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Effects of Chute Block Geometry on the Performance of the USBR II Stilling Basin

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ABSTRACT

Stilling basins are designed to reduce the high kinetic energy of supercritical flow in a downstream spillway. The USBR II stilling basin is distinguished by chute blocks fixed at the upstream end and a dented sill at the downstream end, allowing for the effective dissipation of excess energy. This research investigates the effect of chute-block geometry on the hydraulic performance of the USBR II stilling basin. Six modified chute-blocks with identical dimensions and spacings as standard blocks were constructed and evaluated for six incoming Froude-number values. The results indicate that chute blocks containing stepped side walls are more effective than standard blocks, increasing energy dissipation by 1.47% and decreasing the sequent depth ratio by 3.91%. Blocks with gradually increased spacings lose 0.7% more energy than standard blocks and reduce the sequential depth ratio by 1.91%. However, blocks with prismatic spacings and top surface angles of 152 degrees, relative to the downstream slope of the spillway, are less effective than standard blocks with energy dissipation reduced by 2.73% and the depth ratio increased by 7.24%.

KEYWORDS: Chute blocks, Energy dissipation, Hydraulic jump, Stilling basins.

INTRODUCTION

Energy dissipators are supplementary structures that reduce the downstream-flow energy within hydraulic structures, such as spillways, weirs and gates (Hayder, 2017). High-velocity incoming flow causes downstream river geometry to erode (Saleh et al., 2011). Hydraulic jump is a useful occurrence that can be used as an energy dissipater; hydraulic engineers employ the concept of hydraulic jump to design stilling basins (Bantacut et al., 2022; Ulfiana et al., 2019; Al-Naely et al., 2018) A hydraulic jump is an event characterized by turbulence, air entrainment and fluctuations in pressure and velocity (Carvalho et al., 2008; Macián-Pérez et al., 2020). The classic hydraulic jump (CHJ) occurs in smooth, horizontal, prismatic rectangular channels. To maintain the hydraulic jump within the stilling basin, it is coerced by an accessory, such as block, baffle or sill. This type of jump is referred to as a "forced hydraulic jump" rather than a CHJ (Imran et al., 2013; Peterka, 1978; Bhowmik, 1971). In a stilling basin, excess energy is converted into heat, spray and sound through a turbulent vortex generated by the jump. The inclusion of appurtenances in a stilling basin improves its function, stabilizes the jump motion and increases safety level (Chow, 1959). Such a structure must be efficient in terms of energy dissipation and create economical tail water level, length, scour and cavitation (Velioglu et al., 2012). Stilling-basin types were initially defined by Bradley and Peterka in 1957, who conducted a series of tests on chute blocks, baffle blocks and end sills and classified stilling basins according to an initial Froude number and incoming flow velocity (Bradley et al., 1957). The dimensions of hydraulic jump stilling basin depend on the sequential depth ratio and length of the hydraulic jump (Bejestan et al., 2009). These structures are designed to efficiently dissipate energy and to be cost-effective. According to numerous studies, design engineers believe that the implementation of the US Bureau of Reclamation (USBR) stilling basin design criteria provides superior performance (Hunt et al., 2021).

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The USBR II stilling basin was designed for high-dam and large-canal structures, in which the approach velocity increases and the corresponding Froude number exceeds 4.5. By adding chute blocks and notched end sills, the jump and basin lengths can be reduced by 33% (Chitale, 1959). Chute blocks arranged in an alternating pattern permit flow between chutes at the basin's entry and increase friction between water molecules and blocks, which results in a reduction in flow energy (Ulfiana et al., 2019). These blocks can impede the flow, as well as raise it from the basin floor, thereby requiring less basin length, reducing the amount of concrete needed and hence the associated construction costs. Furthermore, the blocks stabilize the jump in normal conditions, ensuring that it remains steady and is not drowned or washed out (Chow, 1959). The geometry of chute blocks in stilling basins has a considerable impact on the size and type of these structures. Due to their prevalence and usage as energy dissipators in the outlet of hydraulic structures, forced hydraulic jumps have been the subject of extensive studies. Harleman (1955) was one of the initial researchers to evaluate the function of baffle blocks in stilling basins and their effects on flow characteristics. According to Farhoudi et al. (2010), the pressure fluctuation at the upper face of chute blocks and at flow direction reaches its highest value at the toe of the spillway, where it joins the chute blocks and then decreases toward the downstream reach. Additionally, the pressure fluctuation in flow direction on the side face follows a similar pattern to that of the top face, albeit with a different relationship. Al Zubaidy et al. (2016) used direction-diverting blocks (DDBs) consisting of a variety of triangular shapes and apex angles employed as energy dissipaters in a downstream ogee spillway. No negative pressures developed at the edge of these blocks and more energy was lost as the number of blocks and rows was increased and the angle of the block apex reduced. Kaya et al. (2010) studied the effect of wedge, T-shaped, trapezoidal and stepped blocks on the energy dissipation of a flow passing over a chute with different slope angles. Elnikhely (2018) demonstrated that more energy is dissipated when water forms over staggered cylindrical blocks fixed to a spillway, whereas a diagonal arrangement has the smallest energy dissipation.

The geometry of a chute block is crucial when improving the relative loss of the stilling basin. However, the performance of the USBR II stilling basin with various shapes of chute blocks has not been fully investigated. The aim of this study is to investigate the hydraulic performance of six models of the USBR II stilling basin that contain alternate shapes of chute blocks when compared to the typified model in terms of sequent depth ratio and energy dissipation.

Experimental Works

Laboratory Flume

Experiments were conducted at Al-Mustansrya University College of Engineering in the Hydraulic Laboratory using recirculating flume that measures 20 m in length, 0.9m wide and 0.6m deep. The flume is constructed from a steel plate and has an armored plate-glass sidewall. Atop the side walls are two moveable carriages equipped with point gauges, which are mounted on the rails for the measurement of vertical elevations. Along the side of the flume, below the laboratory floor, a large concrete sump tank was constructed; water is stored in this tank and pumped to the flume *via* a centrifugal pump with an axial flow unit of 72 l/s capacity, 960 rpm and an axial flow unit with a three- phase, ten hp motor. Water is supplied to the flume *via* a 0.3-m delivery pipe that discharges into a steel inlet tank measuring 2m long, 1.6 m wide and 0.9 m deep. Water flow is controlled *via* a manually operated valve on the circulation system. A by-pass controlled by a butterfly valve is employed to maintain the pump's stable operation. Prior to the inlet tank, a flow meter was installed on the pipeline system to measure the flow rate. At the downstream end of the flume is a tank measuring 1.7 m in length, 0.9 m in width and 0.8 m in depth, from which the flow enters the pump's suction pipe *via* the sump. Both the inlet and outlet tanks are securely connected to the upstream and downstream ends of the flume and the entire system is mounted on a steel frame with two cylindrical bearings in the center. Four electric- powered screw jacks are attached to one end of the flume and are used to adjust the angle of the slope as required. At the downstream end of the flume, a tailgate was installed to control and adjust the tail-water depth to ensure that the jump occurred at the downstream end of the spillway (toe). To measure passing discharges, a sharp- crested triangular weir was constructed from a metal plate and positioned at the center of the width of the channel, approximately

3m from the inlet tank. Prior to initiating the experiment, the discharge weir was calibrated using a volumetric flow meter. In this study, the discharges ranged from (8 to 33 l/s). A physical model of a spillway was constructed based on the criteria established by the United States Bureau of Reclamation (USBR) for ogee-spillway design (Uncan et al., 1987). This design is based on a maximum discharge of 33 l/s and with the following dimensions: 35 cm high, 90 cm wide, vertical upstream face, a slope of downstream face 0.8 H: 1V and a reverse curve with a radius of 9 cm. The spillway was installed in the middle third of the laboratory flume, 7m upstream of the tail gate. The details, including inlet and outlet tanks of the experimental flume, are illustrated in Figure 1 and Figure 2, respectively.

Figure (1): Inlet and outlet tanks of the experimental flume

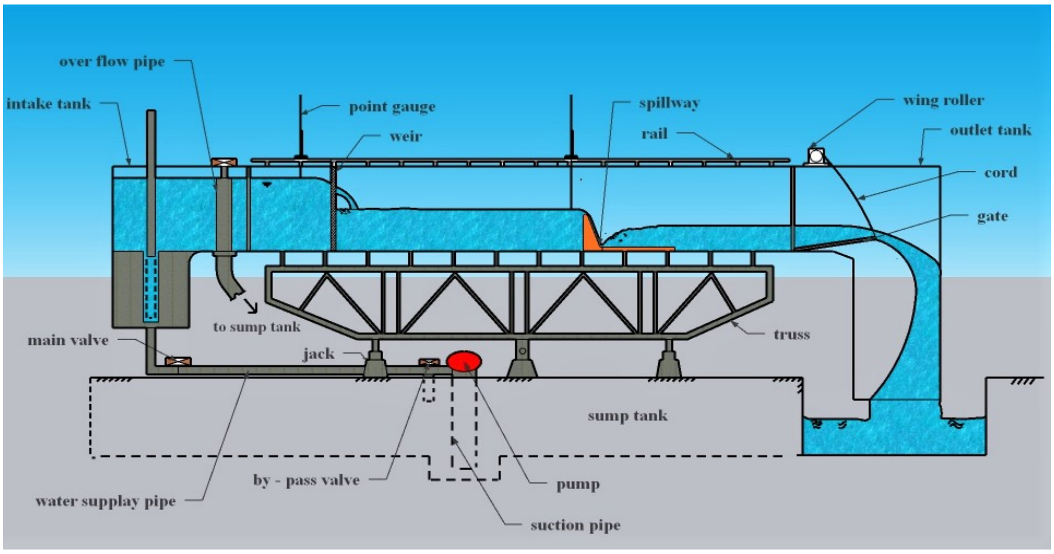


Figure (2): Detailed sketch of experimental flume

Typified USBR II Stilling Basin

The physical model of the stilling basin employed in this study was created per the design blueprints of a USBR II stilling basin (Peterka, 1978). According to the recommendations, the height and width of a chute block should be equal to the depth of the flow entering the basin (y_1) and the spacing between two adjacent blocks should be equal to y_1. Along each wall, a distance equivalent to ($y_1/2$) is advised to minimize spray and maintain desired pressures. The recommended maximum width and spacing for the dentated sill is $0.15y_2$, while the height should be $0.2y_2$ and there should be a dentate adjacent to each side wall. The slope of the continuous end sill part is 2:1. The stilling basin's physical model was created using the following planning parameters: Q_{max}= 33 l/s, y_1 = 1.5 cm, B = 90 cm, Fr_1 = 6.37 and y_2 = 13 cm. The length of basin (L) is related to Fr_1; i.e., L = 53 cm. Figure 3 contains a comprehensive illustration of a typified USBR II, while Figure 4 illustrates its physical model. The energy-dissipation devices of a physical model were created using 3D printing technology.

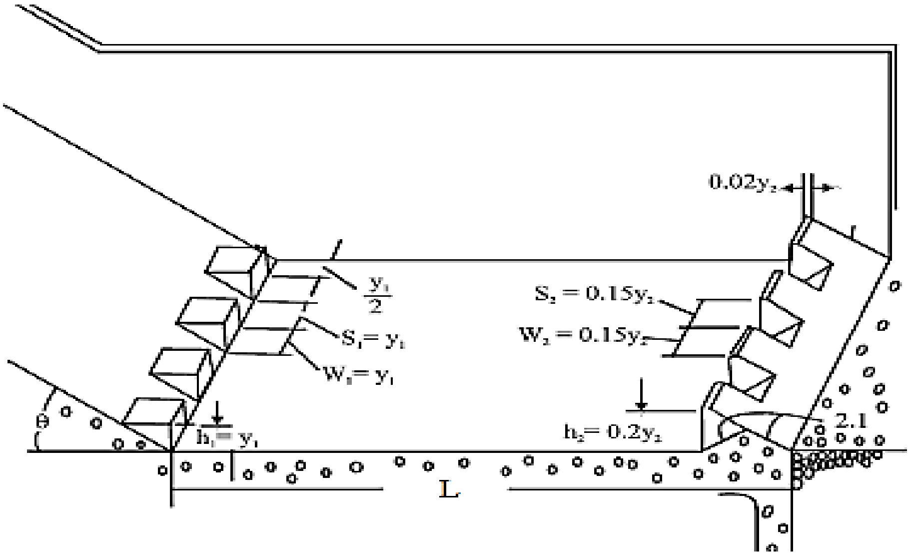


Figure (3): Typified USBR II stilling basin

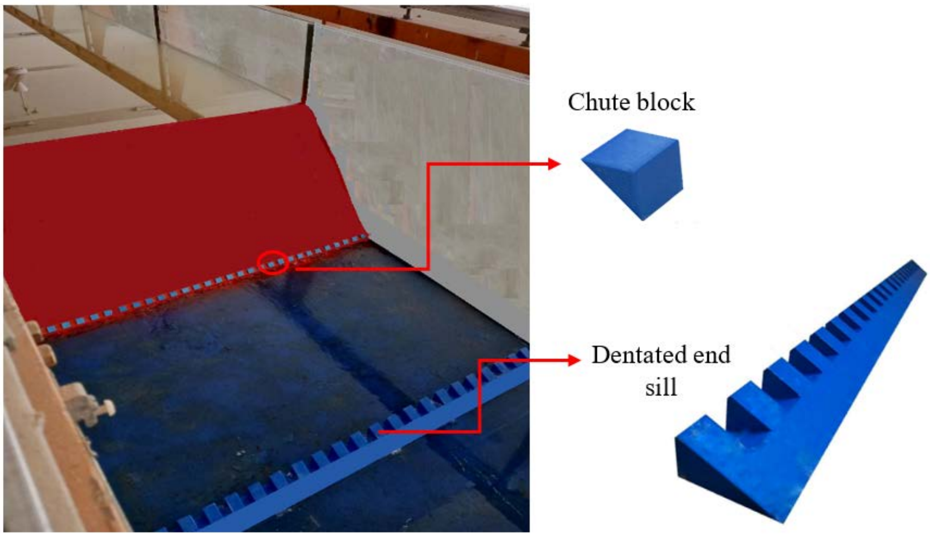


Figure (4): Physical model of USBR type II stilling basin

Modified Stilling Basins

This study modified the standard USBR II model by altering the geometry of chute blocks, while maintaining some parameters, such as height, width and distance between the top edges of adjacent blocks. Consequently, six physical models of the modified USBR II stilling basin were constructed utilizing the chute blocks depicted in Figure 5. Additionally, Figure 6 provides illustrations detailing the block sketches for the six models. These shapes were selected to create a turbulent motion and flow separation by modifying the area of the top surface or the side wall, resulting in a change in the cross-sectional area of flow between two adjusted blocks when compared to a standard one. The geometry and dimensions of the dentated end sill in all models remained identical to the typified USBR II stilling basin. The chute blocks were manufactured with a Creality Ender 3 V2 3D printer utilizing a 3D printing technique. Polylactic acid (PLA), one of the most common thermoplastics, was utilized to print the components, which were then bonded to the downstream end of the spillway.

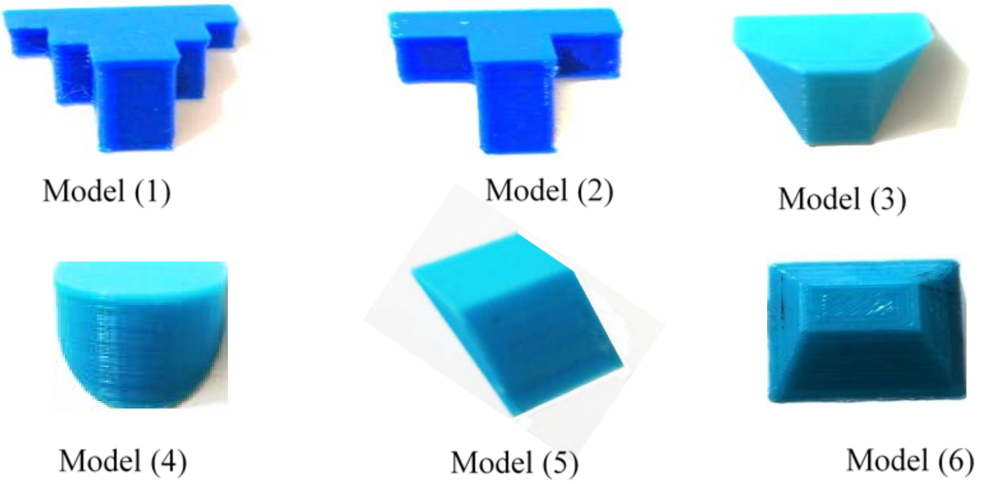
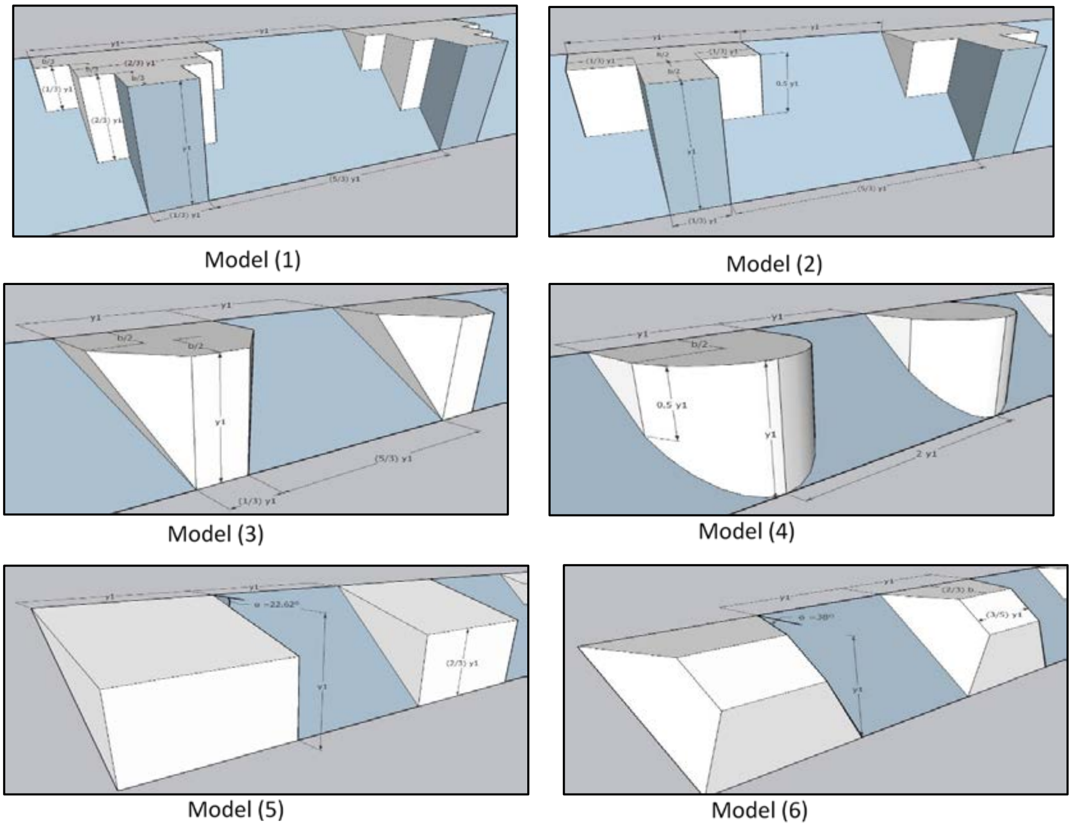

Model (1)
Model (2)
Model (3)
Model (4)
Model (5)
Model (6)

Figure (5): Physical models of chute blocks



Model (1)
Model (2)
Model (3)
Model (4)
Model (5)
Model (6)

Figure (6): Detailed sketches of chute blocks

RESULTS AND DISCUSSION

To study the effects of chute-block geometry on the performance of a USBR II stilling basin, characteristics, such as sequent depth ratio and energy loss, were analyzed and will be discussed in the following sub-sections.

Sequent Depth Ratio

The sequent depth ratio, defined as the ratio between the downstream (y_2) and the upstream (y_1) flow depths, is an important characteristic for defining the hydraulic-jump efficiency. For classical hydraulic jumps, the sequent depth ratio can be calculated using the Belanger equation, which is based on continuity and momentum equations (Chow, 1959):

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1+8{Fr_1}^2} - 1\right) \tag{1}$$

where y_1 is the water depth at the jump toe, y_2 is the sub-critical sequent depth and Fr_1 is the corresponding Froude number of supercritical flow ($Fr_1 = v_1/\sqrt{gy_1}$).

Initially, the sequent depth ratios for classical hydraulic jumps were measured for six discharge values ranging from 8 to 33 l/s and are summarized in Table 1. Following this, under identical hydraulic conditions, the sequent depth ratios were measured in the USBR II stilling basin. The tail-water depth was adjusted in all tests so that the jump began at the toe of the spillway and the tail water depth was approximately equal to the sequent depth. As shown in Table 1, as the discharge increased, the corresponding Froude number for supercritical flow decreased. This indicates that the increasing rate of the supercritical depth (y_1) is greater than the rate for the corresponding velocity (v_1). As a result, determination of Froude-number values is primarily dependent on the initial depth of the hydraulic jump. This finding supports previous studies which indicated the Froude number to be inversely related to the discharge for the hydraulic jump downstream of the spillway in the USBR II stilling basin (Peterka, 1978; Fecarotta et al., 2016; Padulano et al., 2017; Mousavi et al., 2022).

As illustrated in Figure 7, the experimental data concerning the CHJ is slightly lower than the theoretical data based on Belanger equation due to the bed friction force, which is not taken into account in this equation (Chern et al., 2013; Alhamid, 1994).

Additionally, the average sequent depth ratio of the hydraulic jump associated with USBR II is nearly 10% less than in a CHJ. Energy dissipation apparatus, such as chute blocks and end sills, in USBR II stilling basin, can reduce hydraulic-jump dimensions and improve energy dissipation. Consequently, the stilling-basin model gave a lower sub-critical flow depth than the anticipated values for a CHJ. Peterka (1978) stated that the ratio of sub-critical depth in a stilling basin to the sub-critical depth in a classical jump should lie between 0.6 and 1.0, which was corroborated by Macián-Pérez et al. (2020). This ratio corresponds with a value of 0.9 in the current study, which falls within the range. Additionally, Bradley et al. (1957) and Izadjoo et al. (2007) stated that the average value of the dimensional index (I) shown in Eq. 2 for the USBR II stilling basin is approximately 0.15, whereas in the present study it is approximately 0.1.

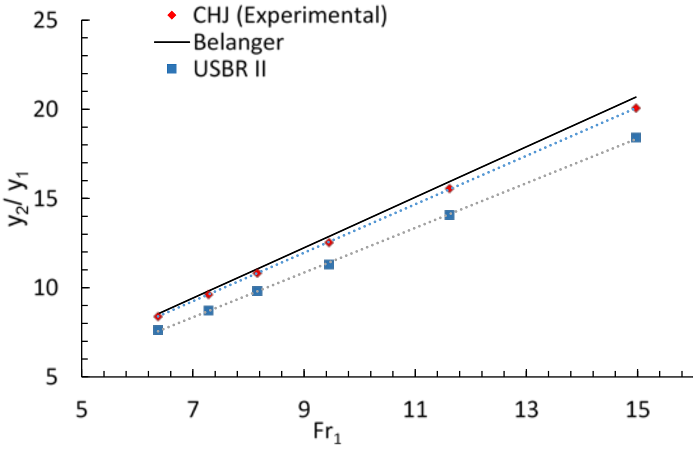


Figure (7): The relation between sequent depth ratios and initial Froude numbers

$$I = \frac{y_{2\,CHJ} - y_{2\,USBR\,II}}{y_{2\,CHJ}} \qquad (2)$$

Under the same hydraulic conditions, sequent depth ratios for six physical models of modified stilling basins were measured and plotted against an initial Froude number (Fr_1) as illustrated in Figure 8. In each test, the tail-water depths were adjusted so that the jump commenced at the spillway toe. Figure 8 indicates that, for a given block height, width and spacing, the tail water depths required to induce jumps within the basin, using models 1 and 3, are slightly less than the depths associated with standard USBR II blocks. In contrast, the depths of the tail-water are slightly greater for hydraulic jumps with blocks of types 2, 4, 5 and 6. Under the same hydraulic conditions of incoming flow, the percentage variations in sequent depth ratios relative to those of USBR II and CHJ were determined for each model using the following equations:

$$V_{USBR\,II}\% = \frac{(y_2/y_1)_{model} - (y_2/y_1)_{USBR\,II}}{(y_2/y_1)_{USBR\,II}} * 100 \qquad (3)$$

$$V_{CHJ}\% = \frac{(y_2/y_1)_{model} - (y_2/y_1)_{CHJ}}{(y_2/y_1)_{CHJ}} * 100 \qquad (4)$$

where $V_{USBR\,II}\%$ and $V_{CHJ}\%$ represent the percentage variation in sequent depth ratio for the model relative to USBR II and CHJ, respectively. The average values of $V_{USBR\,II}\%$ and $V_{CHJ}\%$ for the six models are listed in Table 1. The negative signs indicate less sequent depth ratios.

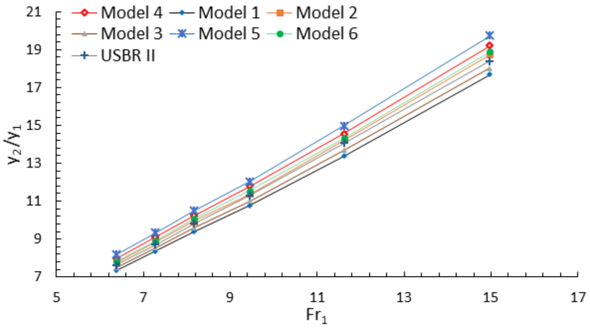


Figure (8): Sequent depth ratios against initial Froude numbers for seven physical models of stilling basins

Table 1. Results of the experimental tests for CHJ

Q (lps)	Fr_1	y_2/y_1
33	6.37	8.40
28	7.28	9.63
23	8.16	10.83
18	9.45	12.53
13	11.62	15.55
8	14.97	20.06

Energy Dissipation

The specific energy at any flow section can be calculated *via* this equation:

$$E = y + \frac{v^2}{2g} \qquad (5)$$

where y and v are the depth and velocity in this section, respectively. The energy lost during the hydraulic jump is equal to the difference in specific energy before and after the jump. The relative energy loss (F) is calculated using this formula:

$$F\ \% = \left(\frac{E_1 - E_2}{E_1}\right) * 100 \qquad (6)$$

where E_1 and E_2 correlate to the specific energy upstream and downstream of the hydraulic jump. The relative energy losses of a CHJ and a forced hydraulic jump in the typified USBR II stilling basin against Froude numbers are illustrated in Figure 9. In this figure, the relative energy loss for the hydraulic jumps created in the stilling basin is slightly greater than that of a CHJ under the same conditions. Thus, the average value of a stilling basin's relative losses is approximately 4 % greater than in a CHJ. Padulano et al. (2017) analyzed hydraulic jump in USBR II with a wide range of initial Froude numbers and obtained values of relative loss ranging from 70% to 75% for $Fr_1 = 9$. Furthermore, according to Macián-Pérez et al. (2020), the relative energy loss in a USBR II is 70.5 % for the $Fr_1 = 9$. These findings are consistent with those of the current study, in which the relative energy loss for $Fr_1 = 9$ is approximately 74%.

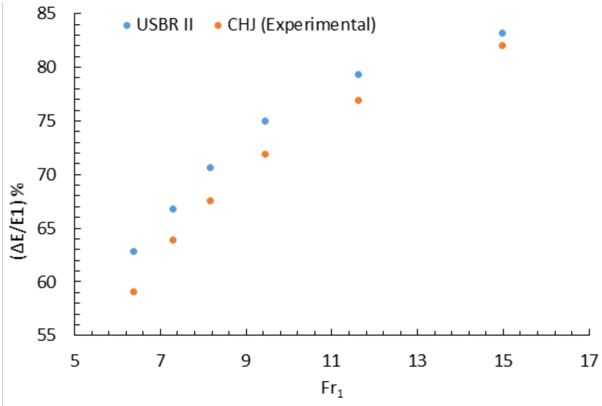


Figure (9): Relative energy loss of CHJ and forced hydraulic jump in the typified USBR II stilling basin against Froude numbers

The relative energy losses for the six modified models of the USBR II stilling basin are plotted against Froude numbers in Figure 10. Additionally, the percentage variations in relative energy loss, relative to those of a typified USBR II and a CHJ with identical flow conditions, are calculated using the following equations:

$$(F_V)_{USBR\,II} = \frac{F_{model} - F_{\,USBR\,II}}{F_{\,USBR\,II}} * 100 \qquad (7)$$

$$(F_V)_{\,CHJ} = \frac{F_{model-}F_{CHJ}}{F_{CHJ}} * 100 \qquad (8)$$

where $(F_V)_{USBR\,II}$ and $(F_V)_{\,CHJ}$ represent the percentage change in relative energy loss for the models relative to USBR II and CHJ, respectively. Table 2 displays the average values of $(F_V)_{USBR\,II}$ and $(F_V)_{\,CHJ}$ for the six models. The negative sign represents a reduction in energy dissipation.

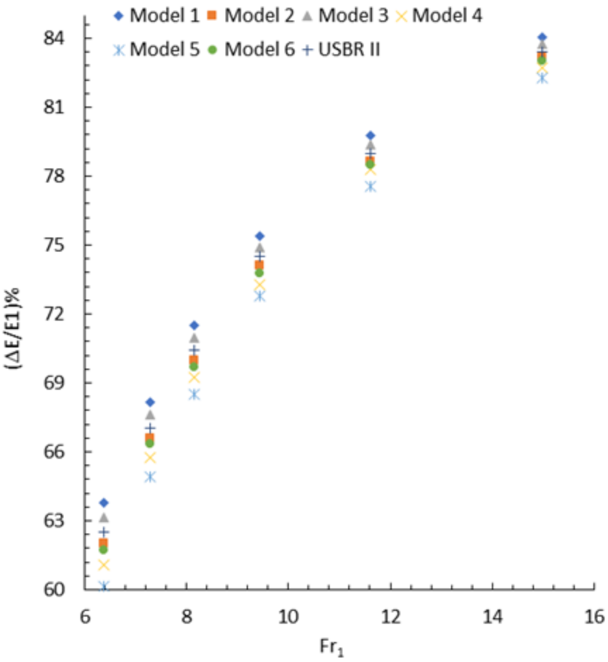


Figure (10): Relative energy loss against initial Froude numbers for seven models of stilling basins

Table 2. The average percentage differences in sequent depth ratio for six models of stilling basins compared to typified USBR II and CHJ

Model	$V_{USBR\,II}\%$	$V_{CHJ}\%$
1	-3.91	-13.2
2	1.39	-8.62
3	- 1.91	-11.3
4	4.27	-5.42
5	7.24	-2.98
6	2.39	- 9.29

Discussion

An effective stilling basin design requires the maximum possible amount of energy dissipation and a minimum value for the sequential depth ratio for a hydraulic jump. In accordance with a specific energy curve, a rise in energy dissipation decreases the sub-critical depth of the hydraulic jump (Bhowmik, 1971; Habili et al., 2018). As anticipated, due to the close relationship between the sequent depth ratio and relative energy losses, increased relative energy losses resulted in lower sequent depth ratios. When assessing all test models, including the USBR II, the results shown in Tables 2, Table 3, Figure 8 and Figure 10 indicate that model-1 chute blocks were most effective at lowering the sequent depth ratio, whereas model 5 was the least effective. Furthermore, models 1 and 3 were more efficient than standard chute blocks, whereas models 2, 4, 5 and 6 were less efficient.

As depicted in Figures 5 and 6, the basic design principle for chute block-models 1 to 4 consisted of modifying the geometry of the horizontal cross-sectional area to increase the cross-sectional flow area between two adjusted chute blocks. This expansion often resulted in flow separation, turbulent eddy motions and flow-energy dissipation (Najafi-Nejad-Nasser et al., 2015). For model 1 of the stilling basin, the chute block has a horizontal cross- section with two steps of sharp-edge corners on each side wall. The streamline cannot perform sharp 90° turns, especially at high velocity; so, the flow separates at the corners, creating turbulent eddies and converting kinetic energy into internal energy. Furthermore, the effective frictional area of the side walls between two adjacent blocks was 42% greater than in the USBR II, increasing energy loss.

In the case of model 3, the second portion of the horizontal cross-sectional area expands gradually. The results indicate that this shape of block is less effective than model 1, but more effective than standard blocks. According to Chaudhry (2007) and Leifsson et al. (2010), head losses caused by abrupt expansion are greater than losses caused by gradual expansion, which results in less turbulence. Additionally, the effective frictional area of the side walls between two adjacent blocks was approximately 18% greater than in the standard one and 24% less than in model 1.

The blocks in the second model dissipated energy less efficiently than the standard blocks and those in models 1 and 3, despite the sudden expansion of the side walls and the fact that the area of the side walls between adjacent blocks was equivalent to that of model 1. The split water between the blocks has a lower frictional area, because the water falls from the forward protruding portion of the horizontal cross-section and forms an air pocket, preventing the split water from completely contacting both sides of the protruding section. Additionally, a portion of the water that separates from the top surface of the block (which has a 33% smaller surface area than in a standard chute block) falls from each side of the protruding portion and assists in the formation of the previously mentioned air pocket. Model-4 stilling basin has chute blocks with rounded corners, since the stream lines become smooth on the round surface and the friction required to disperse the energy is reduced. According to Peterka (1978), rounding the corners, even slightly, tends to streamline the block and decrease its effectiveness as an impact apparatus.

Table 3. The average percentage differences in relative energy loss for six models of stilling basins compared to typified USBR II and CHJ

Model	$(F_V)_{USBR\ II}$ %	$(F_V)_{CHJ}$%
1	1.47	5.27
2	-0.54	3.22
3	0.70	4.53
4	-1.52	2.20
5	-2.73	1.18
6	- 0.89	2.90

Model-6 chute blocks are pyramidal with trapezoidal side walls and are less dispersive than standard chute blocks and those of models 1, 2 and 3. Additionally, block 6 has a reduced top surface area than other models and is approximately 47% smaller than the standard chute. As shown in Figure 6, the top surface of block 6 was inclined at an angle of 167º relative to the downstream slope of the spillway. This caused the streamlines on the inclined to surface to be smoother than in models 1,2,3 and 4 and the standard model, where this angle equals 129º, which reduces the energy dissipation efficiency of block 6. Alternatively, the divergence of block side walls may result in greater energy loss. Model 5 of the stilling basin was the least effective, because the top surface of the block is inclined at 152 degrees relative to the downstream slope of the spillway, resulting in a smoother surface. Compared to other models, the falling jet from the block's top surface falls with a low height and short distance and was measured as being approximately 33% less than in other models. As one of the primary functions of the chute block in a stilling basin is to lift the flow from the basin floor, the shape of this block reduces energy dissipation. In addition, the side walls of block 5 have a smaller surface area than the side walls of other models, resulting in less energy loss when considering the jets that move between blocks. The side walls area of block 5 is approximately 33% smaller than in the USBR II block. Furthermore, the distance between two adjacent blocks is kept constant, which reduces turbulence. A combination of these factors leads to the conclusion that block 5 is the least effective.

CONCLUSIONS

This study aimed to analyze the effect of using six differently shaped models of chute blocks, rather than the current paradigm, on the performance of USBR II stilling basin. The experiments allowed the following conclusions:

1. Compared to standard blocks, chute blocks with stepped side walls are the most efficient, as they reduce the sequent depth ratio by approximately 3.91% and increase energy dissipation by 1.47%. These results occur, because the streamline cannot make sharp 90-degree turns, especially at high velocity, causing the flow to separate at corners, creating turbulent eddies and converting kinetic energy into internal energy. In addition, stepped side walls have a greater effective surface area standard blocks.
2. Model 5 is the least efficient of all models, including standard blocks. Increasing the slope of the chute block's top surface, relative to the downstream slope of the ogee spillway, causes the streamlines to move increasingly smoothly, thereby decreasing energy loss. Additionally, when compared to other models, the jet falls from the block's top surface at a low height and a short distance. The rate of energy dissipation is reduced by approximately 2.73% compared to standard blocks, while the sequent depth ratio increases by approximately 7.24%.
3. Rounding the corners of side walls reduces the efficiency of chute blocks, because the streamlines are smoother and the friction required to disperse the energy is reduced.

Conflict of Interest

The corresponding author confirms, on behalf of all authors, that there is no conflict of interest to be declared.

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