River flow 2008-Altinakar, Kokpinar, Aydin, Cokgor & Kirkgoz (eds)
© 2008 Kubaba Congress Department and Travel Services ISBN 978-605-60136-1-4

Breach formation in a fuse plug lateral weir

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ABSTRACT
A fuse plug consists of a collapsible dam installed on river embankments in order to divert water excess. In case of extreme flood the fuse plug has to collapse in order to evacuate part of the flow towards a selected flooding area. The flood control device requires reliable construction techniques and it needs a good environmental integration. Therefore the designed fuse plug consists of a standardized sand layer with trapezoidal cross section. This device is located in the upper part of the permanent river embankment.

The flood evacuation scenario can be described as follow: A rupture will occur at a predetermined location on the top of the fuse weir and a breach will be initiated due to the erosion provoked by the overflow. The opening will be progressively enlarged until reaching its final width. The initial failure is facilitated by implementation of a water intake on the top of the dam. This leads the water inside the sand dam through coarse aggregate layer. The objective to create the quick development of an internal erosion can thus be achieved.

In this study, three 1:3 scaled models with a 40 cm high fuse plug were tested. This concept allowed developing a 3.5 m length diverting opening within 10 minutes. At the prototype scale, the diverting capacity reaches 1.3 m^3/s m after about 20 minutes, through breaches initiated every 10 m in a 1.2 m high fuse weir.

Keywords: Fuse plug, flood control, dam breach formation, lateral weir

1 INTRODUCTION

Land protection against floods generally consists in increasing the river flow capacity. Nowadays, in Switzerland, the flood management strategy admits the inundation risk (Boillat, 2005). This approach allows creating preferential schemes of river diversion under extreme flood conditions. Therefore, part of the territory will be flooded to protect other regions (Boisseau et al., 1997).

In such cases, the flow will be diverted over a side weir. This typical case of spatially varied flow has been subject to numerous investigations (e. g. Subramanya & Awasthy, 1972 and Hager, 1987). Usually, the main design objective is to estimate the total overflow discharge considering a fixed channel bottom. However, a morphological behavior of the mobile bed has to be taken into account in natural rivers, as revealed by Rosier et al. (2005, 2006).

Nevertheless, in any case the lateral overflow is related to the hydraulic head over the weir crest, which implies that the overflow will start before the water level reaches the crown level of the embankment. In order to delay the initiation of the flow diversion, a fuse weir has to be installed on the upper layer of the dam. The development of an automatic fuse plug lateral weir was the objective of the present study.

The research was developed in the frame of the project DIFUSE whose purpose was to get know-how about flood control structures. In this context, the University of Applied Sciences of Fribourg focused towards the development of a river dam crowning, permitting a safe flow diversion above a predefined river water level.

Even the objective is the protection of selected areas against inundations, the fuse plug lateral weirs should implicitly avoid an abusive overflow on the sacrificed land. As a result, the system should be able to resist until the safety level is reached, and then promptly furnish its diverting capacity. This effect will be obtained here by causing the collapse of a fuse weir (Figure 1).

Therefore the pursued procedure consists in coordinating the opening of successive breaches thanks to fuse plugs installed on the crowning body of the river embankment. This will favor the erosion between the breaches, accordingly with the increase of the flow (Figure 2). The length of the cleared breach has to be relied to the needed diverting capacity.

The main difficulty consists here in the opening process development, especially the setting up of the fuse device as well as the time control of the increasing length on the lateral weir.

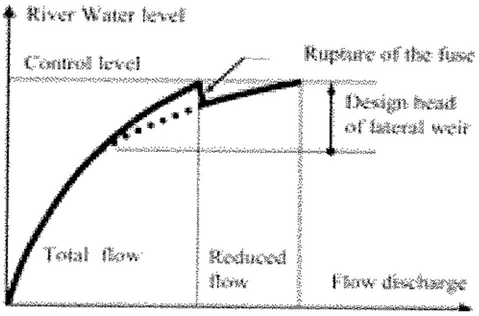

Figure 1. Rating curve modified by the diverted flow

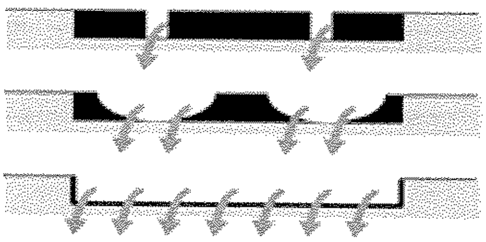

Figure 2. Breach opening process

2 BREACH OPENING CONCEPT

In order to refer to realistic operating conditions, the following design values were taken from the third Rhône rehabilitation project in Switzerland:

- Spillover: 1 to 1.5 m3/s.m
- Design head: 1 to 1.5 m

Throughout the examination of different technical solutions (Volkart, 1989), environmental criteria were considered to conceive a landscape integrated control structure. Therefore the selected configuration proposes a fitting of local standard aggregates, inside a trapezoidal cross section body, superimposed to the main body of the embankment.

Several publications (Rozov, 2003 and Franca, et al., 2000) describing the evolution of breach opening during flood events reveals that the rupture is mostly related to indelicate inclusion of foreign bodies: trees, poles, walls, etc. (Armbruster-Veneti, 1999). Some of the compromising situations report burrows which were horizontally excavated from the upstream face of the dam. The idea therefore is to locally include a specific device to favor the quick increase of a destructive hydraulic gradient inside the crowning body of the dam.

The conclusion of preliminary investigations is that the most appropriate method to engender breach opening will be the erosion of the porous structure caused by interstitial flow.

3 SETTING UP OF THE FUSE DEVICE

The internal structure of the fuse device was developed on two scaled physical models, referred as "narrow" and "broad" models. Considering the order of magnitude of the reference case and in order to reduce scale effects, the fuse device was reproduced at geometrical scale 1/3. The crowning body is therefore characterized by the following values:

- Height: 0.4 m
- Basis width: 1.4 m
- Embankment slope: 2:3
- Crowning width: 0.2 m

3.1 Narrow model

With the perspective to investigate a large number of configurations, the crowning body was first reproduced in a 15 cm wide experimental channel with lateral glass walls (Figure 3). The model was built of dry sand with a grain size distribution between 0.4 and 1 mm. Standard distribution for sand actually lies between 0 and 3 mm. The sand permeability was measured as 2×10^{-3} m/s.

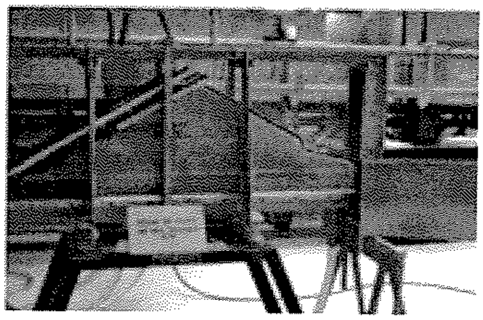

Figure 3. Narrow model experimental setup

The upstream face of the dam is made impervious. Once the water level reaches the pre-defined control level, a valve opens and supplies water into the drainage layer underneath to feed the fuse device. The valve operation simulates the water delivery issued from a constant water level reservoir. Privileged ways are progressively initiated in the porous layer constituted of expanded clay pellets.

The most significant parameter is the time interval between the water submersion initiation and the collapse of the fuse plug. The time lag is measured by an ultrasound sensor installed over the crowning surface of the dam.

The final selected solution is characterized by a 10 cm layer of coarse granules on the upstream face of the dam, connected to a 10 cm thick horizontal layer of same material, located mid height in the fuse part up to the vertical axis of the dam. With this configuration, the collapse time could be reduced to 2.5 minutes while the characteristic duration for other variants was about 12 minutes.

3.2 *Broad model*

Once the fuse concept and its vertical internal position of the porous layer were defined, its horizontal positioning had to be optimized. The objective was to test different transversal configurations getting fast, abrupt and well localized breaches. For this purpose, experimental tests were conducted in a 1.20 m wide channel, with the same vertical fuse plug concept and identical geometrical characteristics as in the narrow model (Figure 4).

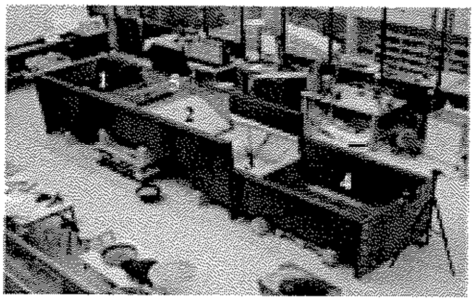

Figure 4. Broad model experimental channel. (1) upstream supply reservoir, (2) fuse plug location, (3) sand trap, (4) restitution basin (5) level measuring ultrasound probes

The iterative working out process was adopted again by combination of following alternatives:

- The 10 cm thick layer of coarse aggregate is either missing, central positioned, or built throughout the transversal width of the dam. An additional particular configuration was installed for test N°8 consisting of a mid height central layer ending with extended lateral wings in T-shape.
- The vertical wall and the horizontal base framing the crowning fuse are either smooth or rough.
- Sand, with a grain distribution between 0.4 and 1 mm, is identical for all tests (desiccated and compacted layers) except for trial n° 5 where dry sand was used.

In all cases, the water supply was provided through the corresponding width of the drain layer.

The characteristics of the main experimental tests conducted on the broad model are summarized in Table 1.

Configuration n° 4 revealed as the best solution regarding the aimed objectives. The narrow centered drain creates a well located breach in approximately 2.5 minutes (Figure 5). It could be observed that the frame roughness and the sand water content have a significant influence on the results.

Table 1. Main tested configurations characteristics

Configuration	1	2	3	4
Sand	wet	wet	wet	wet
Water supply	broad	broad	centered	centered
Internal drain	none	none	none	centered
Frame roughness	smooth	rough	smooth	rough
Breach period	4'48	3'28	10'31	2'35
Sliding form	linear	[illegible]	linear	[illegible]
Breach location	random	both sides	random	centered

Configuration	5	6	7	8
Sand	dry	wet	wet	wet
Water supply	centered	broad	centered	centered
Internal drain	centered	broad	centered	T-shape
Frame roughness	rough	smooth	rough	smooth
Breach period	3'13	2'56	2'48	1'56
Sliding form	[illegible]	linear	[illegible]	linear
Breach location	centered	random	centered	centered

Figure 5. Breach opening on the downstream face of the fuse crowning body

4 BREACH LATERAL EXTENSION

4.1 *Experimental methodology*

Based on the "narrow" and "broad" models, a solution for breach opening in the fuse crowning could be developed. In both cases, experiments were achieved under frontal approach conditions, and focused on the breach opening period.

In order to examine the breaching process and its lateral extension under tangential flow conditions a third model was used in order to simulate the lateral weir behavior. This experimental setup as schematized in Figure 6 was supplied in closed circuit with a 400 l/s flow discharge.

In this case, the focus was put on the erosion progression caused by overflow. This information is required in order to define the adequate distance between two successive fuse plugs.

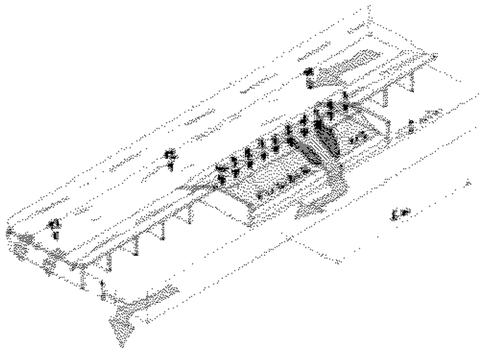

Figure 6. Schematic view of the lateral weir fuse plug model

The fuse crowning was reproduced over a 5 m length, with sand material (grain diameter D=0 to 3 mm and permeability $K= 4 \times 10^{-3}$m/s).

Sinking of the dam crest was measured continuously by 10 ultrasound probes and the water level in the channel by 3 additional ones. The water level in the channel was regulated by a weir at the outlet. At the beginning of the experiment the total discharge was evacuated by the channel. At the end, it was diverted through the opened breach in the fuse weir.

The vertical fuse structure was identical and at same scale than the previous ones (Figure 7). It was supplied through a rectangular mouth, arising at the control level on the upstream face of the embankment. The drain is compound of coarse aggregate wrapped in a geotextile membrane. The imperviousness of the upstream face of the dam is obtained by a PVC sheet up to the drain mouth.

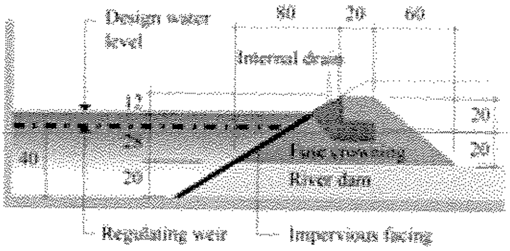

Figure 7. Cross section of the fuse crowning body

4.2 *Results*

The experiments conducted on the third model demonstrated the stability of the crowning body before reaching the water control level. They also confirmed the previous experiments focused on the breach opening process. It should especially be noticed that the breach opens perpendicularly to the main stream (Figure 8). This observation confirms the validity of frontal weir modeling to define a realistic fuse plug device.

Figure 8. Perpendicular breach opening on the lateral weir fuse plug model

The experimental results show that the increasing opening length of the breach develops in 2 stages. First, the overflowing stream axis at the breach location maintains a 90° angular direction related to the main flow. Later the angular difference (α_{bif}) becomes close to 70° degrees and the destruction of the crowning develops quasi linearly towards downstream. A 2.0 m wide opening was released in 4.5 minutes and the maximum opening size of 3,5 meters, limited by the extent of the model, was reached after 9.5 minutes (2.5 minutes for breaching time of the fuse plug included). Globally, the increasing opening length time-function could be defined by equation (1), valid for t>2 ½ minutes.

$$B = 1.14 \cdot \left[(t - 2.5)/60 \right]^{0.3} + 0.43 \qquad (1)$$

where B [m] is the length of the opening and t [min] the time.

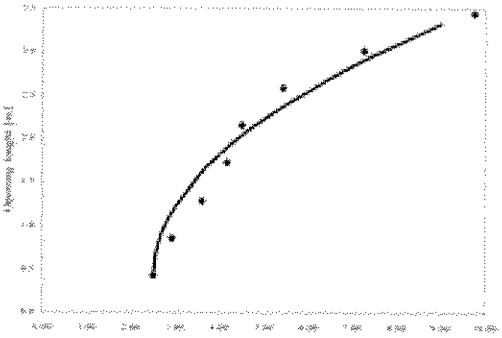

Figure 9. Opening length time-function

The diverted flow Q_{div}, is deduced from the measured water level, as well as from the network flowmeter. The drainage coefficient (C_d) is calculated according to the broad-crested weir formula:

$$Q = C_d \cdot B \cdot \sqrt{2g} \cdot H^{3/2} \qquad (2)$$

The bifurcation coefficient (C_{bif}) specifies the influence of the bifurcation angle (α_{bif}) on overflow capacity. It is calculated dividing the drainage coefficient (C_d) by the corresponding value for a frontal flow on a broad-crested weir $C_{bif} = C_d / 0.385$. Therefore the bifurcation coefficient is 1 when $\alpha_{bif} = 0°$ and 0.52 for $\alpha_{bif} = 90°$. Intermediate values are linearly interpolated. They are in good agreement with observations and with fitted values issued from literature (Lautrich ,1966).

5 PROTOTYPE SCALE APPLICATION

In order to apply the model test results to prototype scale, two distinct hydraulic phenomena have to be considered. On one side, the underground flow is responsible for breach opening, on the other side, free surface flow is responsible for the breach enlargement and for the amount of the diverted flow. Consequently, the respective parameters of both phenomena have to be transposed through distinct similarity rules.

In the next, parameters with index "m" refer to the model whereas index "p" refers to prototype.

5.1 *Flow similarity in porous environment*

The Reynolds number ($Re = V\ D/\nu$) is relevant for flow similarity in porous media ($Re_m = Re_p$). The velocity term is defined by the Darcy formula ($V = K\ I$) where K is the permeability parameter and I the hydraulic gradient. The length term (D) applies to the characteristic diameter of aggregates (often D_{10}).

As the cinematic viscosity (ν) and the hydraulic gradient (I) are identical in the model and in the prototype, it can be accepted that ($K_m = K_p$ et $D_m = D_p$). However, the Darcy formula is relevant only when the porous environment is stable. This condition is not satisfied when the fuse plug breaches. Experimental investigations refer to turbulence effects leading to the destruction of the massif, without giving out any similarity rule. However, first order approximations let think that D_m/D_p should stay between 1 and $(Lm/Lp)^{1/2}$. On this basis, it is suggested that the prototype crowning body can be realized with standard sand (0 to 3 mm), covering the grain size fraction used for the model tests (0,4 to 1,0 mm).

5.2 *Flow surface flow similarity*

Referring to the (L_m/L_p) geometrical scale and considering the Froude similarity, dimensional analysis allows defining the scale ratio for each parameter. Therefore time and discharge ratios become $t_p = t_m / (L_p/L_m)^{1/2}$, respectively $Q_p = Q_m / (L_m/L_p)^{5/2}$. Considering a 1/3 geometrical ratio between prototype and model, the corresponding main parameters are presented in Table 3.

Table 2. Correspondence between model and prototype of the overflow through the opened breach

Parameter		Model (1/3)	Prototype (1/1)
Upstream hydraulics head	H [m]	0.4	1.2
Breach opening lenght	B [m]	3.5	10.5
Breach opening period	t [min]	10	17.3
Diverted flow	Q [m³/s]	0.9	13.8
Unit diverted flow	q [m³/s*m]	0.3	1.3

Referring to the third Rhône river correction project in Switzerland, the total fuse length should approximately be 300 m long in order to divert 400 m³/s, considering a 1,2 m hydraulic head over the total length of the lateral weir. The fuse plug device could so be realized with 30 fuse elements, 10 m distant from each other. However, the water profile has to be considered for each particular application and the concept for successive breach openings has still to be developed.

6 RECOMMENDATIONS

The results presented above are rather conceptual and their application needs some additional considerations before execution. Although constructive details are to be developed, they can take the previously mentioned indications into account.

6.1 *Stability of the crowning body*

The upstream face of the embankment is submitted to the shear stress induced by the main river flow. In case of a water head of about H_p=1,2 m, a river longitudinal slope of about S=1 ‰ and an upstream embankment facing slope of ½, a simple vegetation cover would protect the crowning body from erosion. It has to be reminded that the considered breach opening concept provokes the erosion of the porous constitutive material through internal flow. The dislocation of the vegetation cover will so be obtained consecutively to internal erosion.

The stability of the crowning body before breach opening depends upon the imperviousness of its upstream facing. The choice of material for this purpose has to consider the dislocation capacity of the impervious layer during the breach opening. A clay layer can fulfill both conditions. Synthetic layers can also be considered, however, they should be layered in strips with an appropriate display.

Finally, the experiments showed that the downstream facing of the crowning body must not have a slope inferior to 2/3 in order to warrant a rapid breach opening. In this case, abundant and continuous percolations tend to appear at the base of the crowning. A draining interface between the crowning body and the supporting dam is also required in order to avoid an untimely release of the fuse plug. .

6.2 *Viability of the fuse crowning*

By convenience the fuse device was constituted of coarse aggregates. This device revealed functional in the laboratory but its viability under prototype conditions needs to be questioned: will the top rectangular mouth stay clear over the time? Can the coarse aggregate of the drain be clogged with fine particles? What kind of survey or maintenance will be needed?

To answer these questions, preference will be given to a flexible structure when compared to a rigid tubular installation constituting a solid element throughout the continuous crowning. To prevent the drainage system from clogging a geotextile membrane should wrap the coarse structure. This flexible envelope has however to be permeable in order to diffuse the internal pressure required to open the breach.

7 GENERAL CONCLUSIONS

A conceptual solution for the self destruction of the crowning body of a river embankment in case of superabundant flow could be developed. Based on successive experimental tests an integrated solution could be developed. The conceptual operating process is related to the activation of internal erosion through integrated drains as soon as the water level reaches the threshold limit. Additional developments are required in order to optimize the constructive aspects of the device even though the different trials allowed reviewing some essential practical points. The obtained results furnish a project design basis. Some additional attention is still needed for the operational development of the proposed solution.

ACKNOWLEDGEMENT

This project was financed by the Federal Commission for Technology and Innovation, the Swiss Federal Office for the Environment, the Road and River Department of Canton du Valais and the Buildings Insurance Company of Canton de Fribourg. This project was developed in partnership with the University of Applied Sciences Western Switzerland and the Laboratory of Hydraulic Constructions at the Ecole Polytechnique Fédérale de Lausanne in Switzerland.

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