

Energy dissipation of torrential flows in different basin shapes

Article

Ahmed Benmalek *, Mohammed Amin Hafnaoui, Mohammed Madi & Mosbah Bensaid

Scientific and Technical Research Center on Arid Regions CRSTRA, Biskra, Algeria

* Correspondence: ahmed.benmalek@yahoo.fr

Abstract: The stationary hydraulic jump, more simply called "jump", occurs when there is a sudden elevation change of the free surface flow. This phenomenon occurs when the supercritical regime becomes subcritical over a short distance, the free surfaces necessarily being located on either side of the critical level. In free surface flows, the jump causes an appreciable head loss; moreover, the velocities at the downstream of the jump (subcritical regime) are much lower than the velocities at the upstream (supercritical regime). These properties enable the hydraulic jump to be used as good energy dissipators (total and kinetic).

This study's goal is to conduct a theoretical and experimental investigation of how well various open channels, including the trapezoidal channel, the suddenly expanded trapezoidal channel, and the compound rectangular channel, dissipate energy. There are now proven empirical formulae that express each channel shape's efficiency as a function of the Froude number.

Keywords: Hydraulic jump; Froude number; Stilling basin; Trapezoidal channel; abruptly enlarged trapezoidal channel, Compound rectangular channel.

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1. Introduction

The effect of a continuous transverse weir of the hydraulic jump in a rectangular channel was analyzed by Hager et al. [1]; the authors compared the classic jump with the force jump by sill. A new method of normalization is introduced by referring to the roller length of the classic jump. Additionally, two and three-dimensional flow characteristics were discussed. The dimensioning process was then based on both the hydraulic aspects and those related to the erosion of the riverbed. The works of Hager and Sinniger [2] allowed the explicit calculation of the efficiency « η » of the jump. The jump in trapezoidal channels was analyzed by Wanoschek and Hager [3], in this work the authors presented a study on the internal structure of the flow in the hydraulic jumps encountered in this type of channel. From observations, the three characteristic parameters of the flow are « Y », « L_r », and « L_j ». The results showed that the phenomena are notably different from those encountered in the classic jump. This is attributed mainly to the existence of a background role. The study analyzed the main properties of the flow, such as the sequence depths, the bottom roller length, and the characteristic lengths of the phenomenon.

The hydraulic jump on a horizontal bottom in a non-prismatic rectangular channel was analyzed by Hager [4]. The author distinguished between cases where the flow is un-separated and those where it is separated from the side walls. The results contain formulas for the conjugate depths as a function of the Froude number and the ratio of the corresponding widths, the relative energy dissipation, and the characteristics of the jump length. All equations are presented in dimensionless forms (without units), which facilitates their application to practical problems.

In the trapezoidal channel, Gandhi et al. [5] Compared several models. The results showed a good concordance with the previous research, which supports the accuracy of the models developed in this study. The model presented contains a trapezoidal channel with baffle blocks. It also showed good values of the Reynolds number « R » which is significant for describing both the jump characteristics and the dissipation energy compared to the trapezoidal channel without baffle blocks. Therefore, it can be concluded that these models are suitable for different sizes and positions of baffle blocks.

Omid et al. [6] showed that the increase of the divergence angle of the abruptly enlarged trapezoidal channel leads to decreased conjugate depth, jump length and increased relative energy loss. Therefore, for a trapezoidal stilling basin, the divergence can be used to reduce the sequent depth ratio and the hydraulic jump length.

In an abruptly enlarged trapezoidal channel to a rectangular channel, a theoretical and experimental study presented by Benmalek and Debabeche [7] expresses the effect of enlargement on the sequent depth ratio, surface profile, and energy loss.

In the case of the compound rectangular channel, Khattaoui and Achour [8] have developed an expression that allows the calculation of the efficiency of the jump according to the filling rate and the widening ratio.

The present study concerns the theoretical and experimental analysis of the performance of the jump in three types of open channels. Namely, the trapezoidal channel, the abruptly enlarged trapezoidal channel, and the compound rectangular channel.

2. Theoretical analysis

The hydraulic and geometric characteristics of this study are: the flow « Q »; the initial depth « h_1 »; the final depth « h_2 »; the length of the hydraulic jump « L_j », measured between sections 1 from the toe of the hydraulic jump and the section 2 where maximum surface level occurs; and the roller length « L_r », measured between the initial depth « h_1 » and the roller end [9; 10]. The head loss is represented by « ΔH_{12} ». The dissipation capacity of the hydraulic jump is generally evaluated by the ratio of the head loss that occurs between these initial and final sections and the total head in its initial section.

The torrential flow upstream of the hydraulic jump is characterized by a kinetic coefficient (or Froude number, $Fr_1 > 1$) and represents the relationship between the velocity of the flow and the velocity of propagation of small disturbances.

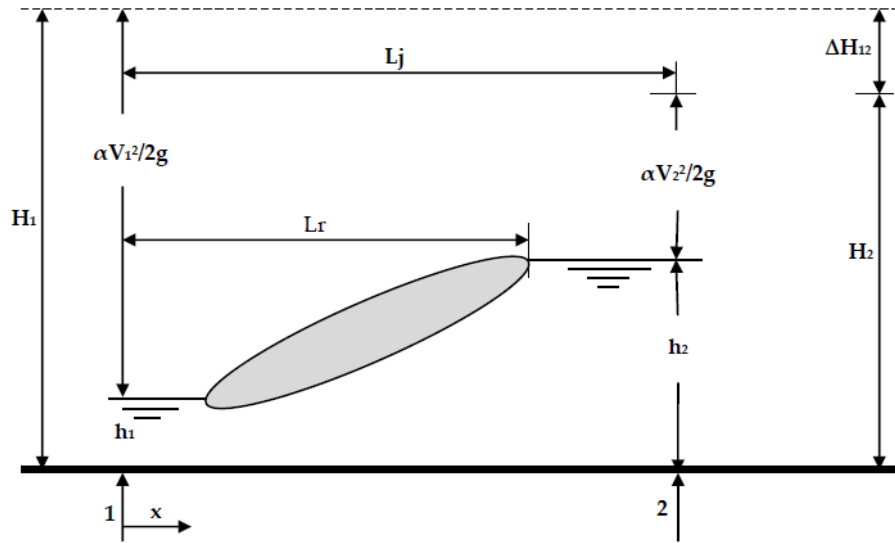


Figure 1: Characteristics of the hydraulic jump

The hydraulic jump causes a significant dissipation of mechanical energy; this phenomenon is irreversible. Turbulence characteristics are very complex and highly dependent on upstream conditions. By applying Bernoulli's theorem, energy loss produced by the jump will be determined by (Eq. 1):

$$\Delta H_{12} = H_1 - H_2 \quad (1)$$

Assuming that ($Z_1 = Z_2$, horizontal channel), (figure 1), « ΔE » is gives by (Eq. 2):

$$\Delta E_{12} = \Delta H_{12} = \left(\alpha_1 \frac{V_1^2}{2g} + h_1 \right) - \left(\alpha_2 \frac{V_2^2}{2g} + h_2 \right) \quad (2)$$

Where, the total head in the upstream section is (Eq. 3):

$$H_1 = \alpha_1 \frac{V_1^2}{2g} + h_1 \quad (3)$$

And the total head in the downstream section is (Eq. 4):

$$H_2 = \alpha_2 \frac{V_2^2}{2g} + h_2 \quad (4)$$

Where: « V_1 » and « V_2 » represent the average flow velocity at the upstream and downstream sections of the hydraulic jump. The kinetic energy correction factor « α » is assumed to be equal to unity. The energy dissipation capacity of a hydraulic jump is characterized by its efficiency « η », which is the ratio of the difference between the initial and final head « ΔH_{12} », and the total head at the initial section of the jump « H_1 ». This last, is given by the following relation (Eq. 5):

$$\eta = \frac{\Delta H_{12}}{H_1} = \frac{H_1 - H_2}{H_1} = 1 - \frac{H_2}{H_1} \quad (5)$$

Due to the permanent nature of the flow, the continuity equation remains in force and we can write (Eq. 6):

$$Q = V_1 A_1 = V_2 A_2 \quad (6)$$

2.1. The Case of the Trapezoidal Canal

In the case of the trapezoidal channel, the initial and final sections are given by the following relations (Eq. 7) and (Eq. 8):

$$A_1 = bh_1 + mh_1^2 \quad (7)$$

$$A_2 = bh_2 + mh_2^2 \quad (8)$$

Where: « m » is the cotangent of the slope angle. The Froude number of the incident flows in a trapezoidal cross-section channel is defined by equation (Eq. 9):

$$Fr_1^2 = \frac{Q^2 (1 + 2M)}{gb^2 h_1^3 (1 + M^3)} \quad (9)$$

Where « M » is being the aspect ratio it given by (Eq. 10):

$$M = \frac{mh_1}{b} \quad (10)$$

«b» is the bottom width of the trapezoidal channel.

Taking into account the previous relationships, the efficiency of the hydraulic jump in a horizontal trapezoidal channel is written as follows (Eq. 11):

$$\eta = 1 - \frac{Y + \frac{Fr_1^2 (1+M)^3}{2Y^2 (1+2M)(1+YM)^2}}{1 + \frac{Fr_1^2 (1+M)}{2(1+2M)}} \quad (11)$$

"Y" is the conjugate depth ratio of the hydraulic jump; it is given by (Eq. 12).

$$Y = \frac{h_2}{h_1} \quad (12)$$

2.2. Case of the abruptly enlarged trapezoidal channel

In the case of the trapezoidal channel abruptly widened to a rectangular channel (figure 2), the initial and final sections are given by the following relations (Eq.13) and (Eq. 14):

$$A_1 = bh_1 + mh_1^2 \quad (13)$$

$$A_2 = Bh_2 \quad (14)$$

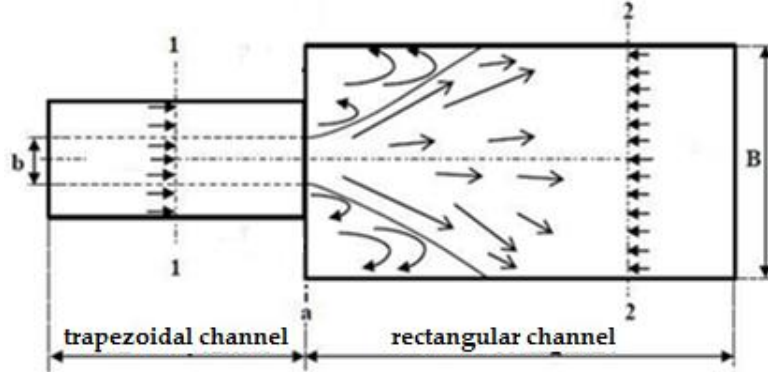


Figure 2: A trapezoidal channel abruptly enlarged to a rectangular channel.

Taking into account the previous relationships, the efficiency of the hydraulic jump in this case is written as follows (Eq. 15):

$$\eta = 1 - \frac{Y + \frac{Fr_1^2 (1+M)^3}{2\beta^2 Y^2 (1+2M)}}{1 + \frac{Fr_1^2 (1+M)}{2(1+2M)}} \quad (15)$$

$\beta = B/b$ being the enlargement ratio.

2.2. Case of the compound rectangular channel

The shape of the compound rectangular channel is given by Figure 3.

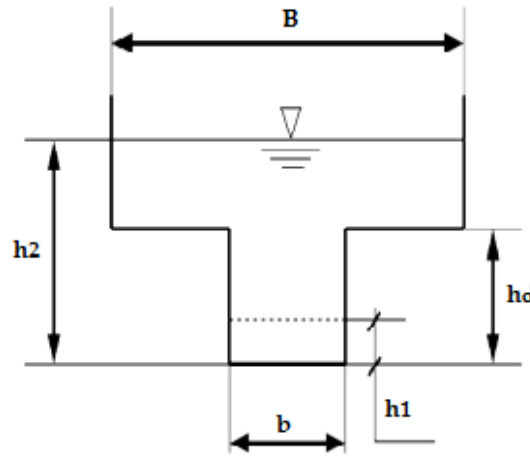


Figure 3: Compound Rectangular Channel

The efficiency is given by (Eq. 16):

$$\eta = 1 - \frac{Y + \frac{Fr_1^2}{2[Y/\beta - (1/\beta - 1)/\tau]^2}}{1 + \frac{Fr_1^2}{2}} \quad (16)$$

Where:

« β » is the enlargement ratio.

« τ » is the being the filling rate (h_1/h_0).

3. Materials and methods

The experimental study focused on the hydraulic jump controlled by a thin-walled weir in three types of channels, which are, a trapezoidal channel with a horizontal bed and an inclination angle of 73° (Figure 4a), a trapezoidal channel abruptly enlarged to a rectangular channel (Figure 4b), and a compound rectangular channel (Figure 4c). The experiments were conducted under four initial flow depths: h_1 (cm) = 2; 3; 4; and 5 (Figure 4d). A wide range of incident Froude number was obtained, corresponding to $3.57 < Fr_1 < 15.72$. The formation of the controlled jump is conditioned by the placement of a sill downstream of the flow. For this reason, sills of different heights were used in the experimental tests (Figure 4e), (Figure 4f), and (Figure 4g).

This study comprised more than 100 experimental measurement points of the hydraulic jumps, which allowed obtaining significant results. The analyses of the hydraulic jump characteristics produce the following dimensionless: The Froude number « Fr_1 », sequence depth ratio « Y », the initial relative height of the jump « M », the enlargement ratio « β », and the filling rate of the compound rectangular channel « τ ».

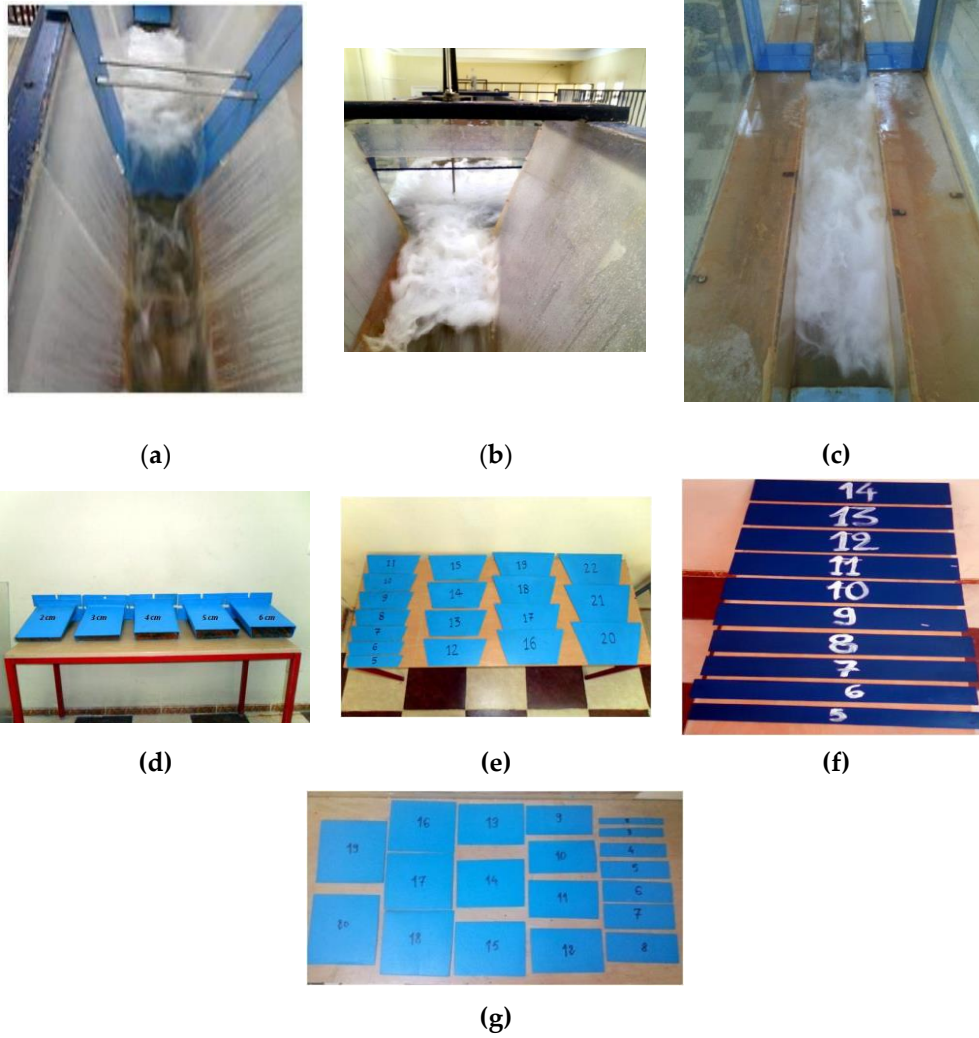


Figure 4: Experimental model

4. Results and discussions

4.1. Trapezoidal channel

Figure 5 expresses the variation of the hydraulic jump efficiency as a function of the Froude number for a trapezoidal channel controlled by a thin sill. The analysis of the experimental data showed that the efficiency can reach a maximum value of 85%. The range of the Froude number values varied between $2.80 \leq Fr_1 \leq 14.20$. These findings have an additional benefit for trapezoidal shaped pools, which dissipate a large amount of energy at the downstream of the dam and protect the structure against overturning. This type of channel is currently usable in practice for performance and implementation reasons.

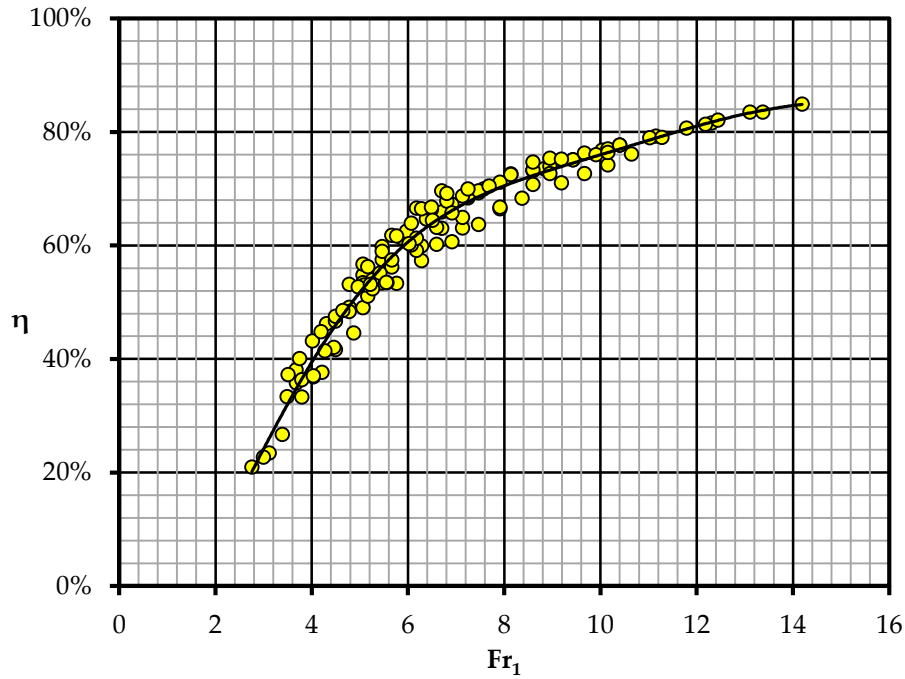


Figure 5: Variation of η as a function of Fr_1 in a trapezoidal channel

4.2. Abruptly enlarged trapezoidal channel

Due to the abrupt enlargement of the trapezoidal channel effect, a large amount of energy will be dissipated when passing from supercritical to subcritical regime. Creating the hydraulic jump in this zone can reduce this energy by up to 70% (Figure 6). These results showed that the energy dissipation ability of these types of basins is somewhat lower compared to the trapezoidal basins. The values of the Froude numbers obtained are small compared to those encountered in practice. These values varied from 3.40 to 8.50.

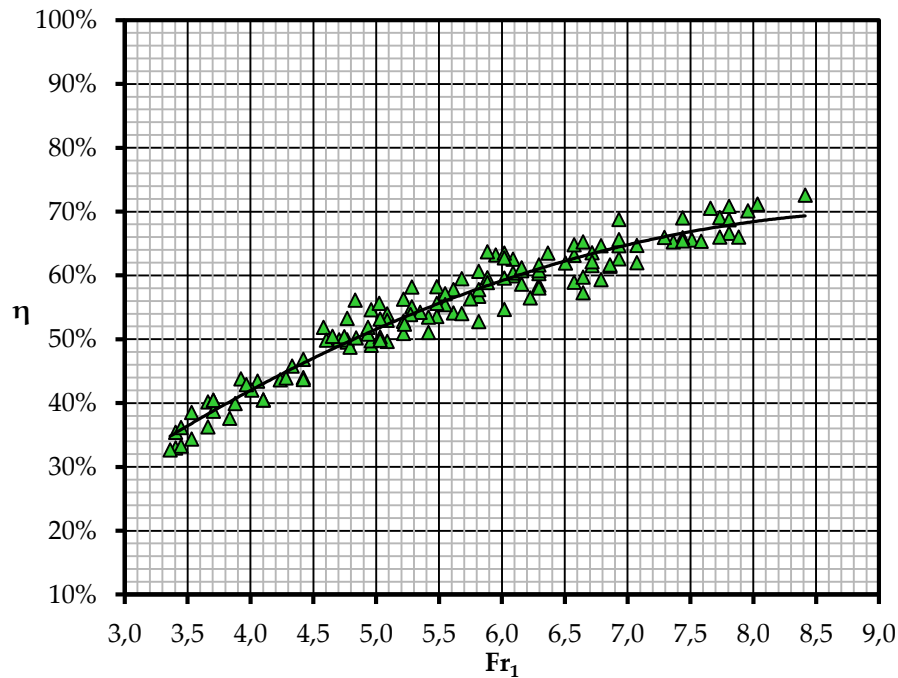


Figure 6: Variation of « η » as a function of Fr_1 in an abruptly enlarged trapezoidal channel

4.3. Compound Rectangular Channel

Figure 7 illustrates the variation of the hydraulic jump efficiency as a function of the Froude number for the experimental tests in the abruptly enlarged trapezoidal channel. The adjustment of the measurement points showed that for this type of channel the energy dissipation can reach 85%, an acceptable performance of the Froude number « Fr_1 » is obtained. These values varied between $3.40 \leq Fr_1 \leq 12.10$, which favors the choice of the compound rectangular channel.

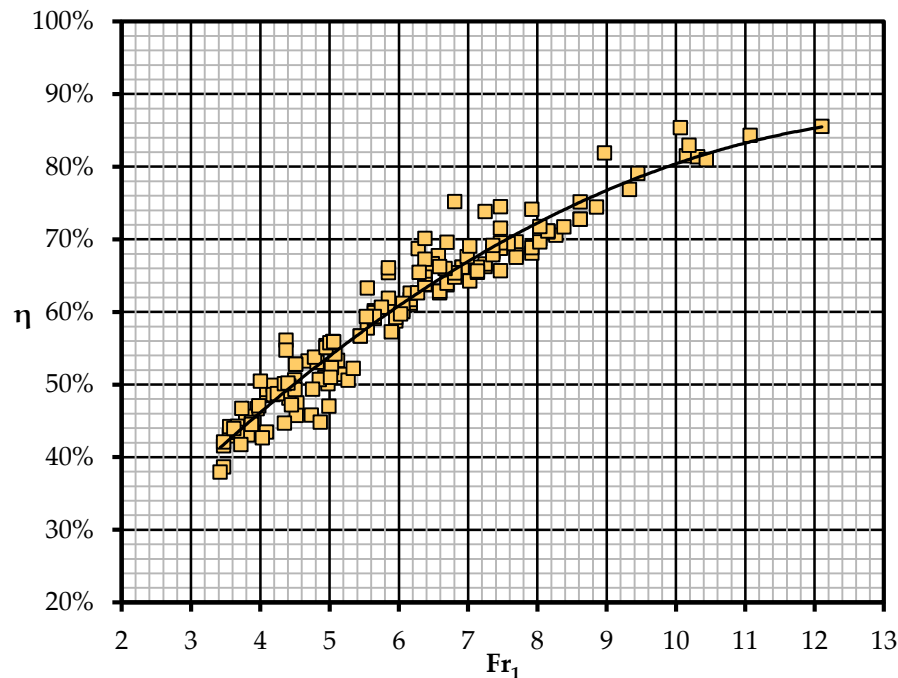


Figure 7: Variation of « η » as a function of Fr_1 in a compound rectangular channel.

5. Conclusion

The analysis results of the experimental tests of the hydraulic jump efficiency variation « η » as a function of the Froude number « Fr_1 » showed that the shape of the basin influenced the energy dissipation performance. In the case of the trapezoidal channel, the efficiency can reach 85% compared to 70% for the abruptly enlarged trapezoidal channel. But in the case of the compound rectangular channel, the efficiency increased by up to 85%. These findings allow concluding that the trapezoidal shape and the compound rectangular shape are the most favorable cases for the choice of the stilling basin type. However, in practice, it is preferable to choose the trapezoidal shape due to its ease of construction, especially for the installation of formwork on construction sites.

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