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An experimental investigation of the influence of zigzag walls in the stilling basin on the hydraulic jump's properties

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ABSTRACT

Objective: The objective of this study is to assess how stilling basin wall geometry (smooth vs. zigzag) affects hydraulic jump behavior and energy dissipation.It also investigates whether zigzag walls improve supercritical-to-subcritical flow conversion, reduce downstream scour, and support shorter, more efficient basin designs.

Method: The study used two stilling basin models in a hydraulic flume at the University of Babylon: Case 1 with smooth walls and blocks, and Case 2 with zigzag walls and the same blocks. Twenty-two runs (11 per case) were tested with discharges of 10–20 L/s, maintaining supercritical inlet Froude numbers of 4.30–5.70, and energy dissipation and downstream Froude numbers were measured for comparison.

Results: The results indicate that the average relative energy dissipation reached 61.1% in Case 1 and 64.9% in Case 2, demonstrating a 3.8% increase attributed to zigzag wall geometry. Additionally, energy dissipation in the smooth-wall basin exhibited high sensitivity to changes in Fr_1, with a 28.1% variation across the tested Froude range, whereas the zigzag configuration showed much more stable performance, with only 5.1% variation. Case 2 also generated lower downstream Froude numbers (Fr_2 between 0.46 and 1.20), reflecting better subcritical flow conditions. The free surface profile differed notably between cases, with Case 2 showing lower water depths in the center than near the side walls, while Case 1 maintained nearly uniform depths across the width.

Conclusions: The study concludes that zigzag side walls significantly enhance and stabilize hydraulic energy dissipation, leading to more favorable downstream flow regimes and reduced scour potential, which directly benefits dam safety. The lower Fr_2 values observed in Case 2 confirm improved compatibility with natural river flow conditions. The higher dissipation efficiency also suggests that zigzag geometry can help reduce the required length of stilling basins, offering a design advantage in both performance and economy. Although the zigzag walls create a non-uniform free surface profile, this behavior contributes positively to increased energy losses. Overall, the findings support the adoption of zigzag walls with middle blocks as an effective option for optimizing stilling basin performance and reducing structural dimensions.

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Introduction

The hydraulic jump and its stability inside the stilling basin represent some of the difficulties that occur after the installation of dam weirs and diversion dams. Large dams and diversion dams that the flood flow passes through are typically damaged by phenomena like scour holes, erosion of the river bed after the stilling basin, and transfer of hydraulic jump to the downstream. Stilling basins are external energy dissipators that are positioned adjacent to a culvert or chute's exit. According to Chow (1998), they can dissipate energy in hydraulic structures, lowering the net uplift pressure beneath them, avoiding scour downstream, and increasing the water level on the structures' downstream side. The hydraulic jump can be controlled in a number of ways. These methods ensure that jumps form inside the stilling basin and control their placement under any operating conditions. One strategy to stabilize the hydraulic jump and reduce the flow's energy when it enters the river is to place building blocks in the supercritical flow area. Tests on a downstream gate in a rectangular channel with hydraulic jump characteristics and energy dissipation revealed a relationship between the energy dissipation of hydraulic jumps and a function of gate opening, Froude, and Weber Numbers. Bhowmik (1991) conducted studies in the lab to illustrate the ability to enhance energy loss and lower the length of basins needed to a particular range for a Froude Number of 2.5 to 4.5. The hydraulic jump has been thoroughly studied using physical models. Ead and Rajaratnam (2002) investigated a series of hydraulic jump tests carried out on corrugated beds in a laboratory. The Froude numbers that were tested ranged from 4 to 10. Three values of relative roughness were investigated. The tailwater depth required to make a jump was shown to be much lower than that of the same jumps on smooth beds. Izadjoo and Shafai (2007) investigated how the flow characteristics of the hydraulic jump were affected by a corrugated bed with a trapezoidal shape. When comparing a trapezoidal-shaped corrugated bed with the same features to a smooth bed, the corresponding conjugate depth and hydraulic jump length show a 20% and 50% decrease, respectively. Abbaspour et. al (2009) conducted an experimental investigation of hydraulic jump characteristics across six corrugated beds with varying wave steepness levels. The corrugation and Froude numbers of the beds varied from 3.8 to 8.6 and 0.286 to 0.625, respectively. According to the data, the tailwater depth and jump length on corrugated beds are smaller than those of the identical jump on a smooth bed. Hayawi and Mohammed (2011) evaluated a hydraulic jump characteristics and energy dissipation positioned in the rectangular channel's downstream gate. They found that the dissipation of hydraulic jump energy was related to Weber Numbers, Froude, and gate opening. Ashraf and Zhi-lin (2012) carried out laboratory investigation with respect to the features of hydraulic jumps associated to a bed which has been artificially roughened that include baffle blocks in the shape of wedges. New experimental formulas that account for the relative bed roughness and the inflow Froude number were used to determine the hydraulic jump length and the subsequent depth ratio. Gandhi and Singh (2016) investigated the hydraulic jump characteristics, sequential depth ratio, jump efficiency, and relative jump length empirically in a trapezoidal channel with and without appurtenances. It is possible to make exact predictions for greater Froude number values by closely fitting empirical models with appurtenances under different dimensions and baffle block placements. Ibrahim (2017) conducted experiments to examine how block shapes affect the flow pattern behind radial gates. Although a level floor without baffle blocks was included in the test program to evaluate the effect of using the blocks, four different baffle block modes were considered. A chute spillway using baffle blocks was created by Christopher and Raphael (2019) The designer is given a range of baffle heights, useful configurations, and baffle spacing through the empirical design process.

Nassrin et al (2020) examined the performance of the new seven baffle block design in terms of reducing the size of stilling basins in irrigation systems. The study's findings demonstrate that the modified baffle block performs better in terms of jump length and hydraulic energy dissipation. Rasoul et al (2020) studied how an ogee spillway's bed-block roughness affects energy dissipation, and evaluated the length of jet. Applying an ogee spillway with block roughness that is set up on the bed at different takeoff angles and with and without a flip bucket. Alireza and Ebrahim (2021) did an experimental analysis to evaluate how the configuration of rectangular zigzag blocks influences the hydraulic jump characteristics in a trapezoidal channel. The results show a decline in the proportion of smooth beds to consecutive hydraulic jump depths with rectangular blocks. Alfiansyah et al (2022) investigated the fluctuations in the energy dissipater and examined the impact on the hydraulic jump and energy dissipation. A physical model was made of the USBR Type IV spillway system. Research has demonstrated that the combination and adjustment of dissipation features, such as riprap lengthening, end threshold, and floor elevation, may effectively dissipate energy downstream effects. A model was investigated by Pillai and Kansal (2022) to determine how new baffle blocks may be used to evolve stilling basins. The results show that in a hydraulic jump stilling basin, wedge-shaped baffle blocks with a vertex angle of 120° dissipate more high-velocity flow energy than rectangular baffle blocks.

The present research conducts experimental analysis on utilizing of zigzag walls and middle blocks in the stilling basin and their effects on the characteristics of the hydraulic jump taking into consideration the water's dynamic energy dissipation and the free surface profile of hydraulic jumps in stilling basins. Physical models were used for experiments in an ogee spillway (USBR alternative Type IV) with and without zigzag walls at a varying range of Froude numbers.

Method

Due to the complicated flow patterns across the USBR stilling basin caused by the interaction of trapped air and turbulent flow. Our understanding of these interactions is incomplete (Wang & Chanson, 2013) The technique for predicting the stilling basin's hydraulic characteristics is physical modeling. Therefore, physical modeling was used for this study, and laboratory work was done to examine the effects of putting zigzag walls in the stilling basin on the hydraulic jump's properties.

Flume and Instruments

Testing was done in a looping flume using the fluid lab at Babylon University's Engineering College, as seen in Fig. 1. The flume's dimensions are 10 m in length, 30 cm in width, and 45 cm in height for the side walls. The maximum discharge capacity of the pump in this flume is 20 l/s. To reduce turbulence in the entry area, a screen plate was placed at the flume's intake. Furthermore, in order to maintain a constant flow, the spillway models were positioned 2.5 m downstream of the entrance tank, where flow entered the laboratory flume gradually. A flow meter is installed on the pipeline and calibrated to measure the discharge of the incoming flow. On a brass rail, three water level sensors with a one-millimeter accuracy were mounted to the top of the flume sides.

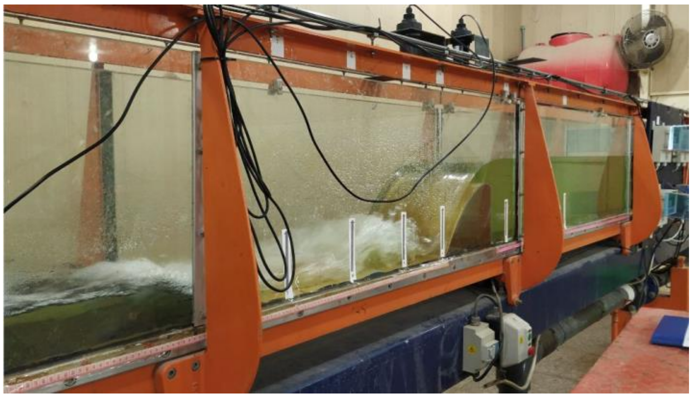


Figure 1. The used flume

Design equations

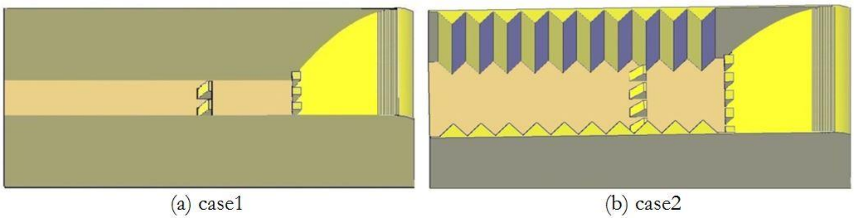
The design model's limitations include a width of 30 cm and discharge rates ranging from 10 to 20 l/s. A spillway was created for those discharge rates based on the flume's dimensions in the lab to achieve a hydraulic jump. The discharge over an ogee crest is given by the following formula (USBR ,1987):

$$Q= C_d \, L \, h_e^{1.5} \tag{1}$$

where: Q is a discharge in m3/s, Cd is a discharge coefficient equal to 2.183 corresponding to the highest discharge in tests, L is a crest's effective length equal to 0.30 m , and he is an actual head under consideration on the crest in m.

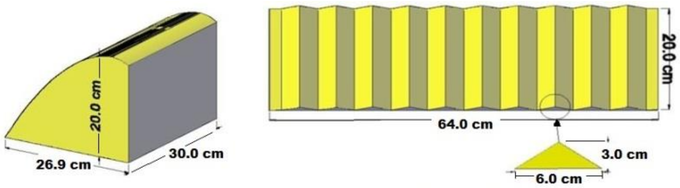
Description of laboratory models

Modified models for the stilling basin alternative type IV are created in the lab using the measurements of this kind. In this research, two laboratory models were made to represent two cases in the test procedure; namely case1 (spillway and stilling basin with smooth walls) and case2 (spillway and stilling basin with zigzag walls) as shown in Fig. 2. These models were constructed from wood and treated with epoxy and varnish to increase their smoothness and stop the wood from expanding from water. These models will not be constructed with the same parts as the prototype; instead, they will be changed. If the flowing surfaces of the water have a comparable form and nearly match the scale in terms of roughness (the model should typically be smoother than the prototype). The model will typically meet your need (USBR ,1987). Thus, in the two lab models, an ogee spillway has the following dimensions: 30 cm in width, 20 cm in height, and 26.9 cm in length. All details of laboratory models elements are presented in Fig. 3.

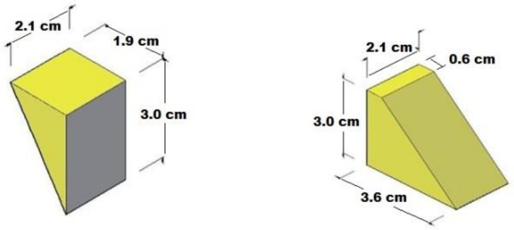


(a) case1 (b) case2

Figure 2. Laboratory models cases



(a)ogee spillway (b) zigzag wall



(c) chute block (d) middle block

Figure 3. Details of all elements of laboratory models

Dimensional analysis

Numerical analysis is the study, development, and use of approximation computer techniques to address continuous versus discrete mathematics problems that are unsolvable using exact and analytical techniques. The term "direct problem-solving methods" refers to a variety of continuous mathematics problems that are exactly resolved by an algorithm. On the contrary, there are numerous situations for which there is no direct solution, necessitating the employment of other techniques like an iterative method or the presentation of physical models. It appears that 11 parameters, which are detailed below, should be taken into account in this laboratory model.

(y_1= depth of flow at the beginning of the stilling basin, y_2= depth of flow after the stilling basin, b_1= channel width before stilling basin, b_2= channel width after stilling basin, L= length of the stilling basin, b_s= the base of the zigzag triangle on the wall of the stilling basin, d_s= the height of the zigzag triangle on the wall of the stilling basin, V_1= flow velocity at the beginning of the stilling basin, g= gravity acceleration, ΔE= amount of energy loss along the stilling basin, E_1= Energy before the spillway, which is considered equal to the energy at the beginning of the basin)

$$\pi_1 = y_1^{\alpha_1}.V_1^{\beta_1}.b_1 = L^{\alpha_1}.L^{\beta_1}.T^{-\beta_1}.L^1 = L^0.T^0 \quad \rightarrow \quad \pi_1 = b_1/y_1 \ , \quad \text{in same methods}$$

$$\pi_2 = b_2/y_1 \ , \quad \pi_3 = y_2/y_1 \ , \quad \pi_4 = L/y_1 \ , \quad \pi_5 = ds/y_1 \ , \ \pi_6 = bs/y_1 \ , \ \bar{\pi}_6 = \frac{\pi_5}{\pi_6} = \frac{ds/y_1}{bs/y_1} = \frac{ds}{bs}$$

$$\pi_7 = Fr \ , \ \pi_8 = \Delta E/y_1 \ , \ \pi_9 = E_1/y_1 \ , \ \bar{\pi}_9 = \frac{\pi_8}{\pi_9} = \frac{\Delta E/y_1}{E_1/y_1} = \frac{\Delta E}{E_1}$$

$$f.\left(\frac{b_1}{y_1}, \frac{b_2}{y_1}, \frac{y_2}{y_1}, \frac{L}{y_1}, \frac{ds}{y_1}, \frac{bs}{y_1}, \frac{bs}{ds}, Fr, \frac{\Delta E}{y_1}, \frac{\Delta E}{E_1}\right)$$

Now, from the above dimensional analysis, the parameter Fr and the factor ΔE/E1 which have been considered in all article and references have been considered as the most important factors. Also, considering the experimental limitation, b2/b1=1 has been considered and large roughness numbers with a constant ratio bs/ds have been considered. The number of zigzags on the wall is constant because of the length of the stilling basin constant therefore, it cannot be an effective parameter.

Test procedure

The tests conducted on the two cases in this part are based on the data from the laboratory model and the design. Three water level sensor readings were collected for each test. As shown in Fig. 4., the third sensor reads downstream at a distance of 120 cm from the spillway toe, while the other two sensors read upstream at a distance of 10 and 60 cm from the spillway beginning.

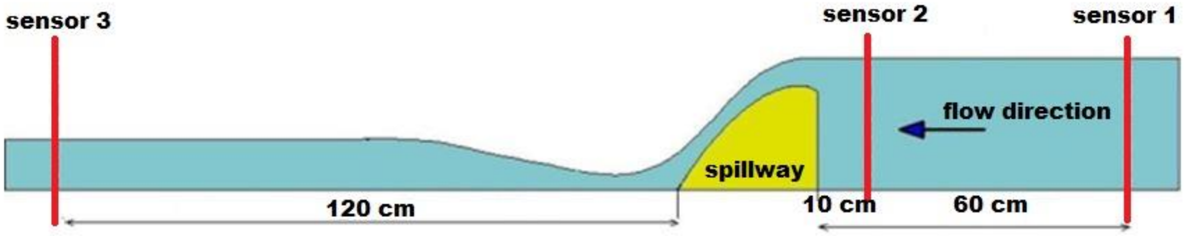


Figure 4. Schematic representation of the sensors measurement sections

The same laboratory test procedure was followed in the two cases. The following is a summary of this test:

- Turning on the flume pump.
- Modifying the flowmeter's reads to get the proper flow rate.
- Measuring the (us) and (ds) water depth from the sensors 1 and 3 respectively in order to calculate the energy losses in these sections.
- Measuring the water depth inside stilling basin in four sections as shown in Fig. 8 by using additional sensors and rulers.
- Eleven tests are carried out for each case, varying the flow rates from 10 l/s to 20 l/s.

Energy Dissipation Calculations

Generally, the difference between the total energy upstream and downstream describes energy dissipation. Therefore, energy dissipation at dams and weirs is closely linked to spillway design, particularly when considering the difference between upstream and downstream water levels.

The Bernoulli Equation below is used in hydraulics to measure the total energy at the channel section for channels with a small slope (Chow ,1959):

$$E = z + d + \alpha \frac{V^2}{2g} \tag{2}$$

where, E is the total energy of flow in m, z is the elevation of a datum in m that is represented by flume zero slope bed, d is the depth below the water surface in m measured along the channel section, V is the flow velocity in m/s, g is the gravitational acceleration in m/s2 and α is Coriolis coefficient. The Coriolis coefficient in ogee weir is one (USBR ,1987). The ratio of energy loss to total energy upstream is known as the relative energy dissipation [19]. In order to determine the energy relative loss along the spillway system, the following formula was utilized:

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

in which the relative energy dissipation ΔE_(r) is represented by the left side of the equation. E_u is the total flow energy at the upstream of the spillway in m. E_d is the total flow energy at the downstream of the spillway in m. ΔE is the energy differential upstream and downstream of the spillway in m.

Results

Results of relative energy dissipation

The effects of zigzag walls on the relative energy dissipation in stilling basins were investigated in twenty-two laboratory tests (eleven tests for each cases 1 and 2). Table 1 shows the relative values of energy dissipation and Froude numbers of these two cases.

Table 1. Relative energy –dissipation ΔE_r for the two cases

	case1			case2	
Q (m^3/s)	**Fr_1**	**ΔE_r**	**Fr_2**	**ΔE_r**	**Fr_2**
0.010	5.70	0.703	0.60	0.671	0.46
0.011	5.48	0.692	0.61	0.669	0.49
0.012	5.28	0.682	0.64	0.663	0.53
0.013	5.11	0.672	0.67	0.655	0.55
0.014	4.96	0.666	0.71	0.650	0.59
0.015	4.83	0.660	0.74	0.647	0.63
0.016	4.69	0.648	1.32	0.645	0.68
0.017	4.59	0.574	1.89	0.643	0.75
0.018	4.49	0.524	2.14	0.643	1.12
0.019	4.39	0.479	2.34	0.633	1.16
0.020	4.30	0.422	2.56	0.620	1.20
Av. ΔE_r %		61.1%		64.9%	

The water stream behavior in the stilling basin for the cases 1 and 2 is depicted in Fig. 5. Fig. 6 shows the effect of the Froude number (Fr_1) that calculated at the beginning of the stilling basin on the amount of relative energy dissipation (ΔE_r). Fig. 7 represents the relationship between Froude number (Fr_1) and the Froude number measured at the tail water by sensor 3 (Fr_2) for cases 1 and 2.

(a) case1 (b) case2

Figure 5. Water stream behavior in the stilling basin for cases 1 and 2

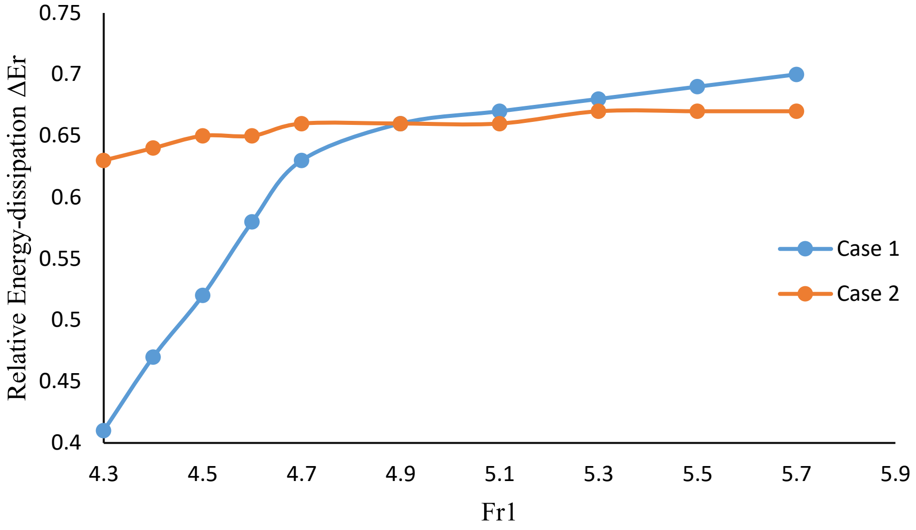


Figure 6. Difference in relative energy dissipation versus Fr_1 for cases 1 and 2

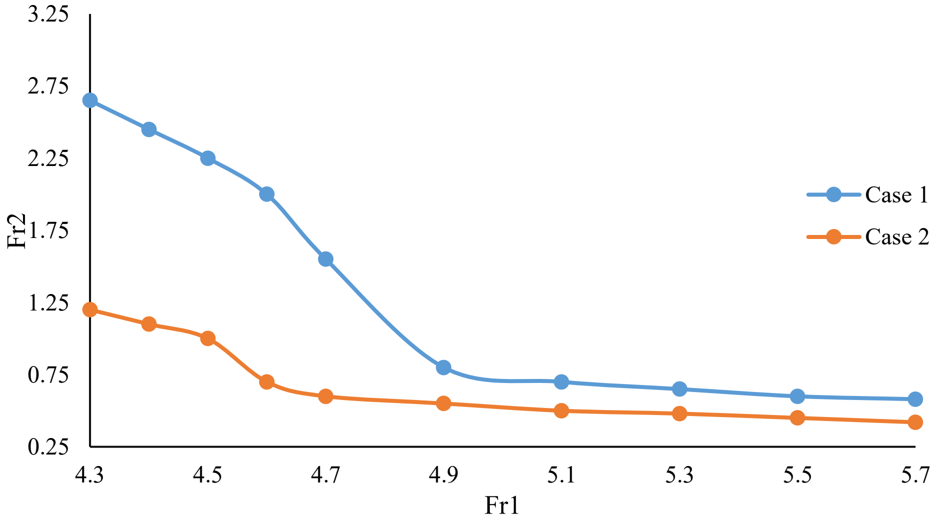


Figure7. Difference in Fr_1 versus Fr_2 for cases 1 and 2

According to Fig.6, it can be noted that case 1 indicates a 5.5% difference in dissipation energy due to a little drop in the rate of energy dissipation with an increase in Froude number 4.69 to 5.70. On the other hand, with a decrease in Froude number to 4.30, the rate of energy dissipation rapidly decrease, resulting in a 22.6% difference in dispersion energy. At Froude number lower than 4.69, the inability to dissipate the energy with the necessary efficiency arises due to the increasing water velocity and fewer energy dissipater blocks. Case2 indicates a little decrease in the dispersion energy difference of 5.1% with increase Froude number. Fig. 7 show that cases 2 is considered the best case because of achieving a small Froude number in the tail water (Fr_2).

Free-surface profiles of water

Although the fact that the jump toe fluctuations and high degree of turbulence cause the free surface profile of hydraulic jumps to be extremely unstable in both horizontal and vertical direction movements. In order to know the behavior and free-surface profiles of water in the stilling basin considering the water depths along the hydraulic jump, which are important for stilling basin wall design, the stilling basin was divided into four sections (A, B, C, and D) as shown in Fig. 8. In each section, middle depth of water (dm) and edge depth of water (de) reads were recorded for the two cases. The depth of the water in the stilling basin is measured using precise sensors, through which the change in water height readings due to flow turbulence and water level fluctuations can be monitored, and the average readings can be taken and recorded. Tables 2 , and Table 3 show the values of dm and de reads in cases 1 and 2 respectively with a discharges from 0.10 m3/s to 0.20 m3/s. Fig. 9, and Fig. 10 show comparison of dm and de free-surface profiles of water for the cases 1 and 2 respectively, with a discharge of 0.20 m^3/s.

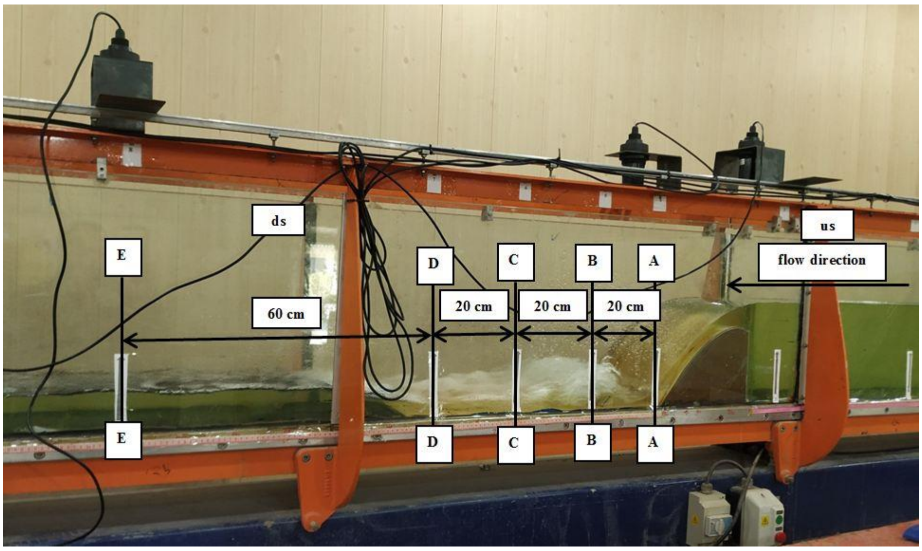


Figure 8. Stilling basin divided sections

Table 2. d_m and d_e reads in the straight stilling basin for case 1

Q (m^3/s)	Fr1	Section No.							
		A		B		C		D	
		dm (m)	de (m)	dm (m)	de (m)	dm (m)	de (m)	dm (m)	de (m)
0.010	5.70	0.014	0.015	0.091	0.080	0.012	0.010	0.015	0.013
0.011	5.48	0.016	0.017	0.104	0.093	0.015	0.012	0.022	0.019
0.012	5.28	0.017	0.018	0.111	0.101	0.019	0.016	0.015	0.013
0.013	5.11	0.020	0.021	0.115	0.104	0.019	0.016	0.020	0.018
0.014	4.96	0.022	0.023	0.120	0.109	0.027	0.024	0.024	0.021
0.015	4.83	0.023	0.024	0.122	0.111	0.032	0.027	0.025	0.022
0.016	4.69	0.025	0.026	0.138	0.129	0.034	0.029	0.027	0.024
0.017	4.59	0.027	0.028	0.141	0.130	0.058	0.053	0.024	0.021
0.018	4.49	0.029	0.030	0.145	0.134	0.054	0.049	0.020	0.018
0.019	4.39	0.030	0.031	0.151	0.140	0.046	0.040	0.019	0.017
0.020	4.30	0.031	0.032	0.152	0.141	0.032	0.027	0.019	0.017

Table 3. d_m and d_e reads in the straight stilling basin for case 2

Q (m^3/s)	Fr1	Section No.							
		A		B		C		D	
		dm (m)	de (m)	dm (m)	de (m)	dm (m)	de (m)	dm (m)	de (m)
0.010	5.70	0.026	0.077	0.067	0.078	0.034	0.059	0.028	0.049
0.011	5.48	0.031	0.080	0.072	0.081	0.035	0.064	0.032	0.051
0.012	5.28	0.034	0.085	0.086	0.083	0.040	0.072	0.032	0.056
0.013	5.11	0.037	0.087	0.091	0.085	0.044	0.082	0.034	0.058
0.014	4.96	0.039	0.089	0.102	0.087	0.046	0.092	0.040	0.064
0.015	4.83	0.040	0.093	0.118	0.088	0.052	0.099	0.044	0.069
0.016	4.69	0.041	0.095	0.124	0.089	0.071	0.106	0.042	0.074
0.017	4.59	0.043	0.099	0.132	0.089	0.077	0.109	0.042	0.082
0.018	4.49	0.046	0.105	0.139	0.090	0.085	0.112	0.039	0.087
0.019	4.39	0.048	0.113	0.140	0.093	0.089	0.114	0.043	0.091
0.020	4.30	0.052	0.119	0.141	0.096	0.092	0.117	0.045	0.093

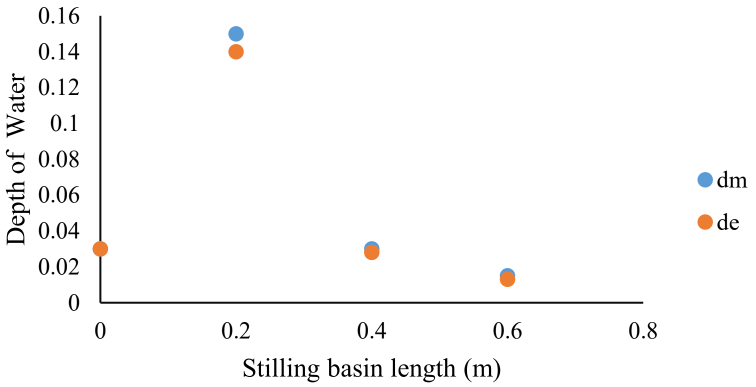


Figure 9. Comparison of dm and de free surface profiles of water case 1; Q= 0.020 m^3/s

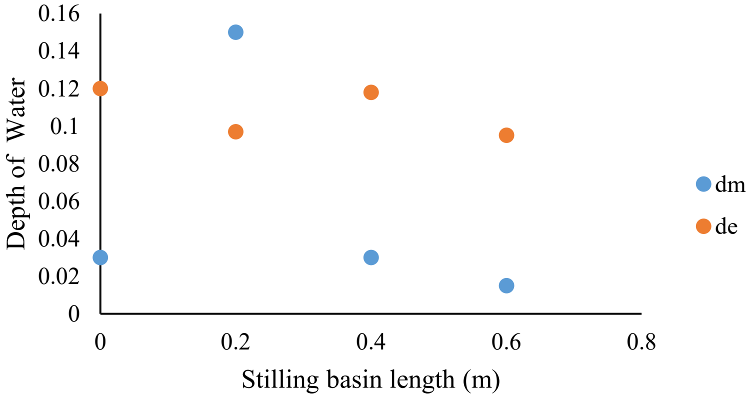


Figure 10. Comparison of dm and de free surface profiles of water case 2; Q= 0.020 m3/s

Conclusions

This research focused on using zigzag walls in stilling basin. The research presented here advances the basic comprehension of these dispersing structures. Two distinct cases were examined experimentally in order to achieve that objective. In fact, as the using of zigzag walls in stilling basin, more upward flow caused more dispersion in the air, which in fact led to higher energy dissipation. By raising the discharge in two cases, as a result of lower flow resistance, relative energy dissipation was also decreased. When dissipating energy for high-velocity flows is necessary, blocks are utilized. However, investigating the cavitation between blocks in the stilling basins remains a problem, and the effect of a block on erosion at a spillway downstream, created by arranging and positioning of blocks on the stilling basin base, in addition to jet flow and a range of block forms. In this research, the effect of employing zigzag walls in a stilling basin on the quantity of kinetic energy dissipation was examined by experimental methods. Subsequently, a laboratory test was used to examine the impact of several independent parameter adjustments on the quantity of kinetic-energy dissipation. Moreover, the average amount of energy dissipation in stilling basin with zigzag walls of stilling basin (case2) is (64.9%) compared to that in a smooth walls in stilling basin which is (61.1%) increased by (3.8%) for discharges of water range from (0.010 m3/s to 0.020 m3/s) for the eleven tests in the two cases. The use of blocks in the stilling basins gives a higher dissipation energy than the use of smooth stilling basins because these blocks are in the flow's direction and because the volume occupied by appurtenances contributes to the creation of a backwater problem (Peterka,1978).

It can be noted that case1 indicates a 5.5% difference in dissipation energy due to a little drop in the rate of energy dissipation with an increase in Froude number 4.69 to 5.70. On the other hand, with a decrease in Froude number to 4.30, the rate of energy dissipation rapidly decrease, resulting in a 22.6% difference in dispersion energy. At Froude number lower than 4.69, the inability to dissipate the energy with the necessary efficiency arises due to the increasing water velocity and fewer energy dissipater blocks. But in this case, the energy dissipation blocks are enough and able to effectively disperse the energy at Froude number ranging from 4.69 to 5.7. Case2 shows comparable behavior, with the exception of a little decrease in the dispersion energy difference of 5.1% with increase Froude number from 4.30 to 5.70. In general, using the second case gave stability in the amount of energy dissipation for all Froude numbers used .

From observing Fig. 10 for case2, it is found that the water heights in the middle of the stilling basin are generally lower than the water heights at the edge, while in Fig. 9 for case1, it is found that the height values are almost equal, in addition to the instability of the water levels along the length of the stilling basin.

From the previous results, it is conclude that the use of zigzag walls in the stilling basin leads to an increase in relative energy losses and the lowest Froude number (Fr2 between 0.46 to 1.20) at the downstream of stilling basin and also leads to reducing the length of the hydraulic jump at the downstream, thus reducing the length of the stilling basin. This reflects positively on reducing the cost and time of construction.

Author Contributions

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

Data Availability Statement

Data available on request from the authors.

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Ethical Considerations

The authors avoided data fabrication, falsification, plagiarism, and misconduct.

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Conflict of Interest

The authors declare no conflict of interest.

References

Abbaspour, A., Hosseinzadeh Dalir, A., Farshadizadeh, D., & Sadraddini, A.A. (2009). Effect of sinusoidal corrugated bed on hydraulic jump characteristics. Journal of Hydro-environment Research, 3(2), 109-117. https://doi.org/10.1016/j.jher.2009.05.003

Alfiansyah, Y., Azmeri, A., Faris, Z., Ziana, Z., & Muslem, M. (2022). An experiment of energy dissipation on USBR IV stilling basin - Alternative in modification. *Journal of Water and Land Development*,53(IV–VI), 68-72. https://doi.org/10.24425/jwld.2022.140781

Alireza J., & Ebrahim, A.(2021). Experimental Study on the Effects of Rectangular Zigzag Blocks Geometry on Hydraulic Jump Characteristics in Trapezoidal Channel. *Journal of Hydraulics*, 16 (2), 31-42. https://doi.org/10.30482/jhyd.2021.261274.1496

Ashraf F., & Zhi-lin, S. (2012). Hydraulic jump basins with wedge-shaped baffles. *Journal of Zhejiang Univ-Sci A (Appl Phys & Eng)*, 13(7), 519-525. https://doi.org/10.1631/jzus.A1200037

Bhowmik, N. G., (1971). Hydraulic Jump Stilling Basin for Froude Number 2.5 to 4.5. *Illinois State Water Survey Publications*, Urbana, USA. https://books.google.com/books/about/Hydraulic_Jump_Type_Stilling_Basins_for.html?id=KUd2GQAACAAJ

Chow, V. T. (1959). Open-Channel Hydraulics. *McGraw-Hill Publications*, New York, USA. https://www.accessengineeringlibrary.com/binary/mheaeworks/

Chow, V. T. (1988). Open channel hydraulics. *McGraw-Hill Book Publications* Columbus, Ohio, U.S. https://www.accessengineeringlibrary.com/binary/mheaeworks

Christopher, B., & Raphael, C. (2019). 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. *Water, mdpi journal*, 7 (1), 13. https://doi.org/10.3390/ECWS-3-05805

Ead, S.A., & Rajaratnam, N. (2002). Hydraulic jump on corrugated bed. *Journal of Hydraulic Engineering, ASCE*, 128(7), 656-663. https://doi.org/10.1061/(ASCE)0733-9429(2002)128:7(656)

Gandhi, S., & Singh, R.P. (2016). Empirical Formulation of Flow Characteristics in Trapezoidal Channels. *Journal of The Institution of Engineers*, (India), 97(3), 247-253. https://doi.org/10.1007/s40030-016-0153-3

Hayawi, H. A., & Mohammed A., Y. (2011). Properties of Hydraulic Jump Down Stream Sluice Gate. *Research Journal of Applied Sciences, Engineering and Technology*, 3(2), 81-83. https://www.researchgate.net/publication/215647334

Ibrahim M. M. (2017). Improve the Efficiency of Stilling Basin Using Different Types of Blocks. *American Journal of Engineering Research (AJER)*, 6(8), 295-304. https://www.researchgate.net/publication/359195975

Izadjoo, F., & Shafai Bejestan, M. (2007). Corrugated bed hydraulic jump stilling basin. *Journal of Applied Sciences*, 7(8), 1164-1169. https://doi.org/10.3923/jas.2007.1164.1169

Nassrin, J., Thair J., Khalid S., & Laith S. (2020). The Effects of Different Shaped Baffle Blocks on the Energy Dissipation. *Civil Engineering Journal*, 6(5), 961-973. http://dx.doi.org/10.28991/cej-2020-03091521

Novak, P., Moffat, A. I. B., Nalluri, C., & Narayanan, R. (2007). Hydraulic Structures. *Taylor and Frances Publications*, New York, USA. https://www.taylorfrancis.com/books/mono/10.1201/9781315274898/hydraulic-structures-novak-moffat-nalluri-narayanan

Peterka, A.J. (1978). Hydraulic Design of Stilling Basins and Energy Dissipators. *United States Department of Interior—Bureau of Reclamation Publications*, Denver, Colorado, USA. https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/EM/EM25.pdf

Pillai, N.N., Kansal, M.L.(2022). Stilling Basins Using Wedge-Shaped Baffle Blocks. *9th International Symposium on Hydraulic Structures Publications*, Roorkee, India. https://doi.org/10.26077/1d83-f83b

Rasoul D., Amir G., Ali A., & Silvia F. (2020). On the Effect of Block Roughness in Ogee Spillways with Flip Buckets. *Water, mdpi journal*, 5 (4), 182. https://www.researchgate.net/publication/344689815

USBR. (1987). Design of Small Dams. *United States Department of Interior- Bureau of Reclamation Publications*, Washington, DC, USA. https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/SmallDams.pdf

Wang, H., & Chanson, H. (2013). Free-Surface Deformation and Two-Phase Flow Measurements in Hydraulic Jumps. Research Report No. CH91/13, *School of Civil Engineering*, the University of Queensland, Brisbane, Australia. https://www.academia.edu/115367311/Free_Surface_Deformation_and_Two_Phase_Flow_Measurements_in_Hydraulic_Jumps