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MORPHOLOGICAL CHANGES OF FUSE PLUG IN AN EARTHEN DAM DUE TO OVERTOPPING FLOW FROM RESERVOIR

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ABSTRACT : Fuse plug works as a safety valve of an earthen dam. It is an earthen embankment, provided to be washout due to overtopping of Flow. The overtopping of flow causes erosion of soil from its surface and the eroded surface of the embankment acts as a board-crested weir. The study on the changes of morphological features during the breaching process of fuse plug helps in the understanding of mechanism associated with the washout of fuse plug. The change in morphology of fuse plug with time controls the breach flow. The location of crest of eroded soil bed profile (X_m) from upstream end of the fuse plug and its height (h_{cm}) are the key controlling parameters to compute breach flow. The height of eroded soil bed profile (h_c) is a function of time and space i.e. h_c f(x, t), where x is measured from upstream of the fuse plug. The computation of change in h_c at different x values in a given time duration help in estimating the soil eroded from the fuse pluge. The reservoir time scale (T_*), length scale (H_*) and soil resisting velocity (V_{SR}) influence the morphological changes of fuse plug with time of breaching. Keeping these in mind the experiments were conducted on physical model of fuse plug with different soil fills and constant inflows to the reservoir for prediction of longitudinal soil bed profiles in fuse plug during the breaching process.

KEY WORDS: Soil bed height (h_c), Crest height of erodible soil profile (h_{cm}), Reservoir time scale (T_*), Reservoir Length scale (h_*) and soil resisting Velocity (V_{SR}).

INTRODUCTION

Dams play a major role in managing surface water resources in a planned way to bring economic development of a nation. Among the various types of dams constructed around the globe, the earthen dams are the most common type and constitute the vast majority of dams. The earthen dams are more susceptible to failure [2,7]. The causes may be due to improper design, excessive sedimentation of reservoir, adopting erroneous reservoir operational rules, or due to unexpected flash flood. The main cause of the failure of an earthen dam is due to overtopping. When dam fails, large quantity of stored water is released causing disaster in the downstream region. Hence, fuse plug is provided to protect the dam against catastrophic failure due to overtopping of water from the reservoir [10,12]. Fuse plug, a pre-defined breach section, works as a safety valve for an earthen dam. The height of fuse plug is the difference between maximum reservoir level (MRL) and full reservoir level (FRL). In an eventuality of failure of crest gates to operate in time, it also serves as an emergency outlet. This is provided intentionally to be washed out during high flood and to be reconstructed after the passage of flood. When water overtop over the fuse plug section, the flow that takes place is a weir type flow[14,16]. So it is desired to know the relation between discharge and head of water over the crest of the erodible weir to ascertain how quickly the excess flood water from the reservoir can safely be released through fuse plug [11,13]. The changing morphology of fuse plug with time of breach controls the breach flow and the rate of washout of soil from fuse plug surface. To estimate breach flow (Q_w), the location of crest height (X_m) and its height (h_{cm}) are essential. The definition sketch is shown in Figure 2 and the reservoir time scale (T_*), reservoir length scale (H_*) which are shown in Figure 3. The soil resisting Velocity (V_{SR}) play major roles in the morphological changes of fuse plug during the breaching. The experiments with physical model of fuse plug were carried out in the Hydraulic Flow Laboratory, University College of Engineering, Burla, Orissa, India.

REVIEW OF LITERATURE

The preventation of damage to main dam due to overtopping flow can be done with an auxiliary outlet. One of these auxiliary outlets are called Fuse plug. The significant interest on dam safety by the designer has compelled to think alternate and cheap structural measures like "fuse plug", which can be washed out due to breaching during the excessive flash flood and can be reconstructed afterward [3,4,]. The literature on experimental or numerical studies on fuse plug breaching is scanty. But a considerable body of literature on earthen dam breaching due to overtopping flow are available [9, 17]. So, in this literature study on fuse plug breaching, the development of the knowledge on earthen dam breaching due to overtopping flow is also included to enhance the thought process on the general principle of erosion under dynamic condition due to breaching [5,6]. The flowing water induces local shear stress and when it exceeds the critical shear stress of fuse plug fill material, the erosive action starts. The general information regarding erosion in soil bed helps to understand embankment breaching [1]. To understand the mechanism associated with washout of fuse plug due to the overtopping flow, the experimental study in the laboratory is planned to be carried out. Due to lack of literature on experimental and numerical model studies on fuse plug washout, the study has its own importance so far dam safety is concerned[18,15].

In particular, the experimental study on washout of fuse plug in a controlled laboratory environment is required to establish the inherent relationships among breach hydraulic, breach geometry and transport of erodible soil from the fuse plug embankment as it will be difficult to measure these breach variables with time during the breach in the field. Prediction of breach flow and breach parameters based on statistical analysis of historical data tends to have significant associated uncertainties. This is due to the rare available historical data. Although understanding and predictability of breach process is at present inadequate. This understanding is improving (Temple and Treat 1998). Small scale investigation of this nature were undertaken by Jack (1966) to provide qualitative and quantitative description of breach erosion process for overtopped homogenous embankment constructed of noncohesive material (Coleman el at 1997).

As described by (Stephen E. Coleman 2002), the understanding and data presented herein for breach geometry and flow based on expression for the erosion and transport of cohesive sediments[19,20].

Aspects of the present results for cohesive materials may have the value of breach process. In terms of applying the present results to the fuse plug breaches of different discharges have its own importance in case of breaching process.

EXPERIMENTAL SETUP AND DATA ACQUISITION

The flume used for the experiments is a tilting flume of 15 m long, 0.6m wide and 0.6m in height. The model of earthen dam was made in wood with a trapezoidal breach section at the centre. This breach section was filled with compacted soil and is called the fuse plug on the dam body. The fuse plug used for experiment is of the following dimensions: H_D = Height of fuse plug = 20cm, B_{ft} = Top width of fuse plug= 40cm, B_{fb} = Bottom Width of fuse plug = 16.88cm, L_{LB} = longitudinal Base length of fuse plug = 1.15m, L_{LT} = Longitudinal Top length of fuse plug = 15cm. The slopes of upstream and downstream faces of the fuse plug =1(V):2.5 (H). The trapezoidal breach section having side slope $\theta = 60^0$ was considered based on the historical dam failure cases due to overtopping flow reported by Singh and Scarlators (1988). Figure-1shows the detailed plan, longitudinal section, and cross-section of the fuse plug adopted for experiment.

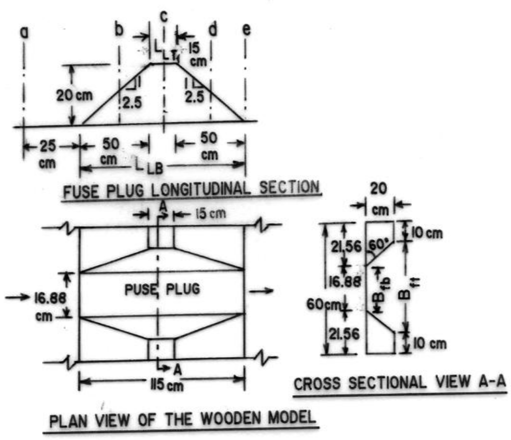

Figure 1. Fuse Plug Model in Plan and Sectional View

SOURCE OF SOIL USED AS FUSE PLUG FILL MATERIAL

In the experiments different types of soil were used as fuse plug fill materials. These soils were collected from the nearby area of University College of Engineering, Burla. The properties of soil such as the angle of friction (Φ) and cohesion (c), particle size distribution were found out conducting tests in the Geotechnical Laboratory of the Institute. Types of soil used for the fill of fuse plug with its properties are given in the Table – 1.

TABLE-1
PROPERTIES OF SOIL USED IN EX PERIMENTS

Type of soil	d_{50} (mm)	ϕ (degree)	C (KPA)	□$_b$ (gm/cc)	w % (OMC)
A	0.51	21	43.16	2.19	10
B	0.40	22	17.66	2.02	11
C	0.60	27	13.73	2.12	12.5
D	0.46	26	10.75	2.22	10.5

PREPARATION OF FUSE PLUG MODEL

The wooden fuse plug model block was fitted inside the flume at a distance 6.0m from the inlet of the flume. The open trapezoidal fuse plug section was filled with soil by compacting, layer by layer, at its OMC till the fuse plug model dimensions were achieved. A constant head overhead water tank is used to maintain constant flow to the reservoir area of the channel. The water level (h_w), soil bed level (h_c) at different transverse sections, as shown in Figure 1 were measured manually with respect to flume bed during breaching using point gauges by five persons referring to a common digital clock. From these basic data other data are computed.

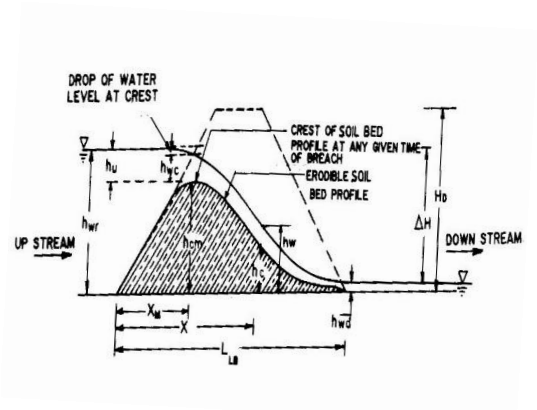

Figure 2. Definition Sketch for the Scales X_M , L_{LB} and h_{CM}.

A Typical Variation of reservoir Water Level indicating reservoir Time Scale (T_*) and Reservoir depth Scale (H_*) with respect to reservoir water level is shown in Figure 3.

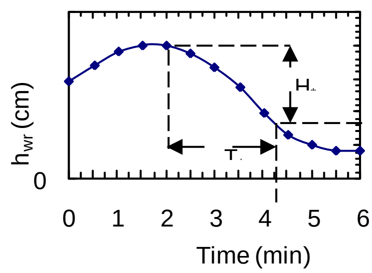

Figure 3. A Typical Variation of reservoir Water Level indicating reservoir Time Scale (T_*) and Reservoir depth Scale (H_*)

The photographs at different sequences of breaching of a fuse plug for a test run are shown in the Figure 4a to 4f to demonstrate the erosion of soil by breach flow over a broad crested type of weir. The crest height of weir and its location goes on changing with time. In Figure 4a the fuse plug is about to be overtopped by reservoir water, in Figure 4b, water just overtopped, where as in Figure 4c and 4d the weir type of flow is clearly visible and in the Figure 4e, it shows the breaching process has come to an end phase and finally in Figure 4f it shows the complete washout of fuse plug.

THE PHOTOGRAPHS AT DIFFERENT SEQUENCES OF BREACHING OF A FUSE PLUG FOR A TEST RUN

Figure 4a. Flow of water to the reservoir before overtopping the fuse plug model

Figure 4b. Flow of water on fuse plug crest after overtopping.

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Figure 4c. Vertical cut in the downstream face of fuse plug along with receding of toe erosion in upward direction

Figure 4d. Vertical of the breach of fuse plug and spillway type crest formation is seen.

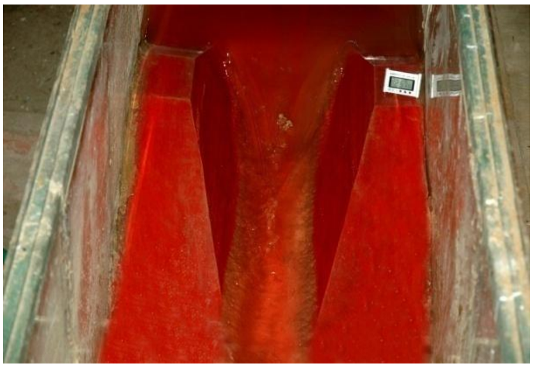

Figure 4e. Reduction in reservoir water level and total breaching process comes to final stage.

Figure 4f. Flow of reservoir water after the completion of breaching process.

ANALYSIS OF DATA

Location of Crest of Soil Bed Profile (X_m)

The height of crest of the soil bed is denoted as h_{cm}. It controls the flow passing through the breach section. Its location and height vary with the time of washout of fuse plug. Hence, it is necessary to know the crest location and its variation with respect to time. The position of the crest of the soil bed profile recedes from downstream top edge towards the upstream as the breach progress. From the recorded bed profile data at five locations along longitudinal direction during the breach, the longitudinal soil bed profiles are plotted at different time of breaching. The X_m and h_{cm} are found for different longitudinal soil bed profiles. The receding length X_m decreases exponentially with drop in water level (η) at the crest of the soil bed profile as shown in Figure 5. The relationship between X_m and η is depicted in Equation-1.

$$X_m=75.092e^{-0.0927(\eta)} \qquad (1)$$

Where, $\eta = h_{wr} - (h_{cm} + h_{wc})$
h_{wr} = Water level measured with respect to flume bed, during breaching
h_{cm} = Crest height of erodible soil profile with respect to flume bed
h_{wc} = Water surface level with respect to crest of the soil bed profile

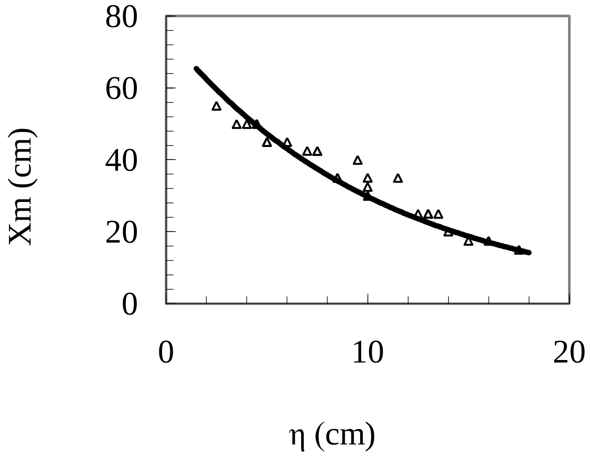

Figure 5. Variation of Receding Length of the Erodible Soil Crest (X_m) with the Drop in Water Level.

Soil Bed Profile: Downstream of Crest.

From the eroded soil profile as shown in Figure 2, it is observed that the soil bed profile, upstream of the crest varies gradually whereas the downstream surface varies very fast with respect to time. The non-dimensional height of downstream sediment surface profile in the form of h_c/h_{cm} is plotted against $[(X - X_m) / (X_{50} - X_m)]$ as shown in Figure 6 and the relation among them is shown in equation- 2.

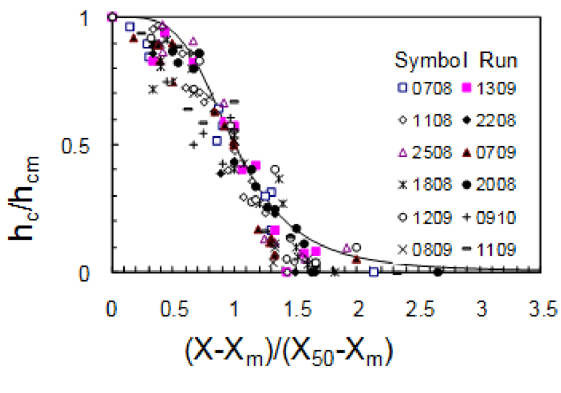

Figure 6.Variation of Nondimensional Erodible Soil Bed Profile Downstream of Crest.

$$\frac{h_c}{h_{cm}} = \frac{1}{1 + \left(\frac{X - X_m}{X_{50} - X_m} \right)^{4.0}} \qquad (2)$$

For estimated h_{cm}, X_m and $X_{50,}$ the $\mathbf{h_c}$ at any value of '**x**' downstream from the crest can be computed. The scales X_m, h_{cm} and X_{50} can be obtained from figure 7, 8 and 13 respectively.

The variation of non-dimensional X_m with nondimensional drop in water level at crest is shown in Figure 7. So for a given H_D and L_{LB}, X_M can be computed for known drop in water level. The relation between them is given as :

$$\frac{X_m}{L_{LB}} = 0.3313\omega^3 - 0.5175\omega^2 - 0231\omega + 0.49 \qquad (3)$$

Where, ω = (Drop in water level at crest/H_D)

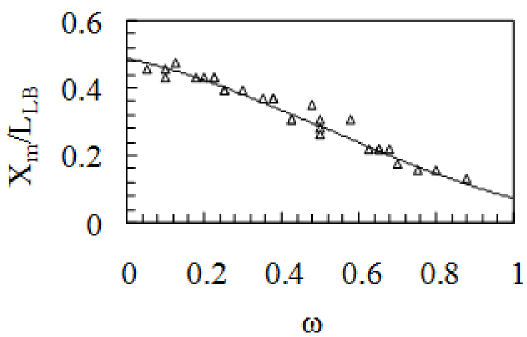

Figure 7. Variation of Nondimensional Receding Length of the Erodible Soil Crest with Nondimensional Drop in Water Level at the Crest.

Crest height of soil bed

During the breaching of fuse plug, the crest height of erodible bed profile can be obtained from Figure 8 provided t_{50}, the time at which the erosion of 50 % of the h_{cm} takes place is estimated.

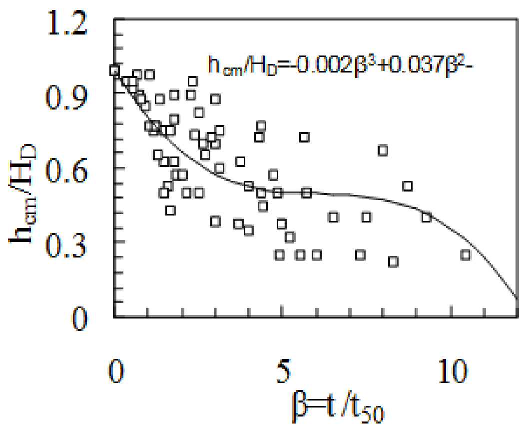

Figure 8. Variation of nondimensional Crest Height (h_{cm}/H_D) with Nondimensional Time (t/t_{50}).

The time scale t_{50} can be obtained for any given reservoir and fuse plug by knowing T_*, H_* and H_D from Figure 12.

Reservoir Time scale and Length scale

In order to predict the breach characteristics of the fuse plug, the only observation that may be possible to measure during the breaching is the reservoir water level variation with time as shown in Figure 3 as a typical case. Considering this as the major information available to develop scales for length and time, the gradient of water surface $\Delta h_{cm}/\Delta t$ is plotted against time as shown in Figure 9. To obtain t_{50}, the reservoir time scale (T_*) and depth scale (H_*) can be obtained from Figure10 and Figure 11 respectively. The soil resisting velocity (V_{SR}) used in Figure 10 and 11 is as follows:

$$V_{SR} = \sqrt{\frac{\Delta\rho}{\rho_w} g d_{50} \tan\phi + \frac{c}{\rho_w}}$$

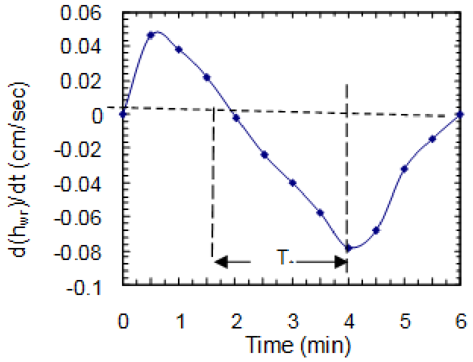

Figure 9. Variation of Rate of Reservoir Water Level with Time indicating Time Scale (T_*)

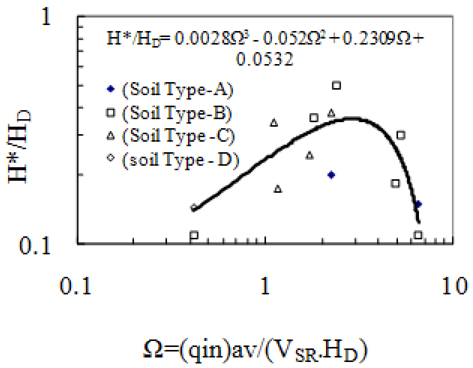

Figure 10. Variation of Nondimensional Reservoir Drop with Average inflow Discharge intensity, Soil Resisting Velocity and Height of the Fuse Plug.

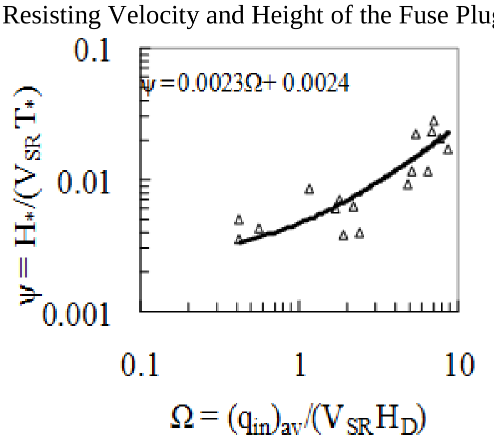

Figure11.Variation of Nondimensional Reservoir Time Scale with Average inflow Discharge intensity, Soil Resisting Velocity and Height of the Fuse Plug.

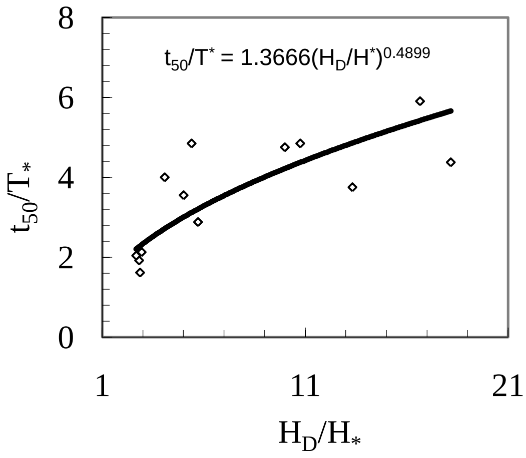

Figure12.Variation of Nondimensional Time Scale of Erodible Soil Bed Profile (t_{50}/T^*) with Reservoir Length Scale (H^*) and Height of Fuse Plug H_D.

The non-dimensional variation of X_{50} with non-dimensional time is shown in Figure13 for a given $T_*$and L_{LB} , the X_{50} can be obtained during the breaching.

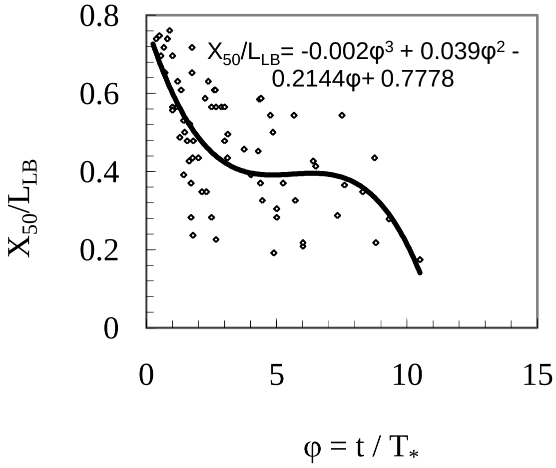

Figure13.Variation of Nondimensional Soil Profile Length Scale (X_{50}) With Nondimensional Time (t)

Flow Chart to predict Soil bed profile height (h_c) at any X value during the breaching

The algorithm to predict the h_c at any location 'X' of fuse plug and at any time during the breach process is shown in the flow chart of Figure no.14. This will enable to compute breach flow and sediment load eroded with time of breaching.

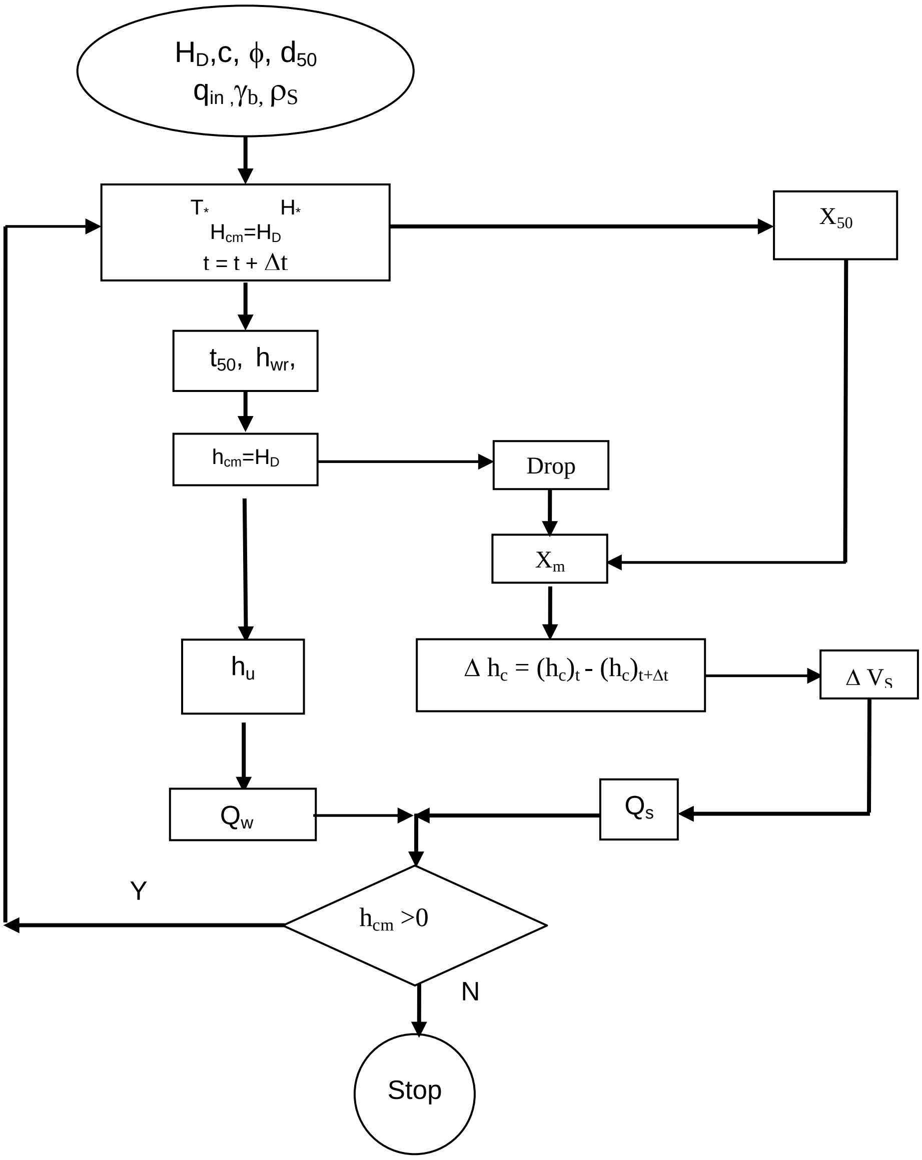

Figure 14. Flow Chart to Compute the Bed Soil Profile Height h_c at any 'X' Value to Compute Breach Flow and Soil Eroded with Time.

CONCLUSION

A methodology is suggested to obtain changing longitudinal sediment profiles of a fuse plug in an earthen dam due to overtopping flow over it from reservoir. This is essential to compute breach flow and sediment load eroded with time of breaching. The computation of Q_w and Q_s will help to ascertain how quickly the excess flood water from the reservoir can safely be released to the downstream of the dam through the fuse plug.

APPENDIX – NOTATIONS

B_{ft} **:**Top Width of fuse plug
B_{fb} **:** Bottom width of fuse plug
d_{50} **:** Median particle size of the soil
$H*$ **:** Reservoir length scale used in fuse-plug analysis
h_c **:** Sediment bed height at any location ‘x’ from the Origin chosen.
h_{cm} : Crest height of erodible soil profile with respect to flume bed
h_{wr} : Water surface level of reservoir with respect to flume bed
h_{wc} : Water surface level with respect to crest of the soil bed profile
h_{wd} **:** Downstream (near toe) water level from flume bed.
H_D **:** Height of fuse plug
h_u **:** Water head over the crest of the sediment bed.
h_w : Water level
L_{LB} **:** Longitudinal length at bottom of fuse plug
L_{LT} **:** Longitudinal Top length of Fuse Plug
Q_w **:** Breach water discharge
Q_s :Sediment discharge at any time ‘t’
q_{in} : Inflow discharge intensity
t **:** Time (in seconds, minutes and hours)
T_* **:** Reservoir time scale used in fuse-plug
t_{50}: Time at which 50% maximum crest (h_{cm}) erosion has taken place
X: Distance along the flow, from the origin of the fuse plug
X_{50}: The distance at which $h_c = 0.5h_{cm}$
X_m: Value of X at $h_c = h_{cm}$
V_{SR} : Soil resisting velocity

d_{50}	:	Median particle size of the soil
ϕ	:	Angle of friction of the soil
c	:	Cohesion of soil
γ_b	:	Bulk density of soil fill in fuse plug
ρ_S	:	Density of sediment particle
ΔH	:	Difference in water level between upstream and downstream of the fuse plug
ρ_w	:	Density of water
$\Delta\rho$		$(\rho_S) - (\rho_w)$
w	:	Optimum moisture content of soil

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