Behavior of the Alternative Types of USBR Basin with Changes in the Geometric Characteristics of the Straight Walls of the Stilling Basin

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Received: 23 November 2024 | Revised: 22 December 2024 | Accepted: 1 January 2025

ABSTRACT

A stilling basin is a vital energy dissipator structure that transitions supercritical flow from a dam spillway into subcritical flow to protect downstream (ds) riverbeds from the scouring caused by high-velocity water. This study evaluates the impact of wall configurations and middle blocks on energy dissipation efficiency in stilling basins by modifying wall shapes and incorporating middle blocks. Five cases were tested: flat walls with middle blocks (Case 1), small zigzag walls without and with middle blocks (Cases 2 and 3), and large zigzag walls without and with middle blocks (Cases 4 and 5). A total of 55 experiments were conducted with discharges ranging from 0.010 m³/s to 0.020 m³/s. The average energy dissipation rates were 61.1%, 58.5%, 65.2%, 63.6%, and 64.9% for Cases 1, 2, 3, 4, and 5, respectively. Case 3, featuring small zigzag walls with middle blocks, demonstrated the highest energy dissipation efficiency, outperforming the other cases. This research highlights innovative designs for stilling basins, enhancing energy dissipation efficiency and mitigating the ds scouring effects.

Keywords-energy dissipator; hydraulic jump; stilling basin; straight walls; spillway

I. INTRODUCTION

One of the critical challenges following the construction of dams/weirs and diversion dams is managing the hydraulic jump and ensuring its stability within the stilling basin. Common phenomena, such as erosion of the riverbed ds of the stilling basin, the formation of scour holes, and the ds displacement of the hydraulic jump, can lead to significant damage to large dams and diversion structures designed to handle flood flows. A proven approach to stabilizing the hydraulic jump and reducing the flow energy upon reentry into the river is the installation of blocks within the supercritical flow zone. These blocks dissipate the flow energy throughout the basin, ensuring that the flow reaches the river entrance with reduced energy. Several researchers have contributed to understanding and improving energy dissipation mechanisms. Authors in [1] tested physical models of check intake structures to evaluate the adequacy of stilling basins and the effectiveness of baffle piers in decelerating flow. Authors in [2], conducted experimental tests on the energy dissipation efficiency of various shapes in stilling basins at different apex angles, while authors in [3] performed laboratory tests on physical models to evaluate the performance of continuous and dentate end sills in energy dissipation within stilling basins. Similarly, authors in [4] employed model studies to enhance the design of energy dissipaters for forced hydraulic jumps. Furthermore, in [5], experiments were conducted with Froude numbers ranging from 2.5 to 4.5, demonstrating increased energy loss and reduced basin length requirements. In [6], the energy dissipation efficiency was investigated using curved appurtenances in stilling basin through field experiments with physical hydraulic models.

The effects of the curved baffle block's size, curvature, and location on energy dissipation and hydraulic jump control were experimentally studied in [7]. According to studies and statistics from the International Commission on Large Dams, over 20% of the dam accidents result from inadequate energy dissipation arrangements [8]. Authors in [9] analyzed the energy dissipation and hydraulic jump characteristics ds of a rectangular channel gate, finding that the hydraulic jump energy dissipation depends on factors, such as the gate opening, Weber numbers, and Froude numbers. Authors in [10] conducted laboratory investigations into a hydraulic jump with wedge-shaped baffle blocks and an artificially roughened bed, developing new experimental formulations for the hydraulic jump length and sequential depth ratios as functions of the bed roughness and Froude numbers. In [11], the effects of baffle block shapes on the flow pattern behind radial gates were studied through experimental testing, considering four distinct block configurations alongside a level floor without baffles for comparison. Authors in [12] designed a chute spillway using baffle blocks, which eliminated the need for a traditional stilling basin. Their designs, based on real-world prototypes from the 1950s, employed an empirical approach, offering flexibility in the baffle height, layout, and spacing. Authors in [13] explored the energy dissipation in an ogee spillway, analyzing the influence of bed-block roughness, jet length, and the presence of flip buckets at varying takeoff angles. Authors in [14] assessed a novel seven-baffle-block design's effectiveness in reducing stilling basin dimensions for irrigation systems, demonstrating an improved hydraulic energy dissipation and decreased jump length, while authors in [15] investigated the variations in energy dissipation and hydraulic jump within a USBR Type IV spillway system, using physical models to evaluate elements like floor elevation, end thresholds, and riprap lengthening.

While the majority of these studies emphasize energy-dissipating structures on the stilling basin bed, limited attention has been paid to the role of wall-mounted appendages as energy dissipaters. The present study aims to fill this gap by conducting experimental analyses on the effects of wall and bed blocks in stilling basins, focusing on the dynamic energy dissipation of water. Experiments were carried out using physical models of an ogee spillway (USBR alternative Type IV) with and without a middle block in the stilling basin. Various zigzag wall configurations and block roughness conditions at the spillway toe were examined across a range of Froude numbers.

II. MATERIALS AND METHODS

The interplay between the turbulent flow and entrapped air creates a complex flow behavior over the USBR stilling basin, which is not yet fully understood [16]. To investigate these relationships, physical modeling was selected for this study. Laboratory experiments were conducted to examine the behavior of the modified United States Bureau of Reclamation (USBR) Type IV basin models.

A. Flume and Instruments

The experimental setup utilized a recirculating flume, as illustrated in Figure 1. The flume measures 10 m in length, 0.3 m in width, and features side walls 45 cm in height. A pump with a discharge capacity of 20 L/s provides flow to the system. To mitigate the turbulence at the inlet, a screen plate was installed at the flume's intake. Additionally, spillway models were placed 2.5 m ds of the entrance tank to ensure gradual and stable flow entering the laboratory flume. A flow meter, calibrated to measure discharge with an accuracy of 1 ml/s, was installed on the pipeline to monitor the flow rate accurately. To measure the water levels, three sensors were mounted on brass rails positioned along the top edges of the flume's side walls. These sensors provided precise water level readings during the experiments.

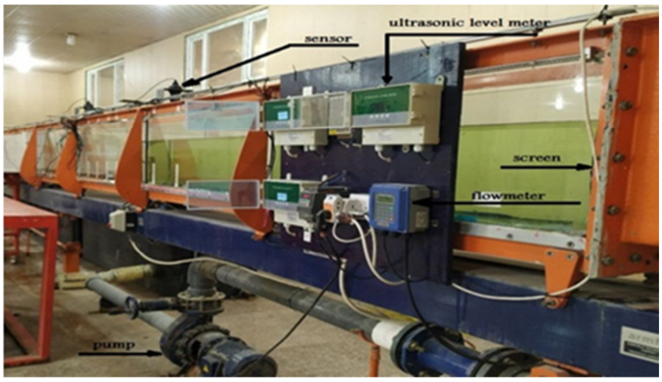

Fig. 1. Experimental setup of laboratory flume.

B. Design Equation

The design model was constrained by the flume dimensions (0.3 m width) and discharges ranging between 10 L/s and 20 L/s. Based on these parameters, a spillway was designed to generate a hydraulic jump under the specified discharge conditions.

The discharge over an ogee crest can be calculated using [17-18]:

$$Q = C_d \, L \, h_e^{1.5} \qquad (1)$$

where Q is the discharge, C_d is the discharge coefficeint, taken as 2.183 for vertical-faced discharge coefficients for ogee crests [19], L is the effective crest length, equal to 0.3 m, and h_e is the actual head in the crest (m). Q and C_d were utilized to calculate h_e.

C. Laboratory Models

Modified models for the alternative stilling basin (type IV) were constructed in the laboratory, following the standard dimensions for this type of block [17]. Five laboratory models were created to represent the five test cases, as displayed in Figure 2:

- **Case 1**: Flat wall with middle blocks.
- **Case 2 and Case 3**: Small zigzag walls without middle blocks.
- **Case 4 and Case 5**: Large zigzag walls without middle blocks.

To ensure durability and minimize expansion in the presence of water, the models were constructed from wood and coated with varnish and epoxy. Typically, smoother surfaces in the model compared to the prototype are considered adequate for experimental purposes [17]. The model designs included five stilling basins and an ogee spillway. Figure 3 provides details of the produced model, including the ogee spillway, stilling basin, walls, and blocks.

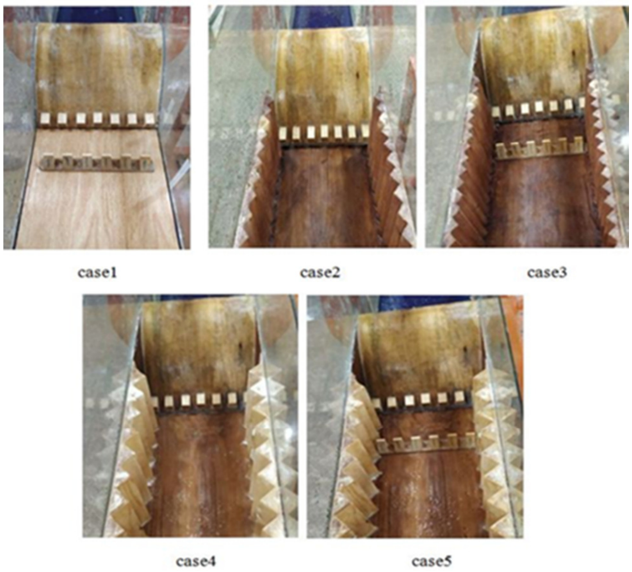

Fig. 2. The five laboratory models of the alternative stilling basin.

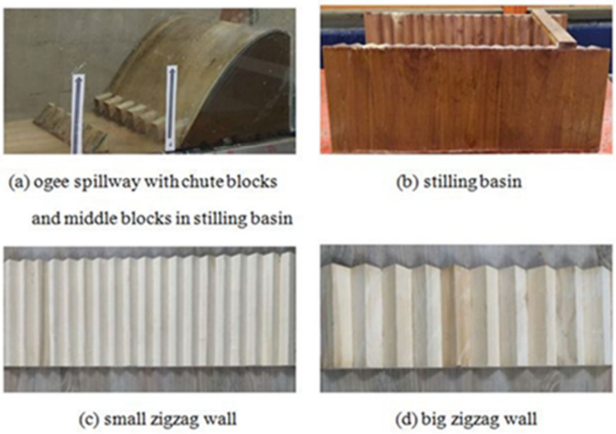

Fig. 3. Laboratory models of (a) the ogee spillway, (b) ths spilling basin, (c) the small zigzag wall, and (d) the large zigzag wall.

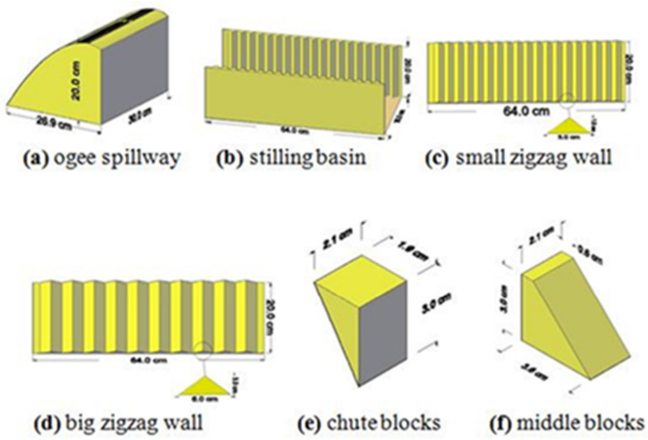

Fig. 4. The dimensioned elements of laboratory models.

The dimensions of each laboratory-built stilling basin model are: 0.3 m width, 0.2 m height, and 0.64 m length. The measurements of the ogee spillway are: 0.3 m width, 0.2 m height, and 0.269 m length. All five cases included seven chute blocks. However, Cases 1, 3, and 5 also included six middle blocks positioned on the stilling basin foundation, 11 cm from the spillway toe's end. Figure 4 presents detailed features of all the laboratory models.

D. *Test Procedure*

Based on the design and data from the laboratory models, tests were conducted on five cases. Three water level sensors were utilized to measure the collected water levels during each test, as can be seen in Figure 5.

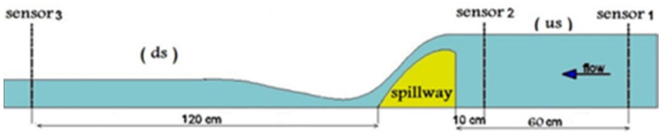

Fig. 5. Representation of the location of water level sensor measurements.

It is evident that one was positioned ds at a distance of 120 cm from the spillway toe, while two sensors were placed upstream (us) at distances of 10 cm and 60 cm from the beginning of the spillway. The placement of multiple us sensors ensured accurate water level measurements across different sections, allowing for the results to be cross verified. The same test procedure was followed for all five stilling basin models. The procedure is summarized as follows:

- Operating the flume pump to circulate water through the system.
- Adjusting the flowmeter to achieve the required flow rate.
- Measuring the water depths using the sensors for both us and ds levels.

E. *Energy Dissipation Calculations*

Energy dissipation is generally defined as the difference between the total energy us and ds of the spillway [20]. Effective energy dissipation at dams and weirs is closely tied to the spillway design [21], particularly the differences in water levels between us and ds, the chosen specific discharge, and ds conditions.

In hydraulics, for channels with small slopes, the total energy at a channel section is calculated by the Bernoulli Equation [22]:

$$E = z + d + \alpha \frac{V^2}{2g} \quad (2)$$

where, E is the total energy of the flow (m), z is the elevation of a datum (m), d is the depth below the water surface (m), V is the flow velocity in (m/s), g is the gravitational acceleration (m/s^2), and α is the Coriolis coefficient. For ogee weirs, the USBR determined that the Coriolis coefficient α is equal to 1.

Relative energy dissipation is defined as the ratio of energy loss to the us total energy [20]. It is calculated using:

$$\Delta E_r = \frac{\Delta E}{E_u} = \left(\frac{E_u - E_d}{E_u}\right) \quad (3)$$

where ΔE_r represents the relative energy dissipation, E_u is the total flow energy us of the spillway (m), E_d is the total flow energy ds of the spillway (m), and ΔE is the difference between us and ds.

III. RESULTS

A. Varification of the Design Model and Laboratory Model

To verify the design model, eleven experimental runs were conducted by maintaining the same values of h_e as measured by Sensor 1. The discharge values for the design model Q_d , and the laboratory model Q_l were obtained for each run, as shown in Table I. A linear regression was performed using the discharge values (Q_d and Q_l). The quality of the fit between the design model discharges and laboratory model discharges was quantified with an R^2 value of 0.97, indicating a strong correlation, as presented in Figure 6. The points closely align with the regression line, demonstrating that the design model and laboratory values are in good agreement.

TABLE I. DISCHARGES FOR DESIGN (Q_d) AND LABORATORY MODELS (Q_l) WITH RESPECT TO H_e

h_e (m)	Q_d (m^3/s) designed	Q_l (m^3/s) measured
0.062	0.010	0.0095
0.066	0.011	0.0105
0.070	0.012	0.0116
0.074	0.013	0.0125
0.077	0.014	0.0137
0.081	0.015	0.0149
0.085	0.016	0.0159
0.088	0.017	0.0170
0.091	0.018	0.0181
0.095	0.019	0.0193
0.098	0.020	0.0203

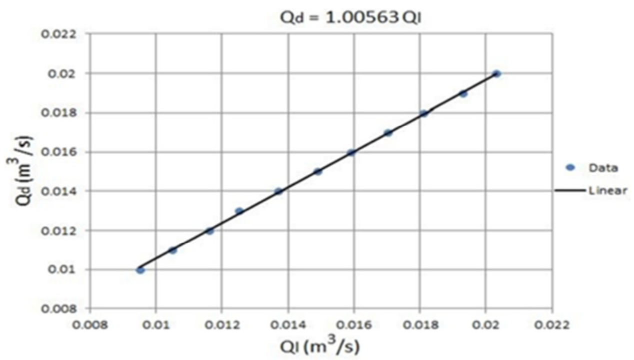

Fig. 6. Scatterplot of the discharge and laboratory values with the linear regression line.

B. Relative Energy Dissipation

Fifty-five laboratory tests (eleven tests per case) were conducted to evaluate the effects of walls, chute blocks, and middle blocks on the relative energy dissipation in stilling basins. These tests were designed to analyze the variations in the water stream behavior and quantify the dissipation efficiency across the five configurations. The flow behavior within the stilling basin for each of the five cases is depicted in Figure 7. Table II presents the relative energy dissipation (ΔE_r) values calculated for each case under varying conditions. Figure 8 provides a comparison of the relative energy dissipation against discharge for the five cases. The trends illustrate how different wall geometries and block configurations affect the energy dissipation efficiency.

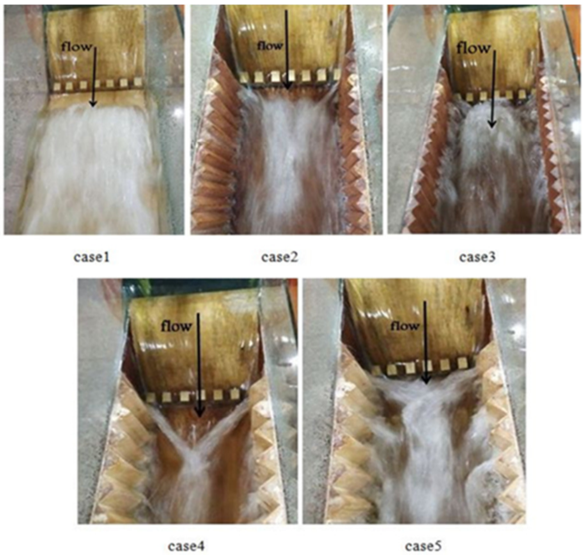

Fig. 7. The flow behavior of water steam in stilling basin for each case.

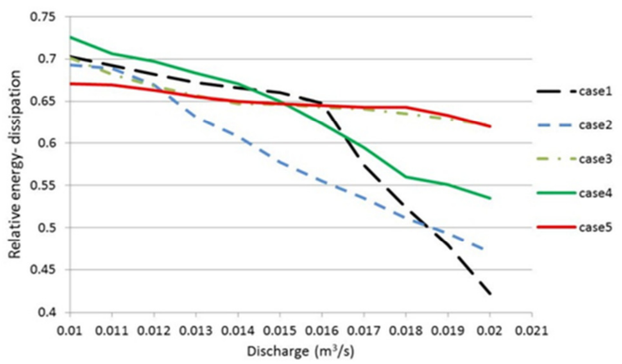

Fig. 8. The relationship between relative energy dissipation and different values of discharges for each case.

TABLE II. RELATIVE ENERGY-DISSIPATION FOR EACH CASE

Q (m^3/s)	ΔE_r				
	Case 1	Case 2	Case 3	Case 4	Case 5
0.010	0.703	0.693	0.701	0.726	0.671
0.011	0.692	0.689	0.682	0.706	0.669
0.012	0.682	0.669	0.668	0.697	0.663
0.013	0.672	0.631	0.657	0.683	0.655
0.014	0.666	0.608	0.647	0.671	0.650
0.015	0.660	0.577	0.646	0.650	0.647
0.016	0.648	0.555	0.643	0.623	0.645
0.017	0.574	0.535	0.641	0.595	0.643
0.018	0.524	0.511	0.635	0.560	0.643
0.019	0.479	0.493	0.629	0.551	0.633
0.020	0.422	0.471	0.621	0.535	0.620
Av. ΔE_r %	61.1%	58.5%	65.2%	63.6%	64.9%

IV. DISCUSSION

The results of the conducted experiments have been analyzed to compare and understand the behavior of the five studied cases, focusing on modeling stilling basins with and without middle blocks while utilizing smooth and zigzag walls. As portrayed in Figure 2, five distinct case configurations were experimentally investigated for this purpose. From Table II, it is observed that Case 1exhibited a small decrease in the rate of energy dissipation with an increasing discharge from 0.010 m^3/s to 0.016 m^3/s, resulting in a dissipation energy difference of 5.5. However, at higher discharges (greater than 0.016 m^3/s), the rate of energy dissipation decreased rapidly, with a difference in dissipation energy of 26.6%. This behavior can be attributed to the increased water velocity and the insufficient number of energy-dissipating blocks to handle higher discharges efficiently. Nonetheless, for discharges between 0.010 m^3/s and 0.016 m^3/s, the middle blocks in Case 1 were adequate for efficient energy dissipation. In Case 2, the dissipation energy difference was 22.2%, which although smaller than in Case 1, demonstrated a nearly constant rate of decline in energy dissipation with increasing discharge from 0.010 m^3/s to 0.020 m^3/s. Case 4 displayed similar behavior to Case 2, but with a lower energy dissipation difference of 19.1%. Cases 3 and 5 showed nearly identical trends, except for slight differences in dissipation energy. Case 3 exhibited a dissipation energy difference of 5.1%, while Case 5 demonstrated a difference of 8% as the discharge increased. The incorporation of zigzag walls as energy dissipaters in stilling basins effectively altered the water's route. These zigzag walls caused water streams to clash, not only with middle blocks but also with opposing streams, creating eddies and disturbances in the water's path as it descended from the spillway. However, the presence of appurtenances increased the potential for backwater effects. Despite this, the use of middle blocks enhanced the energy dissipation compared to smooth stilling basins, as they reduced the kinetic energy of the flow [23].

V. CONCLUSIONS

Although numerous studies have examined energy-dissipating structures downstream (ds) of spillways, limited research has explored the use of walls as energy-dissipating elements in stilling basins. This study introduced the novel concept of employing zigzag walls in stilling basins as energy dissipaters. Five laboratory test cases were examined to assess the effects of various parameter modifications on kinetic energy dissipation, including changes in the zigzag wall dimensions, middle block configurations, and discharge rates. The experimental results showed that the configurations with zigzag walls and middle blocks (Cases 3 and 5) achieved the highest and most consistent energy dissipation, with average relative energy dissipation rates of 65.2% and 64.9%, respectively. Large zigzag walls without middle blocks (Case 4) demonstrated superior dissipation compared to smooth walls with middle blocks (Case 1) and offered practical advantages, such as easier maintenance and sediment removal. Overall, the use of zigzag walls significantly altered the water flow paths, enhancing the energy dissipation efficiency. Based on the findings, zigzag walls with middle blocks are recommended for optimal dissipation, while large zigzag walls without middle blocks provide an effective alternative, where maintenance simplicity is a priority.

REFERENCES

[1] W. E. Wagner, "Hydraulic model studies of the check intake structure-potholes east canal," *Bureau of reclamation hydraulic laboratory report hyd*, vol. 411, 1956.

[2] N. N. Pillai and T. E. Unny, "Shapes for Appurtenances in Stilling Basins," *Journal of the Hydraulics Division*, vol. 90, no. 3, pp. 1–21, May 1964, https://doi.org/10.1061/JYCEAJ.0001038.

[3] W. Rand, "Flow Over a Dentated Sill in an Open Channel," *Journal of the Hydraulics Division*, vol. 92, no. 5, pp. 135–153, Sep. 1966, https://doi.org/10.1061/JYCEAJ.0001501.

[4] D. R. Basco and J. R. Adams, "Drag Forces on Baffle Blocks in Hydraulic Jumps," *Journal of the Hydraulics Division*, vol. 97, no. 12, pp. 2023–2035, Dec. 1971, https://doi.org/10.1061/JYCEAJ.0003166.

[5] N. G. Bhowmik, "Hydraulic jump type stilling basins for Froude number 2.5 to 4.5," *Illinois State Water Survey. Report of Investigation ; no. 67*, 1971.

[6] M. Rasheed, "Hydraulic Performance of Stilling Basins with Curved Appurtenances," M. S. Thesis, University of Baghdad, Baghdad, Iraq, 1990.

[7] A. F. Eloubaidy, J. Al-Baidhani, and A. H. Ghazali, "Dissipation of hydraulic energy by curved baffle blocks," *Pertanika Journal of Science & Technology*, vol. 7, no. 1, pp. 69–77, 1999.

[8] Z. A. Chaudhry, "Energy Dissipation Problems Downstream of Jinnah Barrage," *Pakistan Journal of Engineering and Applied Sciences*, 2008.

[9] H. A. Hayawi and A. Y. Mohammed, "Properties of Hydraulic Jump Down Sluice Gate," *Research Journal of Applied Sciences, Engineering and Technology*, vol. 3, no. 2, pp. 81-83, Feb. 2011.

[10] A. F. Ellayn and Z. Sun, "Hydraulic jump basins with wedge-shaped baffles," *Journal of Zhejiang University SCIENCE A*, vol. 13, no. 7, pp. 519–525, Jul. 2012, https://doi.org/10.1631/jzus.A1200037.

[11] M. M. Ibrahim, "Improve the efficiency of stilling basin using different types of blocks," *American Journal of Engineering Research (AJER)*, vol. 6, no. 8, pp. 295–304, 2017.

[12] C. Brown and R. Crowley, "United States Bureau of Reclamation Type IX Baffled Chute Spillways: A New Examination of Accepted Design Methodology Using CFD and Monte Carlo Simulations, Part I," *Proceedings of the 3rd International Electronic Conference on Water Sciences (ECWS-3),* vol. 7, no. 1, 2018, Art. no. 13, https://doi.org/10.3390/ECWS-3-05805.

[13] R. Daneshfaraz, A. Ghaderi, A. Akhtari, and S. Di Francesco, "On the Effect of Block Roughness in Ogee Spillways with Flip Buckets," *Fluids*, vol. 5, no. 4, Dec. 2020, Art. no. 182, https://doi.org/10.3390/fluids5040182.

[14] N. J. H. Al-Mansori, T. J. M. Alfatlawi, K. S. Hashim, and L. S. Al-Zubaidi, "The Effects of Different Shaped Baffle Blocks on the Energy Dissipation," *Civil Engineering Journal*, vol. 6, no. 5, pp. 961–973, May 2020, https://doi.org/10.28991/cej-2020-03091521.

[15] A. Y. Bantacut, A. Azmeri, F. Z. Jemi, Z. Ziana, and M. Muslem, "An experiment of energy dissipation on USBR IV stilling basin – Alternative in modification," *Journal of Water and Land Development*, pp. 68–72, 2022, https://doi.org/10.24425/jwld.2022.140781.

[16] H. Wang and H. Chanson, *Free Surface Derformation and Two-phase Flow Measurement in Hydraulic Jumps*. Brisbane, Australia: School of Civil Engineering at the University of Queensland, 2013.

[17] *Design of Small Dams,* 3rd ed. Denver, CO, USA: U.S. Department of the Interior, Bureau of Reclamation, 1987.

[18] P. K. Swamee, "Generalized Rectangular Weir Equations," *Journal of Hydraulic Engineering*, vol. 114, no. 8, pp. 945–949, Aug. 1988, https://doi.org/10.1061/(ASCE)0733-9429(1988)114:8(945).

[19] F. Salmasi and J. Abraham, "Discharge coefficients for ogee spillways," *Water Supply*, vol. 22, no. 5, pp. 5376–5392, Mar. 2022, https://doi.org/10.2166/ws.2022.129.

[20] P. Novak, A. I. B. Moffat, C. Nalluri, and R. Narayanan, *Hydraulic Structure,* 4th ed. New York, NY, USA,: Taylor & Francis, 2007.

[21] H. Chanson, *Energy Dissipation in Hydraulic Structures*, London, UK: CRC Press, 2015.

[22] V. T. Chow, *Open-Channel Hydraulics*, New York, NY, USA: McGraw-Hill, 1959.

[23] A. J. Peterka, *Hydraulic Design of Stilling Basins and Energy Dissipators*, Denver, CO, USA: United States Department of the Interior, Bureau of Reclamation, 1964.