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# THEORETICAL AND EXPERIMENTAL STUDY OF THE CONCRETE FUSE PLUGS WEIR

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## ABSTRACT

Reservoir dams are directly exposed to the impacts of climate change. These effects manifest as prolonged drought periods characterized by highly irregular inflows, intense rainfall events, and extreme floods. Such conditions contribute, among other consequences, to the early siltation of reservoirs and to the exceedance of spillway capacities in existing dams.

One of the feasible solutions to increase the storage capacity of reservoirs and enhance the safety level of existing dams involves reshaping the crest of the existing spillway. This approach involves a slight lowering of the original crest, followed by a substantial elevation using fuse devices. This configuration makes it possible to raise the normal reservoir level while ensuring safe and controlled behavior during extreme flood events.

The principle of the fuse system is based on the arrangement of independent concrete blocks placed side by side on the spillway crest. These elements exhibit slightly different characteristics so that each block overturns at a specific upstream water level, thereby ensuring a progressive increase in the discharged flow. This device, referred to as Concrete Fuse Plugs, was first investigated between 2004 and 2006. According to the literature, no design method has yet been established for this type of weir.

In order to better understand the functioning of this device and to propose a simple preliminary design method, theoretical and experimental studies were carried out at the University of Biskra. A comparative analysis between these two approaches was also conducted to assess their consistency.

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**Keywords:** Dam, storage capacity, flood spillway, self-stable weir, fuse systems, fuse plugs.

## INTRODUCTION

Reservoir dams, originally designed to store a specified volume of water and to discharge predicted extreme floods, are now facing the impacts of climate change. According to Ouamane et al. (2006a), this phenomenon has led to premature siltation of reservoirs and has rendered the capacity of many spillways insufficient in the face of newly observed extreme floods. These combined problems cause a reduction in storage capacity and compromise the safety of the structures. To address this, Ouamane et al. (2006b) suggest several alternatives, including remodelling or improving existing spillways, in order to compensate for the lost capacity and enhance dam safety.

In 1989, F. Lempérière introduced the concept of the fuse gate system, also known as the Hydroplus system. This device involves raising the crest of the existing spillway in order to increase the storage capacity of the reservoir or its flood discharge capacity (Falvey, 1995). According to Falvey (1995), these fuse gates, comparable to a fuse plug, operate like a labyrinth spillway where each gate represents one cycle. They are designed to overturn automatically at a predetermined reservoir level, thereby releasing the entire crest for the evacuation of extreme floods. Each fuse gate consists of three main components: a bucket (made of steel or reinforced concrete), a base, and an intake shaft connected to an internal chamber.

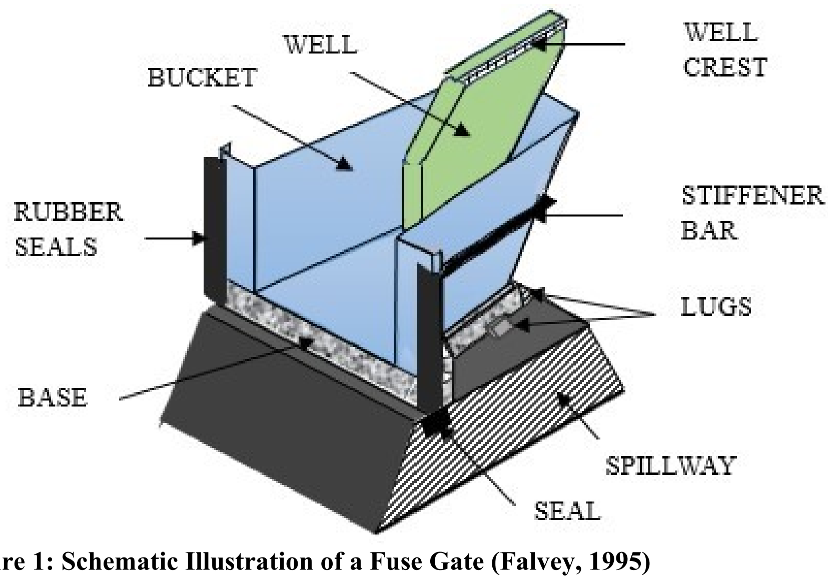



**Figure 1: Schematic Illustration of a Fuse Gate (Falvey, 1995)**

However, this system was patented by Hydroplus, making its implementation costly. To overcome this drawback, F. Lempérière, G.P. Vigny, and A. Ouamane (2006) developed a new fuse system, simpler and more economical, known as Concrete Fuse Plugs. These self-stable blocks stand out for their simplicity and safety compared to gated spillways, as their operation requires neither human intervention nor any external energy source.

Although concrete fuse plugs represent a promising alternative to self-stable devices, they remain insufficiently studied to establish a reliable preliminary design method. Their simple geometry and low construction cost nonetheless justify growing interest in analysing their behavior. In this context, a theoretical study based on the limit-stability principle, validated by reduced-scale model tests, appears relevant to optimize their dimensions and accurately predict the tipping height of each block.

## DESCRIPTION OF THE CONCRETE FUSE PLUGS SYSTEM

The Concrete Fuse Plugs provide an effective means of simultaneously increasing reservoir storage capacity and flood discharge capacity. Installed on the crest of existing spillways, they allow for the utilization of a portion of the water column between the normal water level and the maximum water level, while maintaining a high level of structural safety. This particularly economical solution proves relevant for the rehabilitation of older dams facing increasing siltation and the heightened frequency of extreme floods linked to climate change.

### Geometry of the concrete fuse plugs

Fuse plugs are massive concrete elements placed side by side on the weir crest. They remain self-stable until the upstream water level reaches a critical height that triggers their overturning. Their simple geometry allows for construction using either cast-in-place or precast concrete. Although they have a uniform height, their widths may vary from one block to another. Installed along the weir crest after a slight trimming of the existing crest, they form a watertight barrier thanks to plastic joints placed between the blocks and along the crest (joint running along the downstream edge of the block).

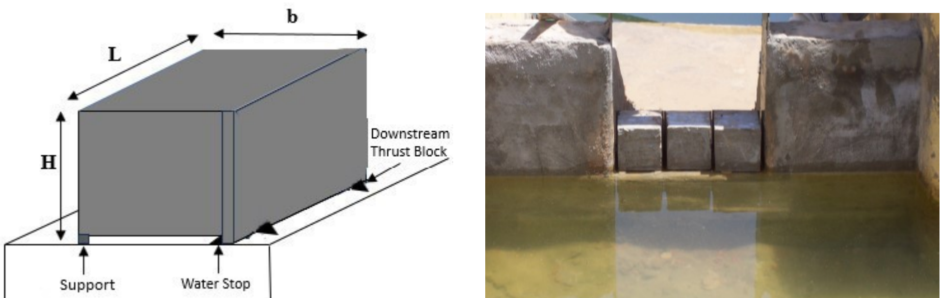



**Figure 2: Schematic Illustration of a Concrete Fuse plug**

**Operating principle of concrete fuse plugs**

The work of F. Lempérière et al. (2006) distinguishes two ways of accounting for uplift pressure at the level of the fuse plugs: a situation without uplift pressure and a situation with full uplift pressure. These two approaches lead to the definition of two types of fuse plugs.

The first type, designed to overturn before overtopping, is not subjected to uplift pressures. These concrete blocks generally have a large height relative to their length, which allows their thickness to be reduced.

The second type, designed to overturn after overtopping begins, bears a water head that can reach up to twice the concrete block's height. Under uplift pressure, the blocks can reach a length up to ten times their height, with a thickness that may be up to three times this height. This configuration provides high precision regarding the water level that triggers overturning, while reducing the requirements for joint watertightness, but at the cost of a larger concrete volume.

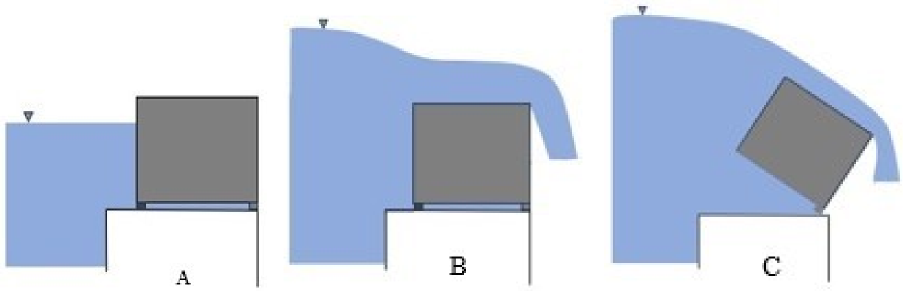



**Figure 3: The three operating phases of concrete fuse plugs**

Fuse plugs act as a crest raised and remain self-stable up to a predetermined upstream level. Their behavior varies with the water level:

- For a level ≤ the crest, they behave like a gravity dam, with each element resisting the hydrostatic pressure by its own weight.
- When the water exceeds the crest, they operate like a broad-crested weir, while remaining self-stable during this phase.
- In the case of a significant flood, the increased water depth induces uplift pressure beneath the plug, abruptly altering its equilibrium and causing it to overturn, thereby fully performing its role as a hydraulic fuse.

## PRELIMINARY DESIGN OF THE CONCRETE FUSE PLUGS

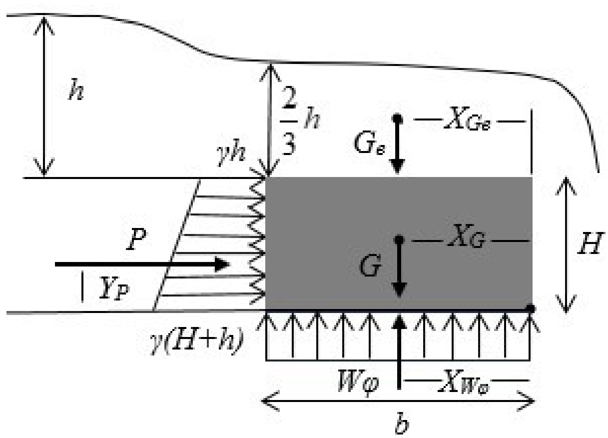
The design of concrete fuse plugs involves determining their geometric characteristics to ensure both hydraulic and mechanical performance. The height of the blocks, which is uniform along the entire length of the weir, is set based on the overflow depth and the desired crest elevation. The length, in turn, depends on the structural significance of the plug, construction constraints, and local site conditions.

The width varies from one element to another when each concrete block is calibrated to overturn under a specific water head; it thus serves as a parameter directly linked to the head that triggering the overturning.

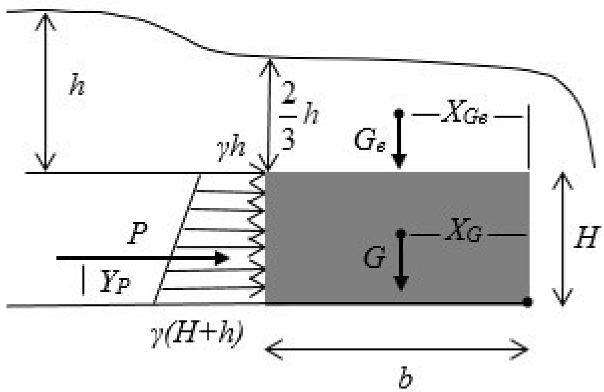
### Theoretical Analysis of the Concrete Fuse Plugs Stability

The theoretical study is based on analysis of the overturning stability of a self-stable block in order to determine the width at which overturning occurs under a predefined water height. The height and length of the block are set in advance.

The overturning is evaluated by calculating the moments applied about the downstream edge. overturning moments result from the hydrostatic pressure acting on the upstream face and, where applicable, from uplift pressure at the base for block sensitive to hydrodynamic effects. The stabilizing moments arise from the self-weight of the block as well as the weight of the water column above it. The flow over the plug is considered similar to that over a broad-crested weir; consequently, the water height along the entire length of the block is taken as 2h/3. The overturning occurs when the overturning moments exceed the stabilizing moments.




a- Block with Uplift Pressure




b- Block without Uplift Pressure

**Figure 4: Fuse Plug stability calculation diagram**

Where:

- $b$ = block width;
- $H$ = block height;
- $h$ = water head above the block;
- $\gamma$= unit weight of water;
- $\gamma_b$ = unit weight of concrete;
- $Ge$ = weight of the water above the plug;
- $G$ = weight of the block;
- $P$= hydrostatic force exerted by water on the upstream face of the plug;
- $W\varphi$ = force exerted by water at the base of the plug (uplift pressure).
- $X_{Ge}$ = moment arm of the weight force of the water above the plug;
- $X_G$ = moment arm of the weight force of the block;
- $Y_P$= moment arm of the hydrostatic force;
- $X_{W\varphi}$ = moment arm of the force exerted by water at the base of the plug (uplift pressure).

The block is subjected to the action of the weight of the water above it (*Ge*), its own weight (*G*), the hydrostatic force (*P*) acting on its upstream face, and the uplift force at its base (*Wφ*). Each of these forces generates a moment that either promotes or resists the overturning of the block (Fig. 4).

- Moment due to the weight of the plug:

$$M_G = \frac{\gamma_b H b^2}{2} \tag{1}$$

- Moment due to the weight of the water above the plug:

$$M_{Ge} = \frac{\gamma h b^2}{3} \tag{2}$$

- Upstream moment due to the hydrostatic force on the upstream face of the block:

$$M_P = \frac{\gamma(H+3h)}{6} H^2 \tag{3}$$

- Moment due to the uplift force at the base:

$$M_{W\varphi} = \frac{\gamma(H+h)}{2} b^2 \tag{4}$$

**Overturning Conditions**

Figure (4) shows the forces applied to a fuse plug, which generate stabilizing or overturning moments about the center of rotation (*O*).

When the upstream water level exceeds the weir crest, the flow invades the uplift pressure chamber, which corresponds to the case of full uplift pressure. The overturning moments then gradually increase with the rising water level, while the stabilizing moment remains constant, since the weight of the plug does not change.

When the water reaches and then exceeds the crest of the block, the overtopping begins, and the water head above the block generates an additional stabilizing moment that adds to the moment from the block weight.

To obtain a dimensionless representation, all overturning and stabilizing moments were normalized by the moment due to the weight of the block.

Figure 5 illustrates the evolution of these moments as a function of the upstream water head: as the water level rises, the overturning moments increase faster than the stabilizing moments, until the two curves intersect. This point defines the limit-stability condition, beyond which the block overturns.

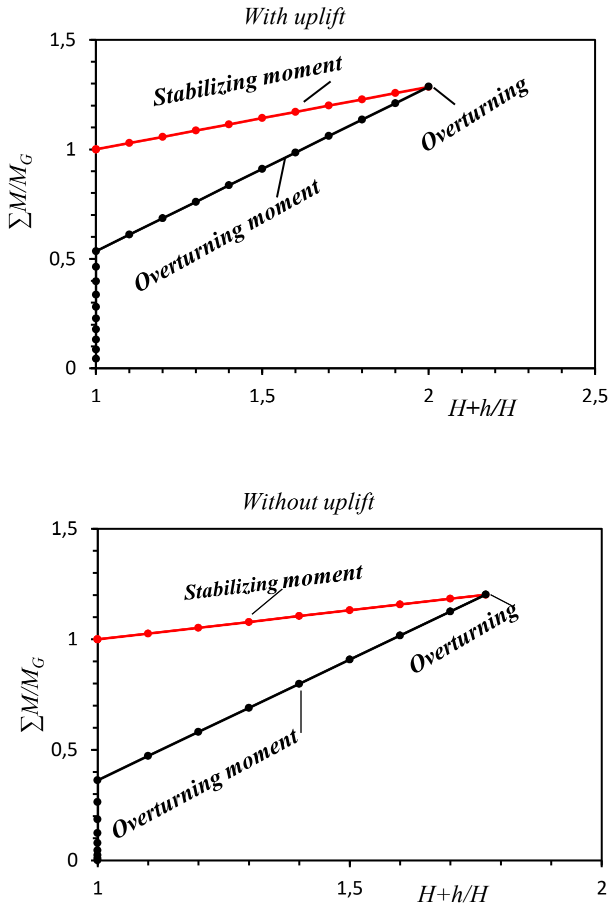



**Figure 5: Diagram of stability of a fuse plug**

The gradual convergence of stabilizing and overturning moments until reaching the limit-stability condition allows the derivation of two analytical relationships. These express the width (b) of the block as a function of its height, the water head above the block, and the unit weights of both the constituent material and water. These expressions form the basis for the preliminary design of the concrete fuse plug.

- Concrete Fuse Plug with uplift

$$b = H\left(\frac{H+3h}{3\frac{\gamma_b}{\gamma}H-3H-h}\right)^{\frac{1}{2}} \quad (5)$$

- Concrete Fuse Plug without uplift

$$b = H\left(\frac{H+3h}{3\frac{\gamma_b}{\gamma}H+2h}\right)^{\frac{1}{2}} \quad (6)$$

These two relationships provide the initial dimensions of the concrete fuse plug (under full uplift pressure and without uplift pressure) for a given overturning water depth and a predetermined block height.

**EXPERIMENTAL VALIDATION ON MODELS**

The theoretical results were subjected to experimental verification in order to assess their reliability for the design of the concrete fuse plug system.

The experimental study was conducted at the experimental station for scale models of the Laboratory of Hydraulic Development and Environment at the University of Biskra (Fig. 6). This experimental platform was specifically designed and sized to carry out hydraulic tests on reduced-scale models of hydraulic structures, ensuring a sufficiently representative scale to guarantee the reliability of observations and measurements.

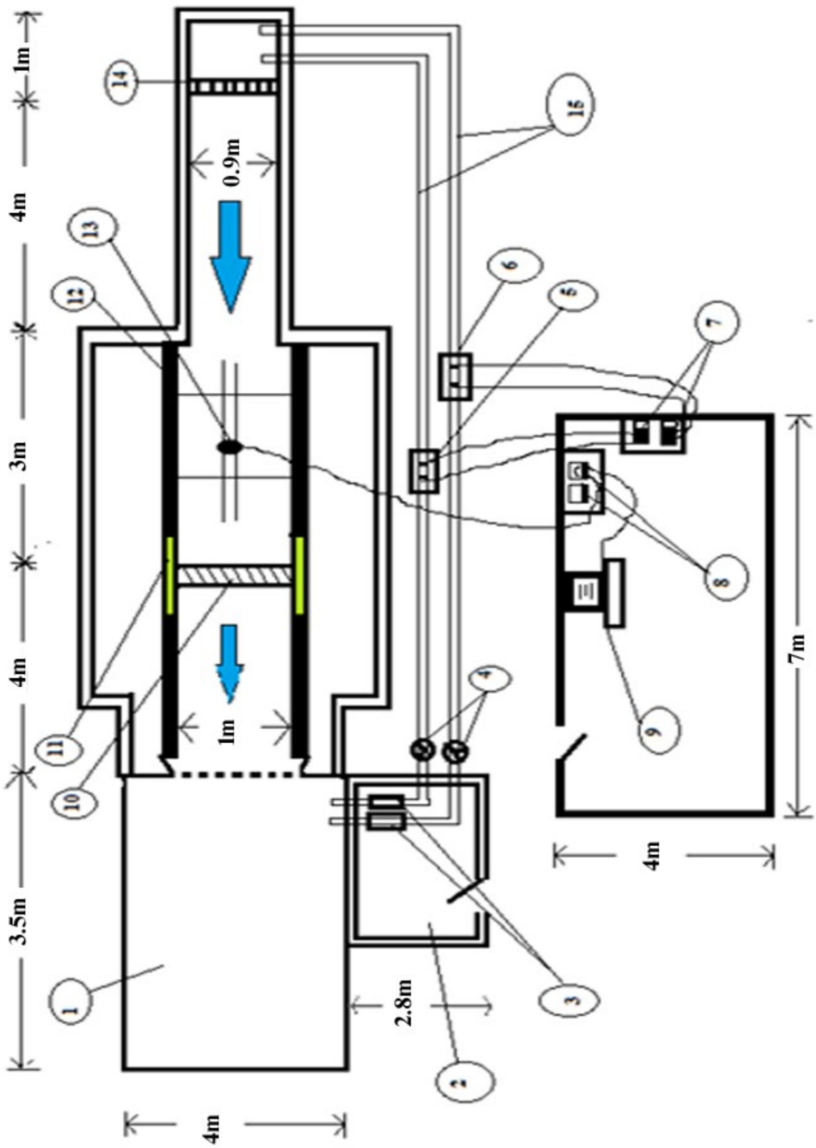



**Figure 6: Descriptive scheme of the experimental setup**

1.Water reservoir, 2.Pumping station, 3.Pumps, 4.Control gates, 5.Ultrasonic flow meter, 6 Electromagnetic flow meter, 7.Flow recorder, 8.Water level recorder, 9.Data processing unit, 10.Weir model, 11.Plexiglass walls, 12.Simulation channel, 13.Water level sensor, 14.Stabilization system.

**Figure 7: Overview of the experimental setup for the scale models**

**Experimental program**

To carry out the experimental study, a series of concrete blocks was fabricated in accordance with the sizing relationships derived from the theoretical analysis. To eliminate lateral friction effects, a base equipped with separating walls and a downstream thrust block was installed on the weir sill.

The blocks were fabricated from concrete cast in molds. A metal plate, with its lower edge extending approximately 5 mm beyond that of the block, was attached to the downstream face of the mold. This configuration was designed to create a gap beneath the block during installation, thereby allowing the formation of an uplift chamber.

The height of the blocks was chosen to be 10 cm for all models, taking into account the height of the uplift chamber, while the length of the blocks was set to twice the height. The width of the blocks varies from one block to another depending on the water level above the block at which overturning is expected.

To conduct this type of test with satisfactory precision, the concrete block must be placed on the weir sill while ensuring its horizontality by inserting a small concrete cube beneath the block as a support at its upstream end (Fig.2). This allows the creation of an uplift chamber under the block. Watertightness between the block and the lateral walls, as well as between the test block and the sill, is ensured by plastic joints (water-stop) (Fig.2).

The experimental procedure involves starting the pump and allowing water to flow into the simulation basin. The water level gradually rises until it reaches the base sill level, then enters the uplift pressure chamber and continues to increase until it reaches the top surface of the block, which remains in a stable position, thus forming a watertight barrier. At this moment, water begins to flow over the block, which then acts as a weir. The overflow continues until the block overturns under a specific water head, which is measured instantaneously by reading the water level in the piezometers.

## RESULTS AND DISCUSSION

### Verification of the relationship between overturning water head and block width

The main objective of the experimentation is to verify the relationship between the block width and the water depth on the block that causes its overturning. To achieve this, tests were conducted on a series of seven blocks with different widths, which were determined from the theoretical relationship (5) developed based on the limit stability of a block with existing uplift pressure. The difference in width implies a different overturning water depth for each block. The tests were repeated several times, and the values obtained for each block were similar. The measured values of the water depth on the block for multiple tests are nearly identical (Fig. 9).

**Figure 8: Downstream view of the flow over the fuse plugs at the moment the central block overturns**

**Table 1: Geometric characteristics and theoretical and experimental results obtained for the seven blocks**

| N° Block / Characteristics | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| $\gamma_b$ (t/m$^3$) | 2.38 | 2.31 | 2.31 | 2.34 | 2.39 | 2.36 | 2.37 |
| $H_b$ (cm) | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| $L_b$ (cm) | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| b (cm) | 8.2 | 9 | 10.3 | 11.5 | 12.7 | 13.7 | 14.9 |
| $h_{th}$ (cm) | 4.9 | 5.7 | 7.8 | 10.0 | 12.4 | 13.7 | 15.6 |
| $h_{pr}$ (cm) | 5.1 | 5.9 | 8.0 | 9.7 | 12.0 | 13.5 | 15.1 |
| $h_{th}$-$h_{pr}$ (cm) | -0.2 | 0.2 | -0.2 | 0.3 | 0.8 | 0.2 | 1.1 |
| Diff (%) | -3.92 | -3.39 | -2.5 | 3.09 | 3.33 | 1.48 | 3.31 |

Figure (9) illustrates the relationship between the block width b and the water depth that triggers its overturning, as observed experimentally. The results obtained for the seven tested blocks reveal an almost linear trend, suggesting that the critical width varies proportionally with the submergence depth. However, this quasi-linearity holds only under the assumption that the material density is identical for all blocks. Any variation in density would indeed modify the self-weight of the blocks and, consequently, their overturning stability.

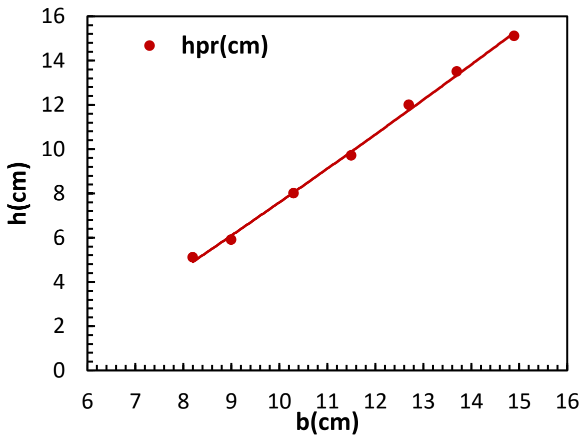



**Figure 9: Graph of the experimental results showing the variation of the overturning head as a function of block width (under total uplift pressure).**

Figure (9) also highlights that the overturning height is strongly influenced by the block width. Thus, to induce overturning under a low water depth, it is sufficient to reduce the block width, which decreases its stability. This observation confirms that fuse plugs are particularly suitable for releasing moderate floods and become less effective for extreme floods associated with long return periods.

$$b = H\left(\frac{H+3h}{3\frac{\gamma_b}{\gamma}H-3H-h}\right)^{\frac{1}{2}} \Rightarrow h = \frac{3H\left(\frac{\gamma_b-\gamma}{\gamma}\right)b^2-H^3}{b^2-3H^2} \tag{7}$$

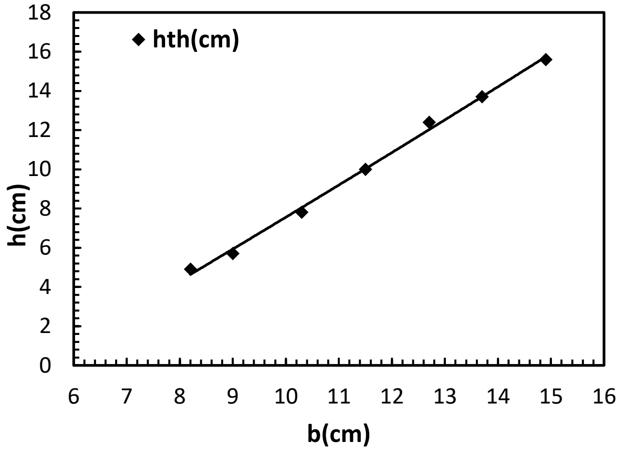



**Figure 10: Graph of the theoretical results showing the variation of the overturning head as a function of block width (under total uplift pressure).**

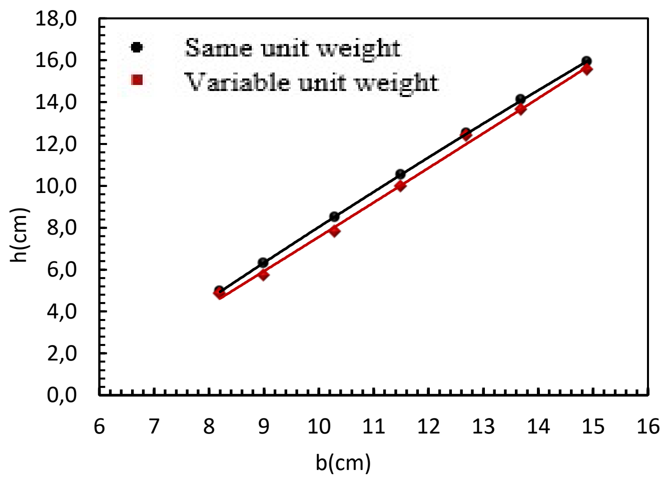



**Figure 11; Variation of the overturning head as a function of the variation in unit weight (under full uplift pressure)**

Furthermore, the graphical representation of the overturning head calculated using the theoretical relation (6) as a function of block width (Figure 10) shows a trend similar to that observed experimentally. This agreement between theory and experimentation is obtained when the calculations consider the same unit weights as those of the tested blocks, which vary slightly from one block to another. This concordance emphasizes the sensitivity of the overturning mechanism to variations in the material density.

However, the comparison of this theoretical curve with that obtained assuming a constant unit weight (Fig. 11) shows that the overturning height of the blocks follows a quadratic polynomial trend, with a quasi-linear increase in the range $b$ = 8.2 – 14.9 cm. The overall shape of the curve remains similar. The curve corresponding to a constant unit weight $\gamma_b = 2.4\ t/m^3$ lies slightly above that obtained with a variable unit weight, reflecting a slightly higher average density (2.4 $t/m^3$ compared to an average of approximately 2.36 $t/m^3$). This observation highlights the subtle influence of material density on the overturning stability of the blocks.

To assess the validity of relation (5), it is relevant to compare the theoretical results with those obtained experimentally. To this end, the graph presented in Figure 12 illustrates the comparison between the theoretical and experimental curves.

The analysis of this graph, which represents the practical $h_{pr}$ and theoretical $h_{th}$ overturning heights as a function of block width, shows excellent agreement between the calculated and experimentally measured values. The maximum difference between the theoretical and practical values does not exceed 4% over the entire range of studied heads. This analysis confirms the robustness of relation (5) under practical operating conditions.

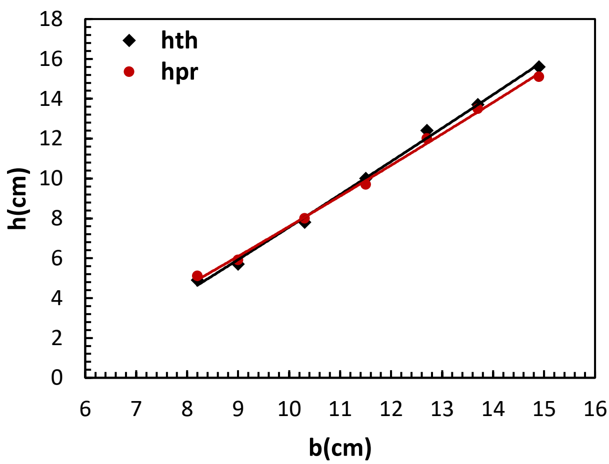



**Figure 12: Comparison between theoretical and experimental overturning head (under full uplift pressure).**

The two curves (theoretical and experimental) are quadratic polynomial in nature. However, their behavior is very close to a linear relationship, particularly in the range of b from 8.2 to 14.9 cm, where the quadratic curvature is weak. This reflects a moderately accelerated increase in h with b. The slight discrepancies observed can be attributed to friction at the contact between the blocks and the separating walls, an effect that was neglected in the development of the theoretical model. This observation highlights the practical accuracy of the relation while acknowledging that secondary effects, such as friction, can introduce minor variations in experimental results.

**Effect of uplift pressure on the sizing of the blocks**

The calculation of the overturning head of fuse blocks must be carried out with precision to ensure the safety of structures equipped with these elements. Such accuracy can only be achieved by knowing the exact value of the uplift pressure, whether it is total or absent.

To evaluate the effect of uplift pressure on the stability of fuse blocks, a comparative study was conducted between previously obtained theoretical and experimental results for two series of blocks: one subjected to total uplift pressure and the other without any uplift pressure.

The experimental tests were carried out on a series of five fuse blocks of different widths, determined from the theoretical relation (6), which was developed based on the limit stability of blocks in the absence of uplift pressure. This approach allows quantifying the influence of uplift pressure on overturning behavior and refining the sizing criteria of fuse blocks for different hydraulic scenarios.

**Table 2: Geometric characteristics and theoretical and experimental results obtained for the five blocks**

| N° Block / Characteristics | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| $\gamma_b$ (t/m$^3$) | 2.55 | 2.55 | 2.51 | 2.52 | 2.51 |
| $H_b$ (cm) | 10 | 10 | 10 | 10 | 10 |
| $L_b$ (cm) | 20 | 20 | 20 | 20 | 20 |
| b (cm) | 5.5 | 6 | 6.6 | 6.9 | 7.3 |
| $h_{th}$ (cm) | 5.5 | 7.7 | 10.7 | 12.7 | 15.6 |
| $h_{pr}$ (cm) | 5.6 | 7.8 | 10.4 | 12.3 | 15.5 |
| $h_{th}$-$h_{pr}$ (cm) | -0.1 | 0.1 | 0.3 | 0.4 | 0.2 |
| Diff (%) | -1.78 | -1.28 | 2.88 | 3.25 | 2.15 |

The graph shown in Figure (13) illustrates the variation of the block width b as a function of the water depth flowing over the block that causes its overturning, as observed experimentally. This representation allows a direct visualization of the influence of block width on overturning stability and serves as an essential tool for comparative analysis of the behavior of the different tested fuse blocks.

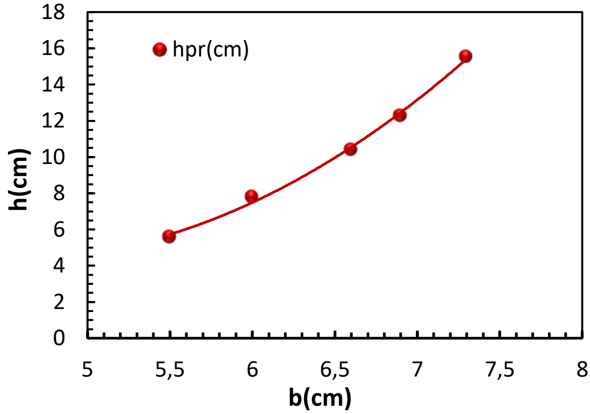



**Figure 13: Experimental curve of the variation of the overturning head as a function of block width (without uplift pressure)**

From these experimental results, it is evident that the overturning head of the blocks increases rapidly with increasing width. For the smaller blocks, the overturning head is almost proportional to their width, whereas the fifth block overturns under a head more than twice its width.

The graph presented in Figure (14) also shows that the overturning of a fuse block depends primarily on the downstream water depth. This observation highlights the relative importance of block geometry and downstream water level in determining overturning stability, emphasizing the key parameters to consider in the design of fuse blocks.

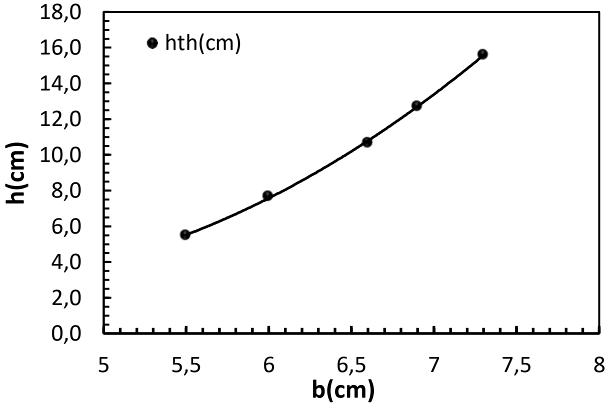



**Figure 14: Theoretical curve of the variation of the overturning head as a function of block width (without uplift pressure)**

Figure 14 illustrates the variation of the overturning head as a function of block width, calculated from the theoretical relation (6). The shape of the theoretical curve is remarkably similar to that obtained experimentally, indicating good consistency between the model and practical observations.

$$b = H\left(\frac{H+3h}{3\frac{\gamma_b}{\gamma}H+2h}\right)^{\frac{1}{2}} \Rightarrow h = \frac{3H\left(\frac{\gamma_b}{\gamma}\right)b^2 - H^3}{3H^2 - 2b^2} \tag{8}$$

The comparison of the theoretical and experimental overturning head results, presented in the graph of Figure 15 for the case without uplift pressure, shows excellent agreement. The maximum difference between the calculated and measured values does not exceed 3.5% across the entire range of studied heads. This small discrepancy confirms the reliability of the theoretical relation, based on the limit stability of the fuse block, and validates its use for the precise design of these elements.

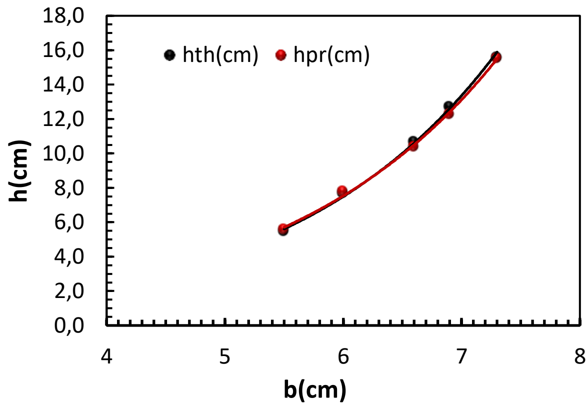



**Figure 15: Comparison between theoretical and experimental load (without uplift pressure)**

The influence of uplift pressure on the stability of concrete fuse plugs can only be fully understood through a comparative study of the behavior of blocks with and without uplift pressure. The comparison of results obtained for two series of blocks one subjected to total uplift pressure and the other without uplift pressure shows that the presence of uplift pressure leads to a notable increase in block width and, consequently, its weight, this increase being proportional to the applied water head. Conversely, the absence of uplift pressure results in a significant rise in the overturning head for a given block width.

For example, in the first test with total uplift pressure, the block with a width of b=8 cm overturned under a head of $h = 4.9$ cm, corresponding to approximately 61% of its width. For the same block without uplift pressure, overturning occurred at $h = 5.5$ cm, or 69% of its width.

For the last block of the series, overturning under total uplift pressure occurred at $h$=15.6 cm, close to its width $b$ =14.9 cm (≈104% of b), whereas the same block without uplift pressure overturned under a head greater than twice its width ($h$ > 200% of b).

These observations indicate that the presence of uplift pressure increases the overturning moment, causing the block to overturn under lower heads than those required in the absence of uplift pressure. Thus, to prevent overturning at a given height and head, it is necessary to increase the block width and, consequently, its weight. In contrast, without uplift pressure, block overturning requires an increase in hydrostatic thrust, achievable only by increasing the water head on a narrower block, thereby also increasing its effective weight.

This analysis highlights the critical role of uplift pressure in the design of fuse blocks and demonstrates that the selection of block width and weight must be carefully adjusted according to hydraulic conditions to ensure overturning stability.

## CONCLUSION

The Concrete Fuse Plugs represent a simple, cost-effective, and fully passive solution for simultaneously improving the storage capacity and flood discharge capacity of existing dams, particularly those affected by reservoir sedimentation or undersized spillways. Their installation on the crest of an existing weir increases the normal storage level while ensuring safe overflow during extreme floods.

In this study, a theoretical approach based on limit-stability analysis was developed to establish an analytical relationship between the block width and the upstream water head that triggers overturning. This relationship was then evaluated through a series of physical model tests on fuse plugs overturning after overtopping, with and without uplift pressure.

The comparison between theoretical predictions and experimental results shows good agreement, confirming the relevance of the proposed formulation for the preliminary design of concrete fuse plugs. The tests also indicate that, for a given height, blocks without uplift pressure exhibit smaller widths and overturn under higher water heads, whereas accounting for uplift pressure leads to larger blocks but ensures a more precise and predictable overturning threshold.

Finally, the experimental observations show that overturning does not depend on the position of the block along the spillway crest but solely on its geometry, particularly its width, which validates the fundamental assumptions of the theoretical analysis.

Overall, the results confirm the reliability of the proposed theoretical relationship and support the development of simplified and robust design methods for fuse plugs used in the rehabilitation of hydraulic structures.

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