Experimental Investigation of Energy Dissipation in Ogee Spillway Using New Distributions of Dissipation Blocks

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Abstract. Ogee spillway is the most important structure used to get rid of excess water during flood. Scouring phenomenon occurring in the downstream region due to high energy dissapation is an envitable. This study aims to reduce the amount of scour occurred at the downstream stilling basin of the ogee spillway by using three dissipation energy blocks namely as baffle, triangle and stepped blocks. A new distribution was proposed for each type of dissipated block, which varied between one row, two rows, and three rows. The flow and scour experimental tests were carried out under Froude numbers ranging from 2.5 to 8.5. During the tests, sequent depths and transverse velocities distribution were measured. The results showed that the used blocks appeared with good results in minimizing flow velocities and sediment scouring within the stilling basin in accordance with proposed distributions, especially with the range of Froude number 4.5-8.5. Also, The stepped block is characterized by reducing the flow velocities compared to the baffle block and triangle block, as it can be seen that there is a decrease in velocities up to 0.85% for all used distributions (A1, A2, A3, B1, B2, and C1).

Keywords: Ogee spillway, Froude number, disipated block, velocity distribution, sequent depth.

1. INTRODUCTION

The increasing need for water supply, flood control, hydroelectric power generation, and recreation has made dam construction a high priority throughout the world. As water is of critical importance for human life, modern techniques in the design of dams are essential for better management of water resources [1]. All dams are equipped with spillways as a safety measure against overtopping. They are provided to safely carry water away from the reservoir when water levels exceed the full supply level. The ogee spillway, which is also known as an overflow or S-shaped spillway, is the most common type of spillway that is used to release water from a dam or levee reservoir to the downstream channels. Hydraulic jump is a common energy dissipater generally observed in open channel flow, especially at the toe of hydraulic structures e.g., spillways. One of the main applications of a hydraulic jump is dissipating the excess kinetic energy downstream of the hydraulic structures. The stilling basin is the most common form of structure to contain the hydraulic jump to achieve the required dissipation of kinetic energy [2].

Water flowing over an ogee spillway crest always remains in contact with the spillway surface as it smoothly flows downstream. Water flowing over an ogee spillway contains high kinetic energy that can cause erosion at its end and leads to dam failure [3and4]. Therefore, stilling basins of different designs are used to dissipate the energy of the flowing water and establish safe flow conditions to protect the downstream end of the spillway from erosion. These basins are usually equipped with different types of blocks and end sills to stabilize, reduce the length of the hydraulic jump, and improve its performance [5-8]. The standard stilling basin, which uses the baffle blocks as a main feature for dissipating the surplus kinetic energy, is introduced in the late 1950s by Bradley and Peterka [9], and this study was further generalized and published as Reclamation Engineering Monograph No. 25 by Peterka A. J. on September 1958 (last re-print at May 1984). Scour is the process of water removing particles from the riverbed and banks of a river or channel. Many scholars have looked at the elements that influence this phenomenon to figure out what causes it and how to fix it [10-14].

Different experimental studies have been conducted to determine the appropriate characterization for each case of development that took place in the stilling basin. Al-Zubaidy [15] investigate the effects of applying the direction- diverting blocks fixed on an ogee spillway surface with different slopes on energy dissipation. The configurations differ in spacing between rows of blocks and the number of rows. When blocks were used, the maximum reduction in Froude Number was 36%, 89%, and 93% for spillway models with slopes 1:1, 0.85:1, and 0.75:1, respectively. Valero et al. [16] carried out an experimental study on the baffle block with a sloping vertical face arranged downstream of a sluice gate, to investigate its effect on the length of the hydraulic jump. The results of this study show that baffle blocks with a sloping front face can reduce the jump's length compared with the free jump. Saki and Shafai [17] used wedge-shaped and baffle blocks to find their effect on the hydraulic jump properties. The results show a reduction in the length of jump and sequent depth ratio compared to those with smooth beds. Baffle block tests showed that the scour processes were faster in contrast to wedge block, which was marked by slower changes in bed profile.

This study aims to: (1) carry out an experimental program for investigating the energy dissipation and sediment scour downstream of the ogee spillway under 2.5-8.5 values of Froude Number. (2) Investigate the effect of blockage distance with the presence of one, two, and three rows of baffle blocks, triangle blocks, and

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stepped blocks on the hydraulic performance. (3) Yield the basic parameters such as velocity distribution at end of the jump and scour effect downstream of the stilling basin.

2. MATERIALS AND METHODS

2.1 Model Similitude

The correlation between physical quantities in the model and the prototype is a critical problem that might be important in hydraulic flow such as viscous effects, surface tension, and gravity effect. The Froude Number similarity requires that $V_r = \sqrt{L_r}$, the Reynolds Number scaling implies that $V_r = 1/L_r$, and the Weber Number similarity requires $V_r = 1/\sqrt{L_r}$, where $Lr = Lp/Lm$. V refers to approach flow velocity, and L refers to the unit length of model. The subscript r refers to the ratio of prototype to model quantity and the subscripts p and m refer to prototype and model parameters, respectively. Froude Number modeling is typically used when friction losses are small and the flow is highly turbulent, e.g., spillways. In each case, only the most dominant mechanism is modeled. In free-surface flow, gravity effects are always important, and Froude Number modeling is used, hence viscous and surface tension effects are negligible in the prototype. According to Chow [18], the model flow must behave as a prototype for Reynolds Number is larger than 2000, and Weber Number is higher than 11, according to [19and20]. If scale effects will become significant in a model, a smaller prototype-to-model scale ratio should be used to minimize the scale effects. In a geometric scale ratio of $50:1$ or $25:1$, the gravity effect is predominant but the viscous effect might be eliminated [21and22]. Under this limit and the dimensions of the laboratory channel are used, then physical models are constructed with dimensions that accomplish a geometric scale of $50:1$. With this geometrical scale, similitude model ratios are listed in Table 1.

Table 1: Physical similitude relations.

Parameter	**Relations**
Discharge	$Q_r = V_r L_r^2 = L_r^{2.5}$
Velocity	$V_r = \sqrt{L_r}$
Energy	$E_r = L_r^4$
Reynolds number	$R_r = L_r^{1.5}$
Pressure	$P_r = F_r/L_r^2$

The primary spillway model is the 1:100 scale ofa large-sized prototype. The spillway model is ten times the size of the upper part of the primary model, as depicted in Figure 1. This scenario was performed hoping to obtain more details at the crest of an ogee spillway. The geometric dimensions for the selected case are summarized in Table 2.

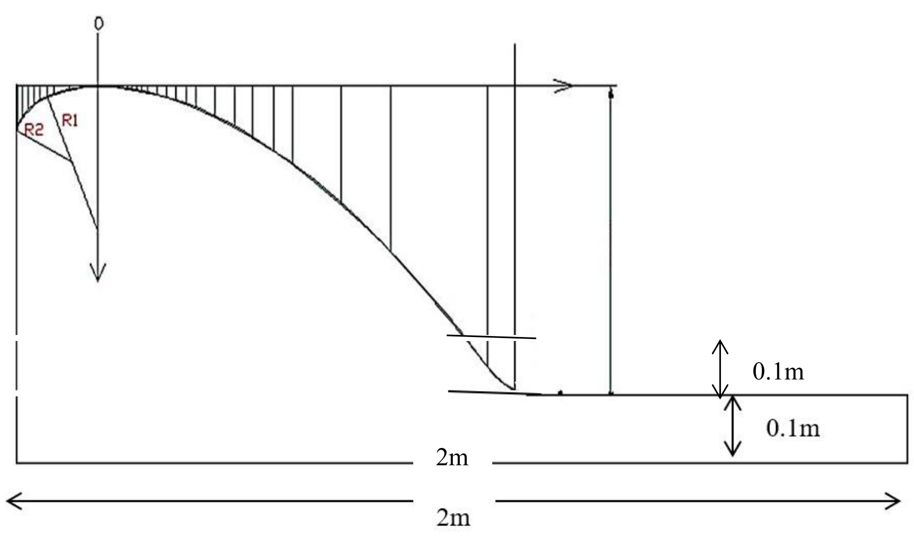

Figure 1: Schematic representation of the scale ogee spillway model.

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Table 2: Model dimensions.

Spillway length(m)	Spillway depth (m)	Crest width (m)	Spillway radius (m)	
			R_1	R_2
2.0	0.45	0.3	0.05	0.02

2.2 Model Setup and Facilities

The test consisted of one ogee spillway installed in a glass flume of 0.45m high, 0.30 m wide, and 12 m in length. The flow rate that could be obtainedin the laboratory ranged from (0.017 m/sec to 0.025 m/sec, which gives the initial Froude from 2.5 to 8.5. The laboratory setup was a closed loop system whereby the outflow system was set up to allow the flow to be re-used. The conceptual laboratory and physical model setup are shown in Figure 2.

Figure 2: Model setup.

An automatic-operated sensor system equipped with a needle gauge (point), which allowed vertical movement alongthe flume, was selected as a better way to measure water velocities along the ogee spillway.

2.3 Configuration and Arrangement of Standard USBR

The standard stilling basin, which uses the baffle blocks as a main feature for dissipating the surplus kinetic energy, was introduced in the late 1950's by Bradley and Peterka, and this study was further generalized and published as Reclamation Engineering Monograph No. 25 by Peterka A. J. on September 1958 (last re-print at May 1984). The shape and dimensions of the block are recommended by USBR at which the upper longitudinal dimension and width of the block are selected as a function of block height (Peterka, 1958). Three-block geometries were used: baffle, triangle, and stepped block. The blocks were made of timber and fixed at the height of 5cm for the entire Fr range (2.5-8.5) so that the width is 3.75 cm, and the length of the base is manufactured at 6 cm, as presented in Figures 3 (a to c).

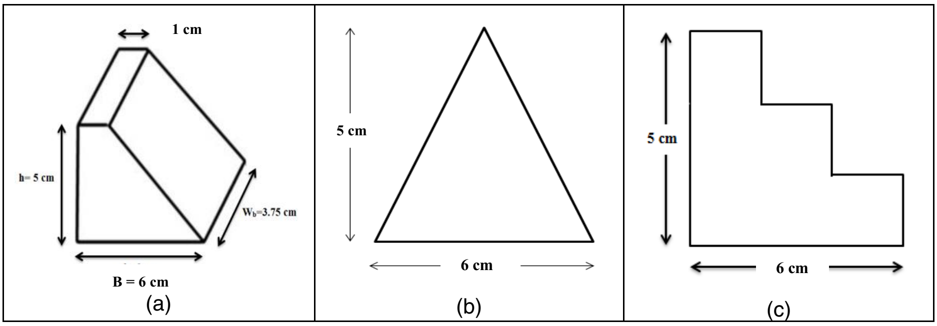

Figure 3: The configuration and dimensions of a: baffle block, b: triangle block, c: stepped block.

2.4 Block Distribution

The three used blocks have been arranged at a new proposed blockage ratio "η" so they do not exceed 0.5. The calculation of the blockage ratio is according to;

$$\eta = \frac{nW_b}{nW_b + \sum_1^{n+1} S_i} \quad (1)$$

Where the W_b, is the width of the block, and S, is the clear spacing between the adjacent blocks. Three groups of block model distributions were used; the first group is one row with two blockage ratios, the second group installed at two rows includes three different distance ratios $\bar{X}$/b, and the third group installed at three rows includes fixed distance ratios $\bar{X}$/b, where $\bar{X}$ is a distance from the front face of blocks of the first row to the front of the second row, as shown in Figure 4. All of these block configurations were installed with different blockage ratios. Table 3 presents these three distribution groups. The test was performed in order to select the most efficient one for improving the characteristics of a hydraulic jump, such as depth ratio and transverse velocity distribution.

Table 3: Characteristics of the models tested.

Group	Setup Style	No. of Rows	Blockage η	Dimensions (cm)			S1 cm	S2 cm	S3 cm	S4 cm	$\bar{X}$ /b
				h	b	W_b					
A	A1	One row	37.5%(1)	5	6	3.75	5.625	3.75	-	-	-
	A2	One row	37.5%(1I)	5	6	3.75	1.875	7.5	-	-	-
	A3	One row	50%	5	6	3.75	1.875	3.75	-	-	-
B	B1	Two rows	50and37.5% (II)	5	6	3.75	1.875	3.75	5.625	3.75	1
	B2	Two rows	50and37.5% (II)	5	6	3.75	1.875	3.75	5.625	3.75	2
C	C1	Three rows	50and37.5 % (II)	5	6	3.75	1.875	3.75	5.625	3.75	3

The design approach was based on the procedure documented in Small Dam Design by USBR (1987). Different configurations have been arranged in single, double rows, and complex rows. The location of the first baffle block from the toe spillway was selected equal to $X_0/y_2^* = 1.3$. It was adopted as recommended by [23], where the X_0 is related to the sequent depth of jump that was calculated by the Belanger equation. This type, in honor of the first definition and put the relations between its initial and sequent depth, was named after him:

$$\frac{y_2^*}{y_1} = \frac{1}{2}\sqrt{1 + 8Fr_1^2} - 1 \quad (2)$$

Since the maximum y_2^* is 17.11 cm according to the minimum incoming water level spillway, incoming Froude number X_0 was fixed at 22.24 cm downstream of the spillway for all runs undertaken. The space between the first block and the wall of the flume was equal to $0.5W_b$ for each side. Figure 4 represents a general sketch of these three used blocks distributions, over the USBR stilling basin.

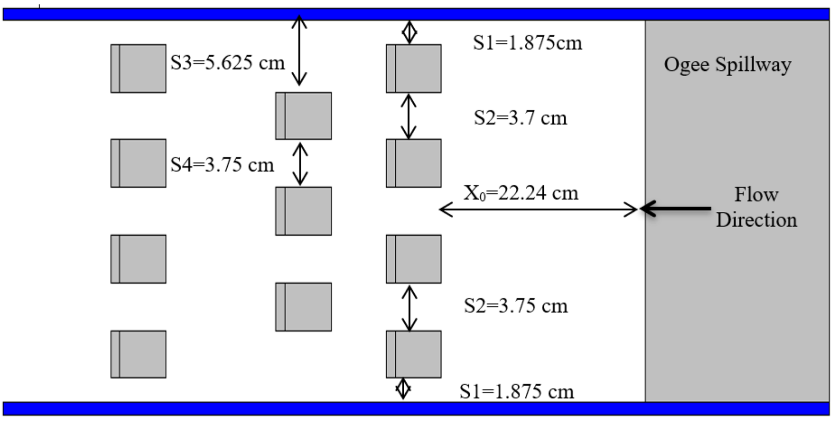

Figure 4: Block distribution along the stilling basin with top view sketch (Block arrangement-C1 three rows, $\bar{X}$ /b=2and η=50 and 37.5%II.).

2.5 Scour and Stilling Basin

One of the parts of the stilling basin is the end-sill. The end-sill is useful to inhibit the super-critic- flow from the crest of the spillway and hydraulic jump, which falls down to the stilling basin, changing to the sub-critic flow behind the end-sill form. End sill is used to evaluate the minimized velocities and hydraulic jump. One-row blocks fixed at the end of the spillway controlled the tail-water depth of flow. The mobile bed of sand was extended to 1.5 m in length with 0.1 m in thickness, as presented in Figure 5. The model sand is uniform with D_{50}= 1.7 mm.

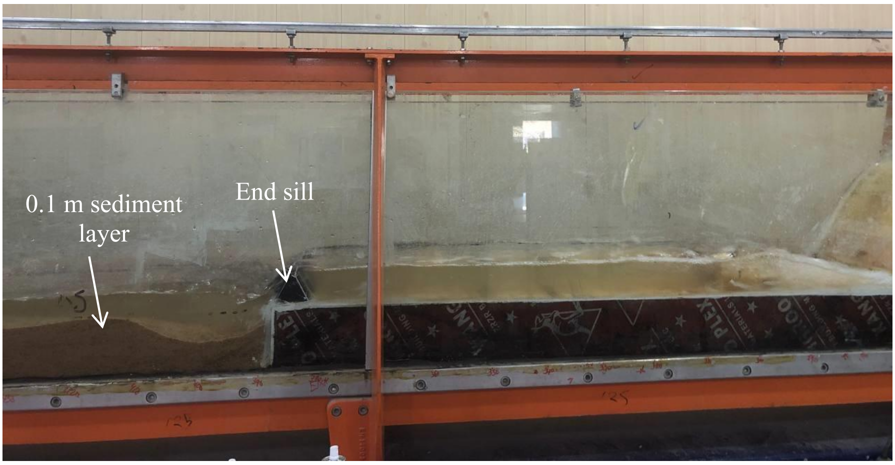

Figure 5: Stilling basin with end sill.

3. RESULTS AND DISCUSSION

The tests were performed to select the most efficient type of block for improving the characteristics of a hydraulic jump, such as transverse velocity distribution and scour downstream of the stilling basin.

3.1 Transverse Local Velocity Distribution Results

The velocity over the flume bed has been measured by the current meter across the flume width at the end section of the jump (location of y_2) to show the feature of velocity distribution transversely. The 99 runs were conducted with used block configurations installed for testing. The aim is to get a uniform velocity distribution across the width at the end of the stilling basin and reduce its value. Achieving this target is considered a positive indicator in terms of minimizing the ability to reduce scour downstream of the Ogee spillway. Figure 6 illustrates the transverse velocity distribution with different block configurations with the inlet Froude number range of 2.5-9.25 (steady jump), respectively. Figures 6 (a to d) also show little disagreement in the amounts and features of velocity distribution between single and double rows. However, with the double-row configurations, the velocity tends towards the uniform distribution across the channel width [24]. The most symmetrical distribution, along with less velocity, registers with configuration A1 and, to a lesser degree, with A2 and A3. The inverse situation was observed at a higher Froude number (within a range of steady jump), and the best distribution was registered with configurations B1 and B2.

For the entire flow range, the velocity distribution when using the configuration-C1 tends to become more uniform across the width despite its values seeming greater than those observed with the other configurations. The important thing that can be seen is that the use of stepped blocks gives significance to minimizing the chance of scour downstream by preventing the concentration of the flow at one side, which, if it occurs, increases the likelihood of failure.

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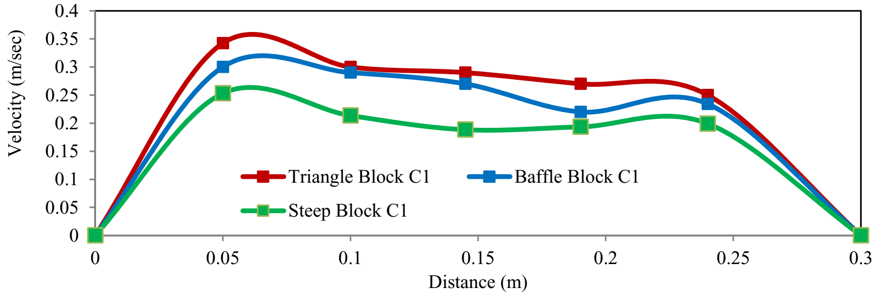
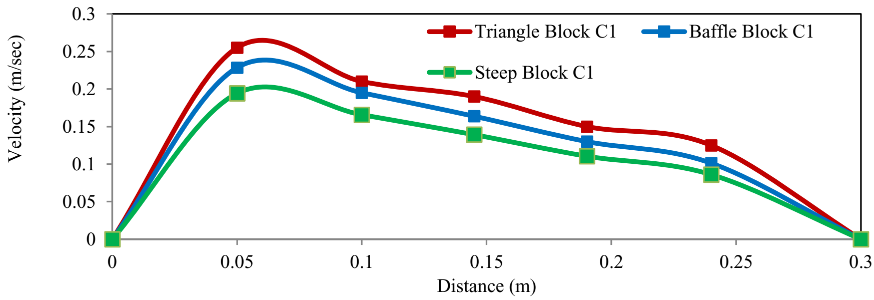
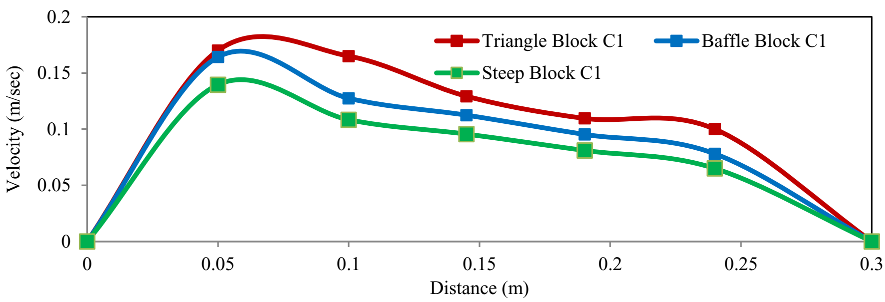


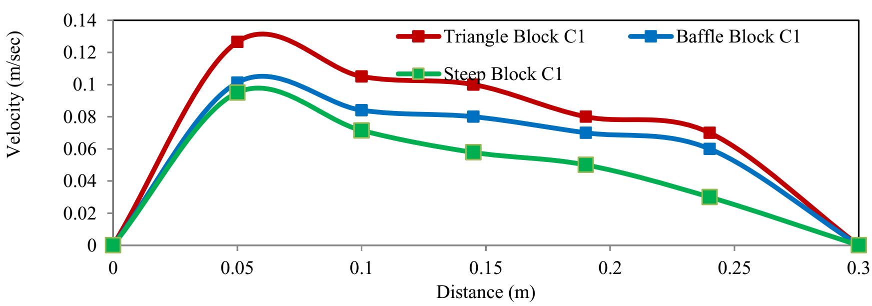
(a) Fr1=2.5.



(b) Fr1=4.5.



(c) Fr1=6.50



(d) Fr1=8.50

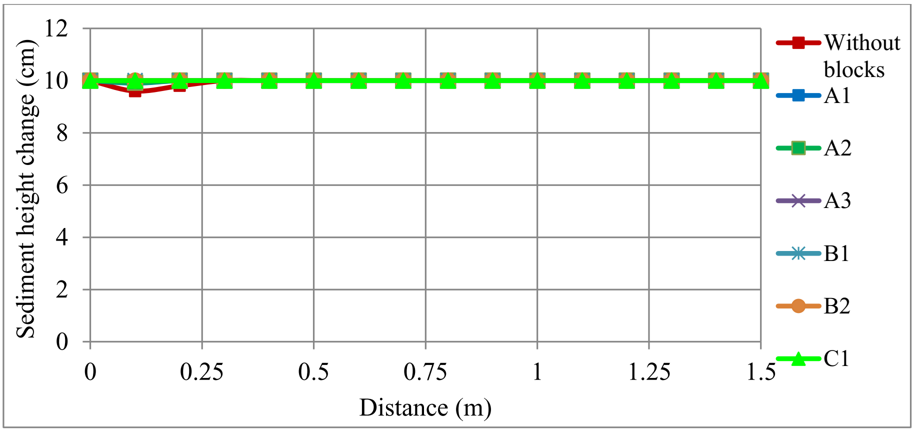
Figure 6: Variation of transverse local velocity with different configurations.

3.2 Stilling Basin with End Sill Results

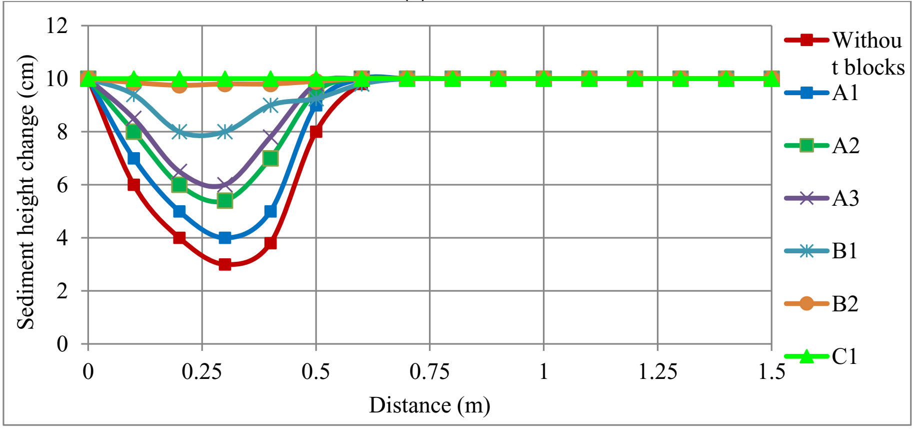
The hydraulic characteristics of the jump are measured and compared with the classical hydraulic jump under variable discharges [25]. The results of the experiments confirmed the significant effect of the sill on the dissipation of energy. The five quantitative measured discharges are gauged by the bend for each of the end-sill models. The parameters of the hydraulic jump measured are upstream depth (y_1) and downstream depth

(y_2), velocities (V_1 and V_2), energy dissipated with the hydraulic jump ΔE, sediment height Δs, sediment affected length L_s, mid sediment affected length L_{min}, water depth at upstream Y_{up}, and water depth at downstream Y_d. The result of hydraulic jump characteristics measurement for the three previously mentioned tests (A1, A2, A3, B1, B2 and C1). The effect of stepped blocks on the downstream scour can be seen when compared with the no-stepped condition, as presented in Figure 7. When the Froude number is equal to (2.5), it can be seen that this type of block is characterized by reducing the erosion that occurs in the stilling basin to a ratio of up to (100%), except the case of the absence of a block, which can be seen in the red line in the same figure. Also, when the value of the Froude number increases to 8.5, the maximum scour value increases from 0 cm to 4 cm.

To discuss the results of scour in the stilling basin, and according to the numerical modeling that was carried out, it can be said that the proposed distribution C1 was distinguished in reducing sediment erosion to a distinct degree, followed by the distribution of B2, B1, A3, A2, and A1, respectively. Among all the stepped block distributions, type C1 presented the best performance when considering the hydraulic jump, effectively ensuring energy dissipation. Although all baffle types with a sill present effective protection concerning the scour downstream of the structure.



(a) Fr1=2.5.



(b) Fr1=8.5.

Figure 7: Scour profiles at downstream flows of the stilling basin.

4. CONCLUSIONS

The findings can be summarized as follows:

- For baffle block configuration with (A1, A2, and A3) block distributions, the A3 distribution appeared with good results of reducing flow velocities within the stilling basin in accordance with A1 and A2 distributions, especially with the range of Froude number 4.5-8.5. Also, a good stability of the hydraulic jump was observed when using A3, which was difficult to achieve by using both A1 and A2.
- The stepped block is characterized by reducing the flow velocities compared to the baffle block and triangle block, as it can be seen that there is a decrease in velocities up to 0.85% for all used distributions (A1, A2, A3, B1, B2, and C1).

- The transverse local velocity distribution across the flume width, when using the C1 distribution, tends to become more uniform across the width. At the same time, these values seem more significant than those that were observed with the other distributions.
- Compared with A1 and A2 distributions, the A3 distribution is distinct with increases in the height of the water column upstream, which reduces the velocity on the same side and thus reduces the effects of the hydraulic jump and reduces scour in the stilling basin.
- According to the scour tests, hydraulic jump, and energy dissipation in the stilling basin, it can be said that the proposed distribution C1 was distinguished in reducing sediment erosion to a distinct degree, followed by the distribution of B2, B1, A3, A2, and A1, respectively.

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