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Flow over an Erodible Broad Crested Weir

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ABSTRACT
The overtopping flow of water over an earthen embankment causes erosion of soil from its surfaces and the eroded surface of the embankment acts as a Broad crest weir. But the longitudinal profile of the weir goes on changing with time of erosion. Hence crest height of the weir goes changing in accelerated flow condition. In this paper, the discharge equation for this type of flow situation is established for different types of soils used in the embankment. Then, the experiments have been carried out as the analogous rigid beds of the captured eroded profiles at any time of erosion of the broad crested weir to compare the discharge equation and to study the energy loss in dislodging the soil from the surface of the weir and transporting them down stream.
Key word: Breach Flow (Q_w), Head of water over the crest (h_u), Crest height (h_{cm}).

I. Introduction

Dams play a major role in managing surface water resources in a planned way to bring economic development of a nation. There are various types of dams constructed around the globe, earth dams are the most common type and constitute the vast majority of dams. Among the dams, earthen dams are more susceptible to failure. The main cause of the failure of an earthen dam is due to overtopping [2]. The causes may be due to improper design, excessive sedimentation of reservoir, adopting erroneous reservoir operational rules, or due to unexpected flash flood. When dam fails, large quantity of stored water is released causing disaster in the downstream region [7]. Hence, fuse plug is provided to protect the dam against catastrophic failure. Fuse plug works as a safety valve of an earthen dam [8]. 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, Fuse plug 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. The fuse plug soil embankment acts as a broad crested weir during the overtopping flow over it [10, 9]. 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. In this regard, with physical model of fuse plug experiments are carried out in the Hydraulic Laboratory, University College of Engineering, Burla, Odisha, India.

II. Review of literature

The prevention 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 considerable body of literature on earthen dam breaching due to overtopping flow is available. 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.

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.

III. Experimental Setup and Data Acquisition

The experiments on washout behavior of fuse-plug, which behave as broad crested weir, were carried out in the flow hydraulics laboratory of University College of Engineering, Burla, Odisha, India. The flume used for the experiments is a tilting flume of 15 m long, 0.6m wide and 0.6m in height. Figure 1(a) and (b) shows the detailed of flume used for the experiment.

The model of fuse plug 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 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 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 from the historical failure cases given by Singh and Scarlators (1988). Figure 2 shows the detailed plan, longitudinal section, cross-section of fuse plug.
The experiments are carried out in two phase's viz. (A) On mobile sediment bed to establish $Q_w \sim h_u$ relationship (B) on analogous rigid bed of mobile bed to study the energy loss due to dislodging of sediments from fuse plug and transporting the same downstream.

3.1 Source of soil used as Fuse plug fill material

In the experiments of phase-A, different types of soil were used as fuse plug fill materials. These soils were collected from the near by 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 shown in the Table – 1.

Type of soil	d_{50} (mm)	ϕ (degree)	C (KPA)	γ_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

The experimental data of Verma [1995] is included only for developing $Q_w \sim h_u$ relationship. He has experimented on non- cohesive soil embankment. The flow behavior an analogous rigid bed of erodible surfaces of the weir during the process of erosion is studied which help to estimate the loss of flow energy in the process of erosion.

3.2 Preparation of fuse plug model

The wooden fuse plug model block was fitted inside the flume at a distance 6mtr. from the inlet of the flume. The open trapezoidal fuse plug section was filled with wet soil with proper compaction layer by layer till the fuse plug model dimensions were achieved. The water level (h_w), bed level (h_c) at different longitudinal position as shown in figure 3 with respect to time were recorded manually using point gauges by five persons referring to a common digital clock. From this basic data other relevant data are computed.

3.3 Flow Parameters

The head of water over the crest of the sediment bed during fuse plug breach is noted as (h_u). This is the difference between reservoir water level (h_{wr}) and crest of sediment bed profile (h_{cm}) as: $h_u = h_{wr} - h_{cm}$

The water discharge *(Q_w)* flowing over fuse plug is computed from the governing equation of continuity of flow [11] as follows:

$$Q_W - Q_{in} = A_s \frac{dh_{wr}}{dt} \quad (1)$$

Where

Q_{in} = Inflow discharge in to the reservoir, which is kept constant throughout the experiment and is measured after completion of breaching of the fuse plug.

A_s = Water surface area in the reservoir (constant in the present case as flume was prismatic),

$\frac{dh_{wr}}{dt}$ = Rate of water level variation in the reservoir.

In the above Equation (1), $\boldsymbol{Q_{in}}$, is a known quantity and is constant through out the experiment which is measured at the end of the experiment from the sharp crested rectangular were placed at the end of the flume and the water level variation *(dh_w / dt)* in the reservoir can be obtained from the measured water surface *(h_{wr})* with time. Thus the outflow discharge $\boldsymbol{Q_w}$ can be computed.

3.4 Outflow Discharge Relation

The outflow discharge $\boldsymbol{Q_w}$ computed from continuity equation is plotted against the head of water acting over the erodible crest *(h_u)* as shown in the Figure 4. It may be observed from weir type flow that Q_w varies almost linearly with h_u instead of $3/2$ power law variation as in the case of weir flow. This variation in power law may be due to energy spending in eroding the soil from solid bed during the breach process [14]. This analysis is further carried out for computing coefficient of discharge C_d based on the weir type flow as:

$$C_d = \frac{Q_W}{\left(\frac{2}{3}L\sqrt{2g}\,h_u^{\frac{3}{2}}\right)} \quad (2)$$

The computed value of C_d is plotted against h_u/h_{cm} as shown in Figure5, where h_{cm} is the height of the crest above the flume bed level. It may be observed that as h_u/h_{cm} increases, C_d decreases.

The regression analysis for the relation between them can be written as:

$$c_d = 0.48\left(\frac{h_u}{h_{cm}}\right)^{-0.25} \quad (3)$$

Combining both the Equation (2) and (3), an equation for discharge Q_w can be written as:

$$Q_w = 0.32L\sqrt{2g}\,h_u^{1.25}h_{cm}^{0.25} \quad (4)$$

The outflow discharge depends on the crest height (h_{cm}) of erodible sediment bed profile along with the head of water over the crest as shown in Figure (4)

From the above regression analysis as shown in figure 5 for (C_d), the power law relation is developed.

There are some scatter of the data is noticed. To get the mean curve the frequency analysis is carried out. The mean (μ) and standard deviation (σ) for this analysis are -0.0437 and 0.174 respectively as shown in fig. 6.

In this analysis, the standard deviation indicates the average order of fluctuation associated with the measured data. In x-axis, range is plotted which mean difference between the observed and fitted value of the C_d.

IV. Study on Analogous Rigid Bed Profile

4.1 Discharge Characteristics

The erodible bed profile is built using cement cover over the chosen mobile bed profiles of selected experiments runs to make rigid bed profile. This is called as the analogous rigid bed profile of eroded sediment profile. In the previous section the relation between discharge and the flow depth was found out. From the relation it was found that discharge over the erodible crest do not follow weir type flow. The value of exponent of the head acting over the erodible crest is of order one. In this section similar relationship among Q_w and h_u is studied. From this study it is found that the value of the exponent of the head acting over the rigid bed profile is of the order of 3/2. It means the flow over the rigid bed profile follow the weir type flow. To verify this difference in flow behavior over the mobile beds and their analogous rigid bed profiles eleven numbers of rigid bed profiles were prepared keeping in mind to represent the flow profiles of different runs with different fuse plug fill materials. Experiments were carried out over those rigid bed profiles with variation of inflow discharge over the model. Rigid bed profiles were constructed with utmost care to maintain the same roughness characteristics of the mobile bed. The discharge and head relations are plotted for the rigid bed profile as shown in Figure 7. The relation among Q_w and h_u is given as:

$$\frac{Q_W}{L} = h_u^{1.485} \times 19.5 \quad (5)$$

Where average width of the fuse plug, L = 28.5cm. From the Equation (5), the coefficient of discharge works out as 0.66. In the present study it is found that the flow takes place through the average width, which is smaller than the full width of fuse plug. Such type of flow is known as contracted weir type flow. The discharge considering the contraction of either side of rigid portion of the fuse plug can be obtained by using effective width (L_{eff}). This effective width can be computed by using Francis Formula as:

L_{eff}= (L-0.1n h) Francis Formula
L_{eff}= (L-0.2h_u) (6)

Here, n = Number of end contraction by using this effective length the discharge relationships is analysed and shown in the Figure 7. The Equation can be written a $\frac{Q_W}{L_{eff}} = h_u^{1.51} \times 20$ (7)

The Coefficient of discharge, c_d is computed as 0.68. From this analysis it is noticed that the flow characteristics over rigid bed crest follows exactly the weir relation. But the flow characteristics over the mobile bed crest does not follow the standard weir relation. It may be postulated that the crest level goes on changing rapidly with time due to erosion, so, some flow energy is spent in eroding the soil fill on fuse plug and transporting the same. Probably this may be the reason for the deviation of discharge formula for erodible weir from rigid weir profile.

4.2 Energy Loss Characteristics

During the process of erosion of soil over the fuse plug model, some energy is lost. This energy loss takes place due to energy spent in eroding and transporting the sediment material. Energy level is computed at upstream of fuse plug (E_a) and the downstream of fuse plug (E_e) respectively. The difference in energy level between upstream and down stream of the erodible weir is known as energy loss during the process of erosion. This energy ratio E_e/E_a is plotted against h_u/h_{cm} as shown in the Figure 8(a&b).

It is observed that h_u/h_{cm} increases as energy ratio E_e/E_a increases. It is noticed from the Figure that h_u/h_{cm} reaches to a higher value of the order 0.3, after that the curve remain almost horizontal. Because the energy level (E_e) almost nearly same to the energy level (E_a) after complete washout of soil bed from the erodible weir.

V.Figurs

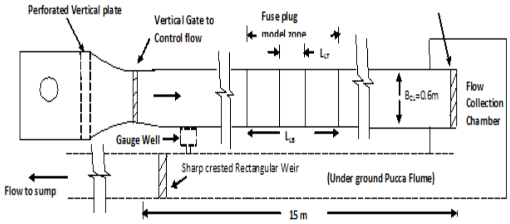

Fig.1a. PLAN VIEW OF TILTING FLUME WITH FUSE PLUG MODEL

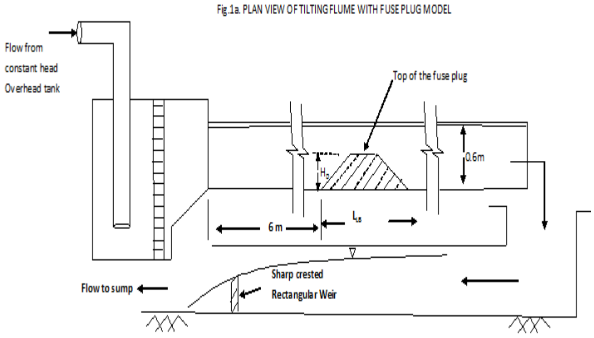

Fig. 1b. LONGITUDINAL SECTIONAL ELEVATION OF TILTING FLUME WITH FUSE PLUG

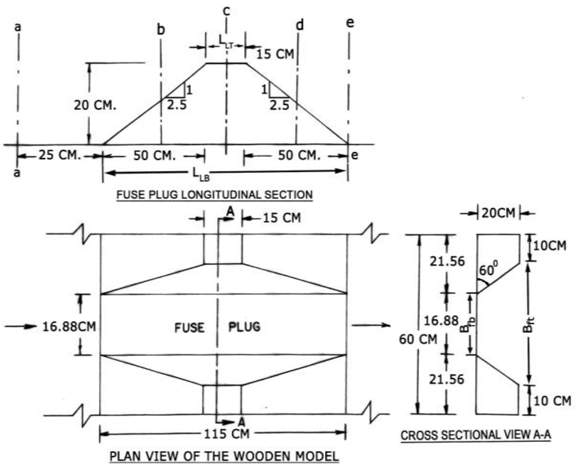

Fig. 2. Fuse plug model in plan and sectional view

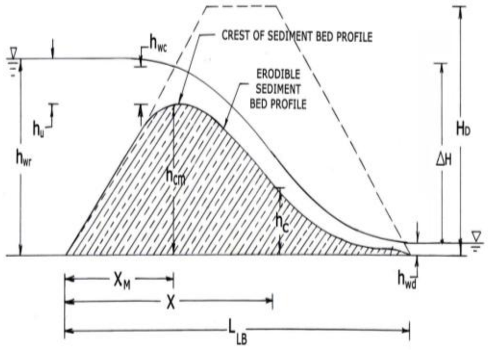

Fig.3. Definition Sketch for the Scales X_m , L_{LB} and h_{cm}.

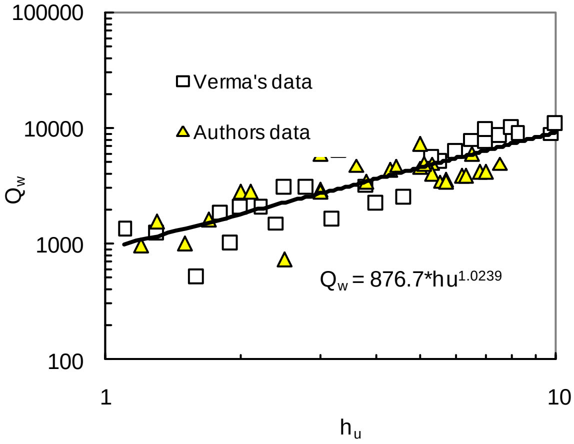

Fig 4 : Relation between head of water over erodible sediment crest (h_u) with outflow discharge Q_w

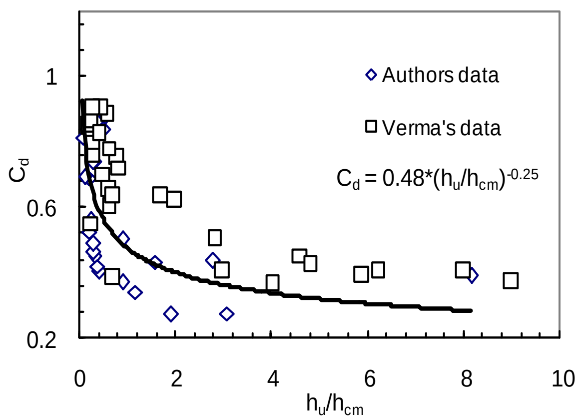

Fig.5. Variation of co efficient of discharge (C_d) with ratio of head of water over erodible sediment crest to the height of the erodible crest.

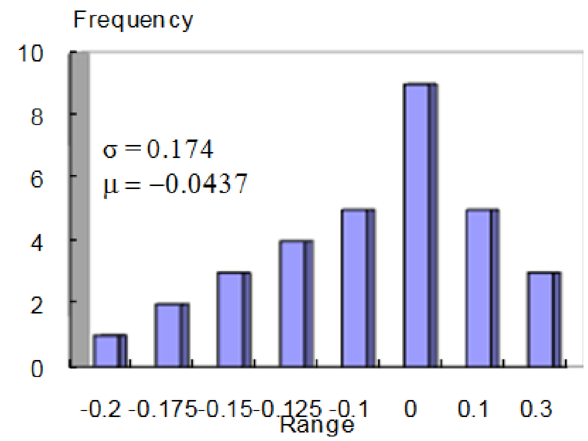

Fig 6. Frequency analysis of deviation of discharge coefficient from Fitted mean curve.

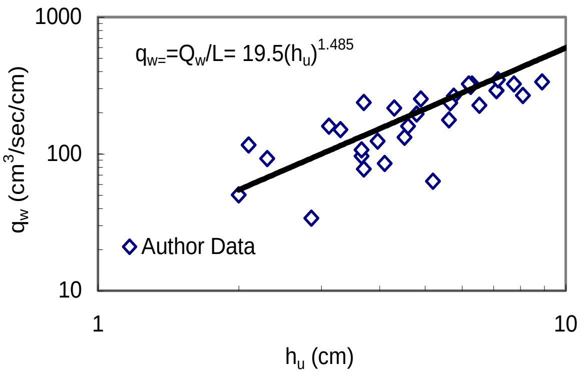

Fig.7. The relation of head of water over analogous rigid sediment bed crest with its corresponding outflow discharge intensity (q_w) without considering contraction length of weir.

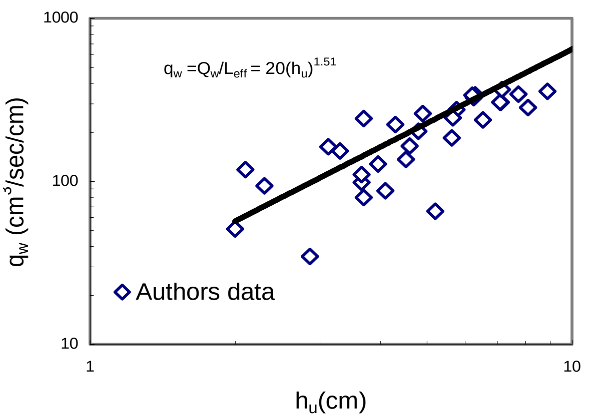

Fig 8 (a). The relation of head of water over the crest of analogous rigid sediment bed with its corresponding out flow discharge intensity (q_w) by considering the contraction length of weir.

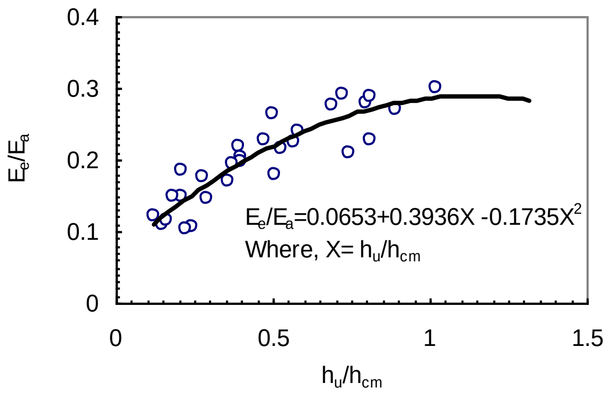

Fig. 8(b).Variation of energy ratio between downstream and upstream of fuse plug to the ratio of head of water over the rigid crest of analogous erodible sediment bed to its crest height

V. Conclusion

The discharge relation for an erodible broad-crested weir is established with different soil properties. The Coefficient of discharge, C_d is computed as 0.68. The flow characteristics over rigid bed crest follows exactly the weir relationship. Whereas the flow characteristics over the mobile bed crest does not follow the standard weir relationship. The ratio h_u/h_{cm} increases as energy ratio E_e/E_a increases. From the study is found that h_u/h_{cm} reaches to a higher value of the order 0.3, after that the curve remains almost horizontal. Such information will help the design engineers for similar type of study in future.

Notation

A_s **:** Reservoir Water surface plan area
B_{ft} **:**Top Width of fuse plug
B_{fb} **:** Bottom width of fuse plug
C_d **:** Discharge coefficient of erodible weir
d_{50} **:** Median particle size of the soil
E_a **:** Upstream energy head
E_e **:** Energy level at the downstream end of the fuse plug
h_c **:** Sediment bed height at any location ‘x’ from the Origin chosen.
h_{cm} **:** Crest height of erodible sediment profile
h_{wr} **:** Water surface of reservoir
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.
L_{LB} **:** Longitudinal length at bottom of fuse plug
L_{LT} **:** Longitudinal Top length of Fuse Plug
Q_w **:** Breach water discharge
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 $h_c = h_{cm}$
ϕ **:** Angle of friction of the soil
σ **:** Standard deviation of a variable
μ **:** The mean value of variable
γ_b **:** Bulk density of soil fill in fuse plug
ΔE **:** Energy variation
$(E_e)_{mobile}$ **:** Energy level at toe of the fuse plug for mobile sediment bed at any time of breach in fuse plug washout study.
$(E_e)_{rigid}$ **:** Energy level at toe of the fuse plug for rigid sediment bed at any time of breach in fuse plug washout study
ΔH **:** Difference in water level between upstream and downstream of the fuse plug
ρ_S **:** Density of sediment particle
ρ_w **:** Density of water

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