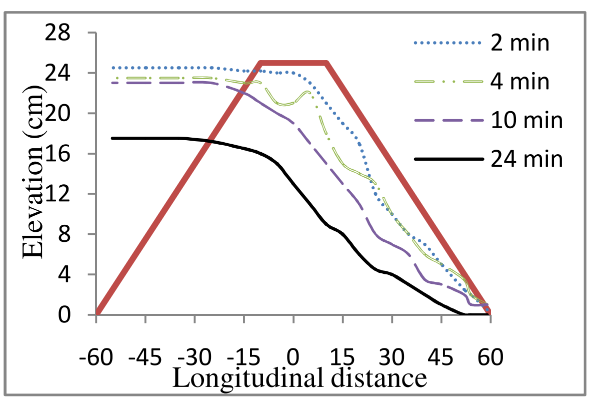

Fig. 11 (a): Embankment profile for test 7

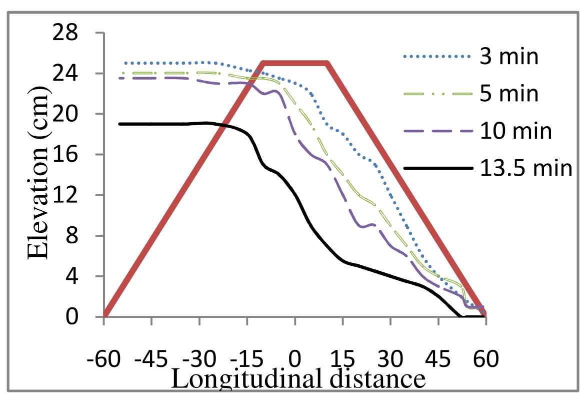

Fig. 11 (b): Embankment profile for test 15

For cohesive soil as shown in Figure 10 (a) and 10 (b), the headcut widens and rate of erosion is largely affected by cohesion of soil and the slope of headcut steepens. So, the soil material influences the rate of erosion and the influence may vary several orders of magnitude.

breach width at the top is more than the bottom, except for test 15, which concludes the trapezoidal shape of breach.

As observed through the laboratory experiments, breach width at the bottom is less than the width at the top exhibiting a triangular shape. Johnson and Illes (1976) observed breach shapes resulting from overtopping and described that an initial breach is formed through the dam as shown in Figure 12 however, the location and shape of this initial breach is a function of a number of factors and hence not easily predictable.

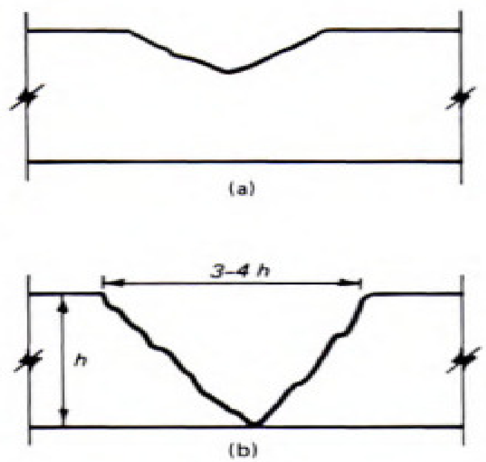

Fig. 12: (a) initial breach shape, (b) "V" shape breach formed when softer dam material is eroded away (Johnson and Illes, 1976)

MacDonald and Langridge- Monopolis (1984) analyzed breaching characteristics of a number of historical dam failures. They concluded that for both earthfill and non-earthfill, the breach shape could be assumed to be triangular with 2 V : 1 H side slopes, provided the breach did develop to the base of the embankment , and trapezoidal with 2 V : 1 H side slopes if additional material was washed away after the breach reached the bottom of the embankment. It should be used only if the breach size is less than the embankment size.

This can also be explained that as the water starts moving through the triangular notch thus formed, the under- cutting is limited to a smaller wedge of this notch. This progressive action leads to disintegration of the embankment in the lower vertical direction more than the lateral direction. The situation is similar to the natural shape of a river valley.

Results of laboratory tests correlates with the data given in the literature. Moreover, it is concluded that the breach shape is independent of soil composition,but time-to-breach increases for the tests using FP-2, by keeping the other parameters constant. It concludes that lateral widening of fuse plug modelhelps in flow of water in controlled manner and increase the evacuation time. The water surface profile of different tests indicates that for non-cohesive soil the breacing progresses gradually but in case of cohesive soil, it is steep erosion (headcutting) rather than progressive. The constant hydraulc conditions for all tests and limited fuse plug models used for the tests are some limitations of this study. Rather than the results of the study will be useful for designing embankments and developing evacuation plans.

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