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Performance of Using Advanced Stilling Basin as an Energy Dissipation by Using Three-Dimensional Numerical Model

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A B S T R A C T

A numerical simulation using Flow-3D software was conducted to study the characteristics of forced hydraulic jump. The purpose of this study is mainly to improve the efficiency of the stilling basin for increasing energy dissipation. The generated model is a spillway followed by a stilling basin that contains scattered baffle blocks as energy dissipators in different shapes and arrangements, placed in regular or staggered rows, and followed by a positive step at the same height. Sixty runs were considered, and each configuration of baffle blocks was tested under five values of discharge (80, 100, 120, 140, and 160 liters per second). The numerical results showed that the obstacles have a significant effect on improving the flow characteristics and increasing energy dissipation. The best case is installing seven rows of circular baffle blocks in a staggered way at equal distances in the stilling basin, and the relative energy loss ranges from 50% to 60% according to flow conditions.

1. Introduction

Heading-up structures are used to store water and control the required passing discharge. The potential energy in the reserved water turns into excess kinetic energy downstream of the structure, causing erosion of the bed materials, which causes failure and collapse of the structure if this kinetic energy is not somehow dissipated. The stilling basin type hydraulic jump (HJ) is considered one of the most efficient solutions for water energy dissipation. HJ is defined as a natural phenomenon that occurs in an open channel when the flow moves from a supercritical condition to a sub-critical one, and the stilling basin is the place that contains it. Therefore, the length of the stilling basin should exceed the length of the HJ. There are two types of jumps, according to the channel bed characteristics, namely; classical hydraulic jump (CHJ) and forced hydraulic jump (FHJ). The first occurs in horizontal, smooth, and prismatic rectangular cross-sectional channels [1]. While, the second occurs over a rough bed and helps reduce the length of the stilling basin [2]. The FHJ can be achieved by using separate baffle blocks in the stilling basin, which act as obstacles that limit the energy of water and reduce its impact on the erosion of the bottom and sides of the watercourse.

Figure (1) shows classification of HJ according to channel bed characteristics.

Many researchers conducted experimental or numerical studies to get a perfect control on the HJ to

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decrease its length and the stilling basin's length as well, find the most efficient solution for energy dissipation, and prevent scour problems downstream of the hydraulic structures.

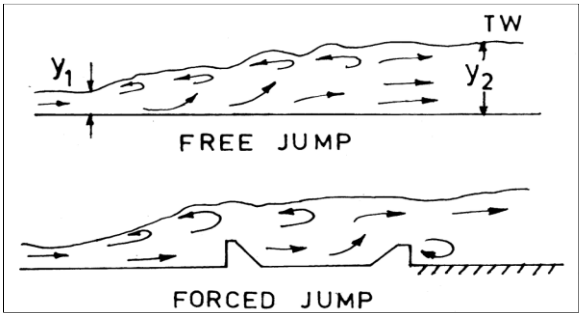


Fig. 1. Classification of HJ according to channel bed characteristics.

Ezizah et al. [3] tested a new shape of roughness elements (U-shape) to improve the efficiency of the stilling basin and prevent scour downstream hydraulic structures. The study aimed to find out the best intensity and length for the (U-shape) roughness element. The results showed that the best relative intensity is 12.5% and the best relative roughness length with respect to initial water depth is 18 as these values give minimum relative jump length and minimum relative sequent depth. A comparison between the U-shape with other roughened shapes and smooth bed showed that the best performance was achieved when using the U-shape roughness.

The experimental study of Abdelhaleem [4] predicted the effect of installing one row of semi-circular baffle blocks on energy dissipation and scour which occurs through the stilling basin downstream of a Fayoum type weir. A one hundred and fifty-three runs were performed for various configurations of the blocks and under different hydraulic conditions.

In a laboratory environment, Ahmed et al. [5] investigated the effect of a spaced triangular strip of corrugated bed on the characteristics of submerged HJs that occurs downstream of a vertical sluice gate. In this study, thirty experimental runs were conducted to examine the characteristics of HJs under different values of Froude number. The results depicted that the corrugated beds outperformed the smooth ones in enhancing the characteristics of HJ.

Eltoukhy [6] carried out laboratory experiments to investigate the potential of HJs as an energy dissipator downstream of hydraulic structures. Five values of bed slope were used for the open channel; in addition to, three different heights of sill were positioned along a stilling basin model at three different longitudinal distances. Out from this study, the sill has a substantial effect on energy dissipation.

Parsamehr et al. [7] investigated the HJ characteristics over a rough bed downstream of a sluice gate in terms of “sequent depth, relative jump length, and energy loss” on a rough bed with irregular roughness elements of a lozenge shape over an adverse slope. Two roughness element heights, dispersed in a staggered way with a density of 10.67%, and two adverse slopes were considered. The results showed that the HJ exhibits an unstable behavior on smooth beds with adverse slopes; however, the installation of roughness elements acts as stabilization for the jump.

Hayder [8] conducted a laboratory study in order to investigate the HJ properties and make a comparison of roughed bed by using semicircular elements that cover the stilling basin downstream of Ogee spillway. The water surface profile (WSP), roller length, and jump length were all measured for each rough element shape with Froude number ranging from 4 to 11. When the results were compared to earlier studies, it was shown that the presence of semicircular-shaped baffles can increase the shear force and, hence, decrease the jump length and subsequent flow depth.

An experimental study was carried out by Fathi-Moghadam et al. [9] to evaluate the HJ characteristics due to different heights and positions of a perforated sill, with one row of circular holes and four ratios of openings, downstream of vertical gate. The results showed that the perforated sill has a considerable effect on HJ characteristics. The sill height was more sensitive to the inflow Froude number than the sill location or basin length, and the optimum perforation ratio was assessed to be 50%. In general, using the perforated sill caused a reduction in jump length and increasing in energy dissipation ratio.

Abbas et al. [10] also studied the HJ characteristics through a stilling basin of an adverse slope with different configurations of baffle blocks. In the experimental tests, four models of baffle blocks were used; A, B, C and D. Model A is the standard USBR baffle block. Model B is a trapezoidal baffle block with a top angle of 53^o. Models C and D were the same as B but with different apex angles of 70^o and 90^o, respectively. The results showed that the use of baffle blocks caused a reduction in HJ length, the roller length and sequent depth ratio, but the energy dissipation ratio increased. Model D of baffle blocks has good results when compared with the other models.

Abdelghany et al. [11] experimented a new technique for dissipating the residual energy of the

HJ downstream of hydraulic structures, which consist of one vent with a vertical gate, by using a hanged pendulum sill with different relative heights and different locations, and compared the results with those of the other researchers. The used physical model was a hollow cylindrical steel sill with a constant diameter of 5.0 cm, and its weight was changed by filling it partially with sand material. The experimental results showed that the new technique increases the energy dissipation and decreases the floor length compared with the previous techniques by using sills with different shapes and locations. Although the pendulum sill has the advantage of being a fixable method for energy dissipation as it is possible to change its position and height, it was found that staggered blocks with a certain intensity are still better than the hanged sill.

Syamsuri et al. [12] applied a smoothed particle hydrodynamics model to investigate the effect of porous media on the HJ characteristics such as conjugate depth ratio, energy dissipation, and bottom shear stress. The gate opening was changed to adjust the HJ. The results showed that the validations are in a good agreement with previous studies and the average error between numerical and experimental data was less than 7.2%. Energy dissipation is compared among cases with three porosities, with and without a solid obstacles or porous media and the porosity of 0.68 is found to dissipate more energy than other porosities.

Ibrahim et al. [13] carried out an experimental investigation to introduce another technique for energy dissipation downstream of the spillway using bed water jets installed to a classical smooth stilling basin. In addition to the reference case of non-jetted systems, three different arrangements of bed water jets were used. The results showed that activating the middle three rows of water jets can reduce the average hydraulic jump length by 48% and increase the hydraulic jump efficiency in energy dissipation up to 70.8% when compared to a non-jetted system.

Singh and Roy [14] conducted a series of laboratory experiments to establish if perforated screens function effectively as energy dissipators in mixed triple wall mode in the case of small hydraulic structures. Each layer of the screens had openings that were either circular, square, or triangular in shape, and the porosity of each layer was 45% per unit of screen depth. The results showed that the use of perforated screens can effectively dissipate the energy of supercritical flows. The difference in energy dissipation between upstream and downstream of the screen was greater than the difference in energy dissipation caused by CHJ.

Sajjadi et al. [15] investigated the effect of a submerged counterflow jet (SCJ) on the hydraulic jump characteristics of stilling basin. Experiments were carried out for three SCJ cross-sections, and three placement distances from the ogee spillway toe. The results indicated that the SCJ showed good performance on decreasing the sequent depth and hydraulic jump length by 19.6% and 32.8%, respectively.

These previous studies aimed to reach the most economical and efficient solution for energy dissipation through stilling basin, as well as a perfect control on the jump to decrease its length and decrease the length of the stilling basin as a result. The experimental work is time-consuming and more costly than using software, and there is a shortage of numerical simulation of the phenomenon of water energy dissipation through stilling basins. The present numerical study aims to improve the efficiency of the stilling basin downstream of the spillway using new configurations of scattered baffle blocks in square or circular cross-section in different arrangements to determine the best alternative for improving the flow characteristics and maximizing the energy dissipation.

2. Materials and method

2.1. Dimensional analysis

The dimensional analysis method using Buckingham's theorem was used to correlate the different variables affecting the energy dissipation through the pool stilling basin using scattered baffle blocks. Figures (2, and 3) show the factors affecting energy dissipation through a stilling basin using scattered square and circular baffle blocks, respectively.

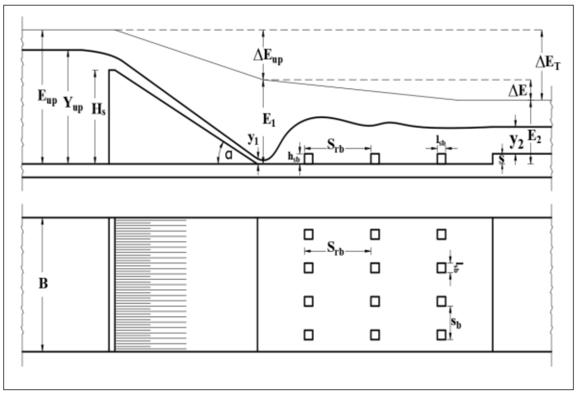
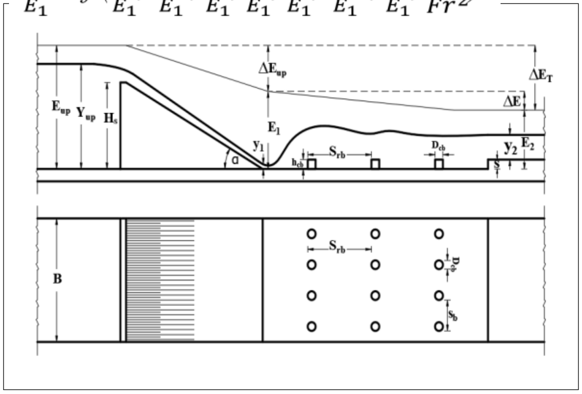


Fig. 2. Factors affecting the energy dissipation

$$\frac{\Delta E}{E_1} = f\left(\frac{E_2}{E_1}, \frac{Y_{up}}{E_1}, \frac{y_1}{E_1}, \frac{y_2}{E_1}, \frac{L_j}{E_1}, \frac{S_{rb}}{E_1}, \frac{S_b}{E_1}, \frac{1}{Fr^2}\right) \quad (6)$$



through stilling basin using square baffle blocks.

Fig. 3. Factors affecting the energy dissipation through stilling basin using circular baffle blocks.

The different variables affecting the energy dissipation through the stilling basin using baffle blocks with square and circular cross-sections in different arrangements may be written in equations

$$f(H_s, B, \alpha, L_s, h_{cb}, D_{cb}, S_{rb}, S_b, s, Y_{up}, y_1, y_2, E_1, E_2, \Delta E, L_j, Q, g, \rho, \mu) = 0 \quad (1)$$

$$f(H_s, B, \alpha, L_s, h_{sb}, l_{sb}, S_{rb}, S_b, s, Y_{up}, y_1, y_2, E_1, E_2, \Delta E, L_j, Q, g, \rho, \mu) = 0 \quad (2)$$

(1, and 2), respectively.

Equations (1, and 2) were treated by the Buckingham's theorem and the resultant dimensionless parameters were shown in equations

$$f\left(\frac{H_s}{y_1}, \frac{B}{y_1}, \frac{E_1}{y_1}, \frac{E_2}{y_1}, \frac{\Delta E}{y_1}, \frac{L_j}{y_1}, \frac{L_s}{y_1}, \frac{h_{cb}}{y_1}, \frac{Dcb}{y_1}, \frac{S_{rb}}{y_1}, \frac{S_b}{y_1}, \frac{Y_{up}}{y_1}, \frac{y_2}{y_1}, \frac{s}{y_1}, \frac{1}{Fr^2}, \frac{1}{R_n}, \alpha\right) = 0 \quad (3)$$

$$f\left(\frac{H_s}{y_1}, \frac{B}{y_1}, \frac{E_1}{y_1}, \frac{E_2}{y_1}, \frac{\Delta E}{y_1}, \frac{L_j}{y_1}, \frac{L_s}{y_1}, \frac{h_{sb}}{y_1}, \frac{l_{sb}}{y_1}, \frac{S_{rb}}{y_1}, \frac{S_b}{y_1}, \frac{s}{y_1}, \frac{Y_{up}}{y_1}, \frac{y_2}{y_1}, \frac{1}{Fr^2}, \frac{1}{R_n}, \alpha\right) = 0 \quad (4)$$

(3, and 4):

Reynold's number (R_n) has a very small effect in the open channel, and H_s, B, α, L_s, D_{cb}, h_{cb}, h_{sb}, l_{sb}, and s are constants, then their effect can be neglected.

The relative HJ length:

$$\frac{L_j}{y_1} = f\left(\frac{E_1}{y_1}, \frac{E_2}{y_1}, \frac{\Delta E}{y_1}, \frac{Y_{up}}{y_1}, \frac{y_2}{y_1}, \frac{S_{rb}}{y_1}, \frac{S_b}{y_1}, \frac{1}{Fr^2}\right) \quad (5)$$

The relative energy loss:

Where equations (1, 3, 5, and 6) apply to baffle blocks of circular cross-section, and equations (2, 4, 5, and 6) apply to baffle blocks of square cross-section.

H_s is spillway crest height, B is width of channel, α is angle of spillway back slope, L_s is stilling basin length, S_b is spacing between baffle blocks in each row, S_{rb} is spacing between rows of baffle blocks, D_{cb} is diameter of circular baffle block, h_{cb} is height of circular baffle block, h_{sb} is height of square baffle block, l_{sb} is length of square baffle block, s is height of positive step, Y_{up} is upstream water depth, y_1 is initial water depth of HJ, y_2 is sequent water depth of HJ, E_1 is specific energy of the supercritical flow at y_1, E_2 is specific energy of the subcritical flow at y_2, ΔE is energy loss through the HJ ($E_1 - E_2$), L_j is length of HJ, Q is flow rate, g is gravitational acceleration, ρ is density, and μ is dynamic viscosity of fluid.

$$F_r = \frac{V}{\sqrt{g\,y}} \quad (7)$$

$$R_n = \frac{V\,y}{\nu} \quad (8)$$

V is velocity of flow, and ν is kinematic viscosity of fluid.

2.2. Overview of software

Flow-3D is Computational Fluid Dynamics (CFD) software that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows. It provides a complete simulation platform for engineers studying the dynamic behavior of fluids in a wide range of industrial applications and physical processes and focuses on free surface and multi-phase applications. The Flow-3D software solves numerically the Naiver-Stocks equation by the finite volume method.

AutoCAD-3D is used to prepare a three-dimensional model of the spillway and obstacles of circular or square cross-sections of baffle blocks that are installed in the stilling basin downstream.

2.3. Governing equations of Flow-3D software

The Navier-Stokes equations provide numerical solutions of fluid motion equations in cartesian coordinates (x, y, and z). These governing equations are three-dimensional momentum equations and continuity equations.

For incompressible fluids (ρ is a constant), continuity equation in three-dimensional cartesian coordinates is given by:

$$v_f \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(uA_x) + \frac{\partial}{\partial y}(vA_y) + \frac{\partial}{\partial z}(wA_z) = \frac{P_{SOR}}{\rho} \quad (9)$$

Where: (*u*, *v*, and *w*) represents the velocity components, and (A_x, A_y and A_z) are cross-sectional areas of flow in the x, y and z directions respectively. ρ is the fluid density, v_f is the volume fraction of the fluid, P_{SOR} is a mass source term.
Three-dimensional momentum equations are given by equations 10, 11, and 12:

$$\frac{\partial u}{\partial t} + \frac{1}{v_f}\left(uA_x\frac{\partial u}{\partial x} + vA_y\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial P}{\partial x} + G_x + f_x \quad (10)$$

$$\frac{\partial v}{\partial t} + \frac{1}{v_f}\left(uA_x\frac{\partial v}{\partial x} + vA_y\frac{\partial v}{\partial y} + wA_z\frac{\partial v}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial P}{\partial x} + G_y + f_y \quad (11)$$

$$\frac{\partial w}{\partial t} + \frac{1}{v_f}\left(uA_x\frac{\partial w}{\partial x} + vA_y\frac{\partial w}{\partial y} + wA_z\frac{\partial w}{\partial z}\right) = -\frac{1}{\rho}\frac{\partial P}{\partial x} + G_z + f_z \quad (12)$$

Where: P is the pressure of the fluid, (G_x, G_y, and G_z) are body accelerations, and (f_x, f_y, and f_z) are viscosity accelerations in the cartesian coordinates.

The volume of fluid (VOF) method is used to simulate the water surface and includes three components: VOF function, solving VOF transport equation, and applying boundary condition on a free surface. In order to model a free surface and the boundary between water and air, the volume of fluid function (F) should be defined to meet the following governing equation. Volume fraction of the fluid (v_f) is calculated regarding the following equation:

$$\frac{\partial F}{\partial t} + \frac{1}{v_f}\left[\frac{\partial}{\partial x}(FA_xu) + \frac{\partial}{\partial y}(FA_yv) + \frac{\partial}{\partial z}(FA_zw)\right] = 0 \quad (13)$$

Where: F represents the volume occupied by air in each cell. When F (x, y, z, and t) = 1, the entire cell of control volume is filled with fluid. The control volume is filled with air if F (x, y, z, and t) = 0. A part of the cell is occupied with fluid and another part is occupied with air for F ranges from zero to one [16].

2.4. Fluid properties, turbulence models, and physics

Several physical mechanisms can be applied in simulation. Gravity and non-inertial reference frame, viscosity, and turbulence options are selected in modelling in this study. All fluid properties being entered into modelling depend on the CGS system of units (for length use cm, for mass use gram, and second for time). Water at 20°C with dynamic viscosity of 0.01 g/ (cm.s), and density of 1 g/cm³ are selected. Gravity acceleration is 981 cm/s^2 and is activated in the negative direction of the z-component. Flow-3D software uses different types of turbulence models to simulate the flow turbulence, such as the Renormalization Group (RNG) model and the two-equation (k-e) model. Both turbulent models have almost similar outcomes, but the run time of the RNG model was shorter, as shown in the research results for Moghadam et al. [17].

2.5. Boundary and initial conditions.

The solution of flow motion equations requires boundary and initial values. The boundary conditions in this study are defined as volume flow rate (vfr) at the upstream boundary ($x_{min.}$), which varied in each model to describe experimental discharge, specified pressure at the downstream ($x_{max.}$) and this pressure equals the tailwater depth in the experimental results, walls in the bed ($z_{min.}$) and on both sides ($y_{min.}$ and $y_{max.}$), and symmetry for the upper boundary ($z_{max.}$). Initial conditions should be generated that include water zones upstream and downstream of the model. The purpose of the water zone upstream of the spillway is to minimize the run time, and the downstream water zone is to simulate the downstream gate action and generate the tailwater depth to form the jump.

All boundary and initial conditions are illustrated in Figure (4).

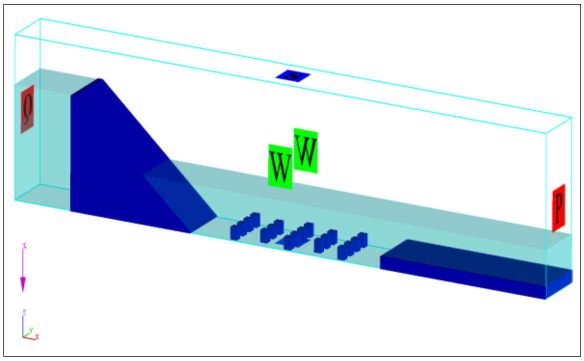


Fig. 4. 3-D model, boundary and initial conditions.

2.6. Validation of the program using experimental data.

To validate the numerical results and make sure that the Flow-3D software can simulate the behavior of flowing water and the formation of HJ in the stilling basin downstream of the spillway, some results for practical experiments obtained from the research of Hager and Bretz [18] were simulated

using the program to check the percentages of variation between the practical and numerical results.
One group of experimental results was selected.
($H_{7.6}$: A-jump and positive step, s = 7.6 cm, α_1 = 90°, and Q = 40, 60, 80, 100, 120, 140, 160, 180, and 200 liters per second (l/s)) for example, to validate the Flow-3D software.
Where: s is height of positive step and α_1 is positive step sloping angle.
Thus, all these experiments were simulated using Flow-3D software, and the rates of variations between the numerical and practical experimental results were analyzed.
Table (1) shows a comparison between the results of both laboratory experiments and numerical models obtained from the program to simulate the phenomenon of water energy dissipation.

Table 1. Comparison between the results of physical and numerical models.

A-Jump, Positive Step, s = 7.6 cm, α_1 = 90°									
Q (l/s)	40	60	80	100	120	140	160	180	200
y_1 (cm) physical model	2.5	3.45	4.25	5.15	6.05	7.1	8.05	8.9	9.8
y_1 (cm) numerical model	2.5	3.45	4.4	5.4	6.8	8.3	9.6	11.4	12.1
y_2 (cm) physical model	12.1	17.6	22.0	26.9	30.5	33.6	36.9	39.2	41.8
y_2 (cm) numerical model	12.1	17.6	22.0	26.9	30.5	33.6	36.9	39.2	41.8

Figure (5) shows the relationship between the values of the initial water depth of HJ (y_1) resulting from numerical modeling using the Flow-3D program and (y_1) resulting from experimental models for A-Jump and Positive step, which are used to validate the program.

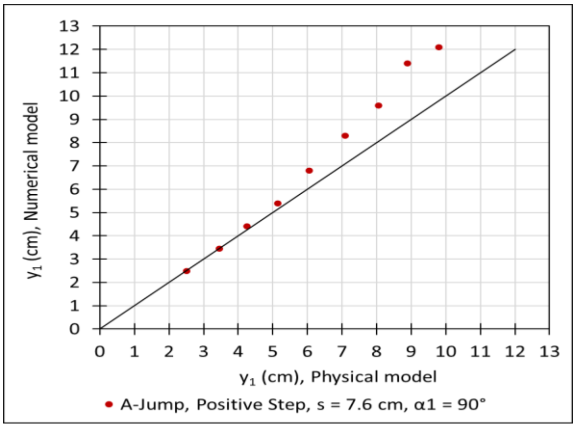


Fig. 5. Relationship between (y_1) for physical and numerical models for A-Jump, positive step.

Good agreement was observed between numerical and laboratory results. The comparison between the experimental and numerical results showed that the difference between both results did not exceed 20%, from which one can consider the results from the Flow-3D software acceptable.

2.7. Description of generated models

New scenarios with different configurations of baffle blocks, which are installed in the stilling basin and followed by a positive step at the same height (s = 7.6 cm, α_1 = 90°), are generated to study their effect on dissipating the excess kinetic energy of flow through the pool stilling basin using the Flow-3D program. The length of the stilling basin is 6.00 m including the obstacles and positive step, and its upstream end is bounded by a spillway of height 70 cm and its angle of back slope is 30°. The channel bed width is 50 cm.
All generated models are as follows:

1. Stilling basin contains (seven, five, three, or two) rows of square baffle blocks at equal distances (4 blocks in each row) and is followed by a positive step with the same height (S_7, S_5, S_3, or S_2).
2. Stilling basin contains (seven or five) rows of square baffle blocks in a staggered way and is followed by a positive step with the same height (S_{s7}, or S_{s5}).
3. All groups of square baffle blocks are compared to circular baffle blocks of the same numbers and arrangements placed in the stilling basin and followed by a positive step with the same height (C_7, C_5, C_3, C_2, C_{s7}, or C_{s5}).

Each configuration was tested under five values of the discharge (60, 80, 100, 120, and 160 (l/s)).
It is worth noting that all these numerical models depend on the data taken from practical experiments in the research of Hager and Bretz [18], such as the dimensions of the channel and spillway, as well as discharge values used and sequent water depth for HJ.
Table (2), and Table (3) show illustration for all generated models of stilling basing contains different configurations of square and circular baffle blocks, respectively:

Table 2. Illustration for all generated models of square baffle blocks.

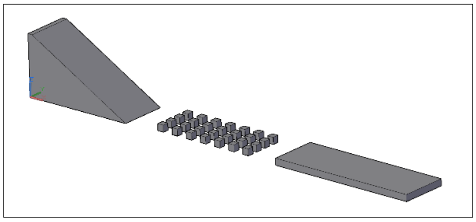
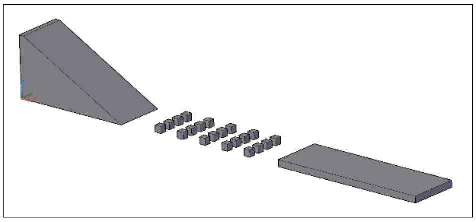
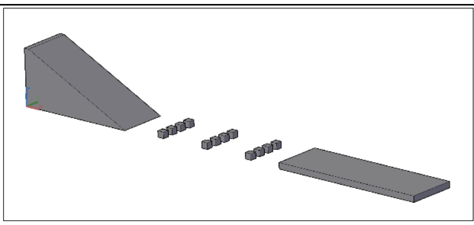
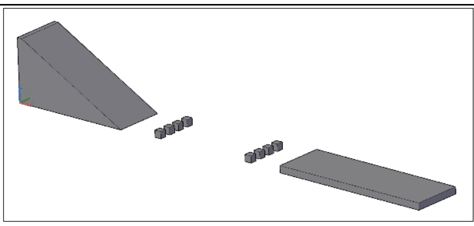
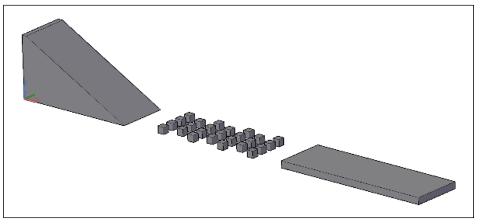
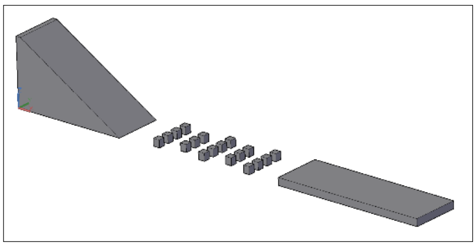
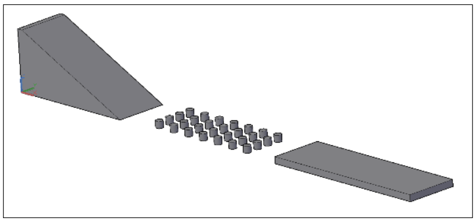
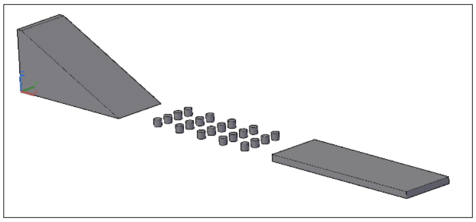
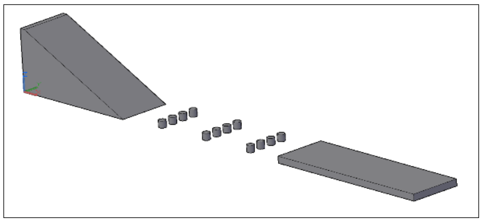
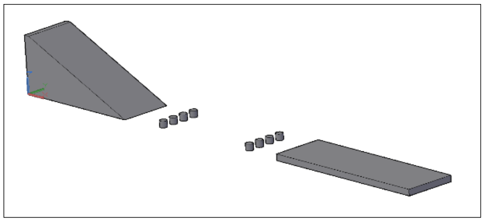
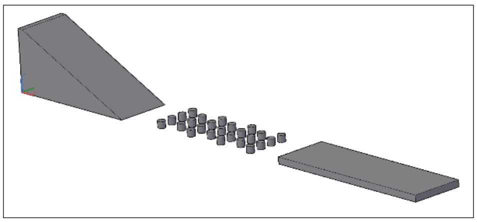
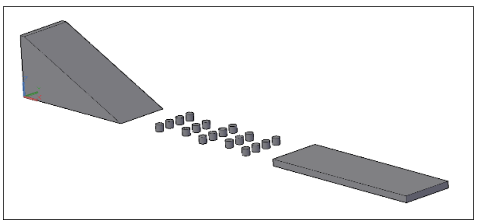
Square baffle blocks	
S_7	
S_5	
S_3	
S_2	
S_{s7}	
S_{s5}	

Table 3. Illustration for all generated models of circular baffle blocks.

Circular baffle blocks	
C_7	
S_5	
S_3	
S_2	
S_{s7}	
S_{s5}	

3. Results and discussion

Twelve groups of runs were considered to study the forced HJ characteristics.

The discharge of flow and configurations of baffle blocks were changed.

The super-critical Froude number (F_{r1}) was chosen to signify the flow condition for each discharge:

$$F_{r1} = \frac{V_1}{\sqrt{g\,y_1}} \tag{14}$$

where: V_1 = upstream velocity at initial water depth for HJ (m/s).

The dimensionless parameters such as the relative energy loss ($\Delta E/E_1$) and the relative jump length (L_j/y_1) are two indicators for the good performance of the HJ.

The results include the (WSP) along the centerline of the generated models, the relative energy loss, and the relative jump length due to the presence of baffle blocks as follows:

(A) Water surface profiles

Figure (6) shows an example for Flow-3D simulation after jump formation.

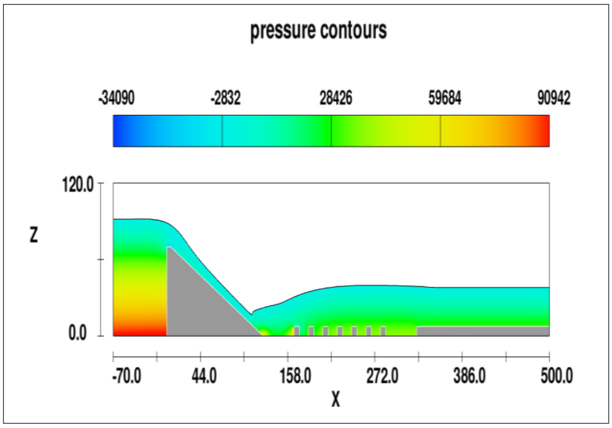


Fig. 6. Example for Flow-3D simulation after jump formation.

Figures (7, and 8) show the (WSP) along the jump length for different cases of square and circular baffle blocks, respectively, at the same value of discharge.

The results showed that there is a clear difference in water surface profiles between different cases of baffle blocks at the same value of discharge. The difference appears in the location of the beginning of the HJ formation, which affects the difference in its length in different cases.

At a distance of 350 cm from the origin of the generated model, it was observed that the flow is uniform.

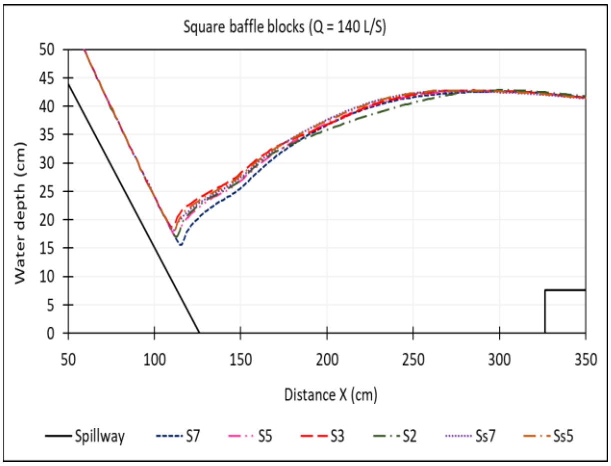


Fig. 7. WSP for different cases of square baffle blocks at Q = 140 l/s.

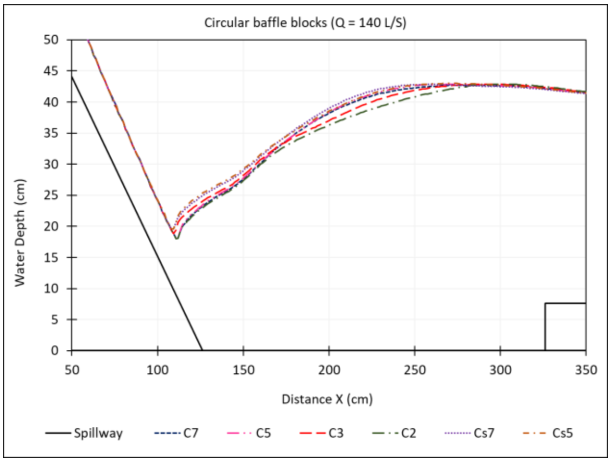


Fig. 8. WSP for different cases of circular baffle blocks at Q = 140 l/s.

(B) Energy dissipation.

The energy dissipation through the pool stilling basin is founded by estimating $\Delta E/E_1$, which E_1 and E_2 represent the energy at the upstream and downstream of the generated HJ, respectively.

$$E_1 = y_1 + \frac{v_1^2}{2g} \tag{15}$$

$$E_2 = y_2 + \frac{v_2^2}{2g} \tag{16}$$

$$\frac{\Delta E}{E_1} = \frac{E_1 - E_2}{E_1} \tag{17}$$

Figure (9) presents the relationship between the relative energy loss ($\Delta E/E_1$) and the supercritical Froude number (F_{r1}) for four groups of the stilling basin that contain different arrangements of square baffle blocks (S_7, S_5, S_3, or S_2), and is compared with the case of stilling basin without slices ($H_{7.6}$).

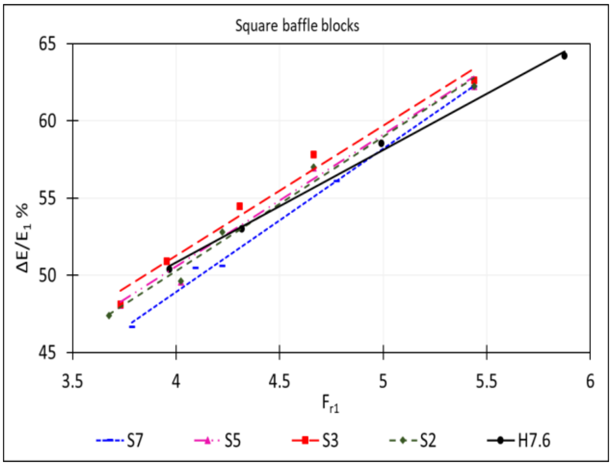


Fig. 9. Relationship between $\Delta E/E_1$ and F_{r1} for cases of square baffle blocks.

The results showed that the relative energy loss increases as the distance between rows of baffle blocks increases until three rows are present, at which point the effect decreases. So, it is maximum in the case of S_3 in comparison with other studied cases.
Figure (10) presents the effect of seven and five rows of square baffle blocks in a staggered way on the percentages of energy dissipation and they were compared with the case of S_3 as the best case of square baffle blocks.

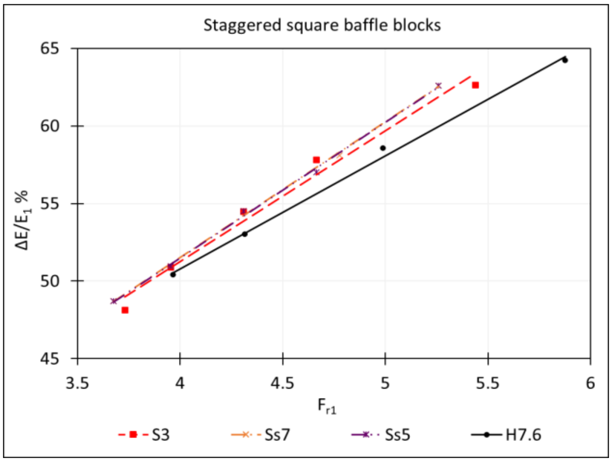


Fig. 10 Relationship between $\Delta E/E_1$ and F_{r1} for rows of square baffle blocks in a staggered way.

The seven and five rows of square baffle blocks in a staggered way have the same effect on energy dissipation rates, and their effect is better than the case of S_3.
Figure (11) presents the relationship between ($\Delta E/E_1$) and (F_{r1}) for four groups of the stilling basin that contain different arrangements of circular baffle blocks (C_7, C_5, C_3, or C_2), and is compared with the case of ($H_{7.6}$).

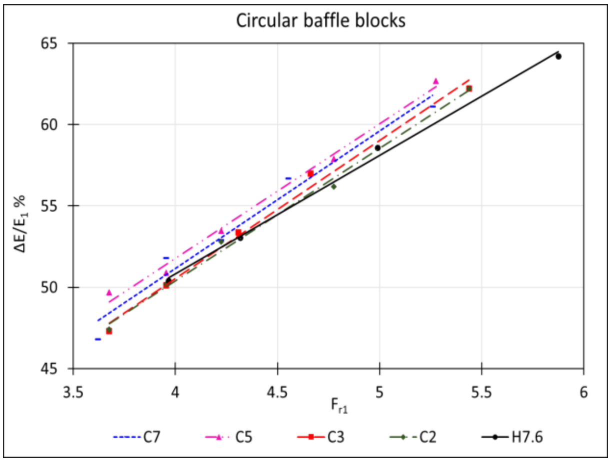


Fig. 11. Relationship between $\Delta E/E_1$ and F_{r1} for cases of circular baffle blocks.

It could be seen that the case of C_5 has the best effect on percentages of energy dissipation in comparison with other cases of circular baffle blocks.
As previous, Figure (12) shows the effect of the presence of seven or five rows of circular baffle blocks in a staggered way on the percentages of energy dissipation and they were compared with the case of C_5 as the best case of circular baffle blocks.

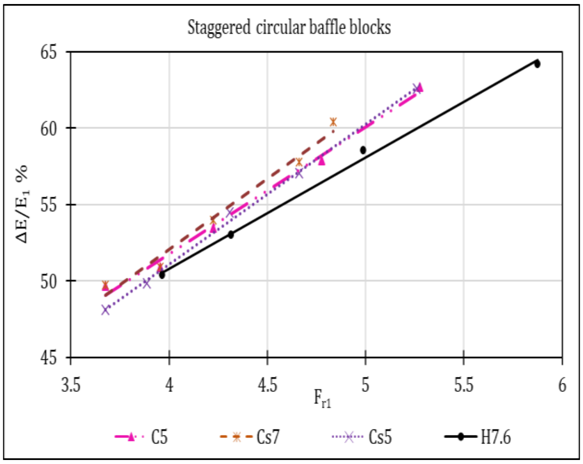


Fig. 12. Relationship between $\Delta E/E_1$ and F_{r1} for rows of circular baffle blocks in a staggered way.

The results showed that the case of C_{s7} has the best effect on increasing relative energy loss.

Figure (13) shows a comparison between the results of the case of S_{s5} with the case of C_{s7} as the best of the previous cases. It was found that the case of the C_{s7} had the best effect.

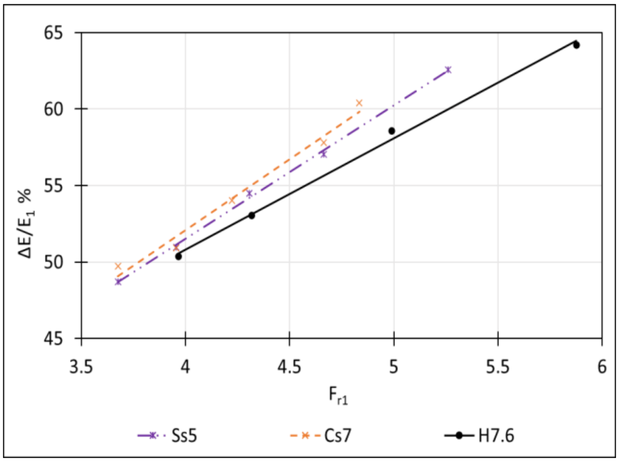


Fig. 13. Relationship between $\Delta E/E_1$ and F_{r1} for the cases of S_{s5}, C_{s7} and $H_{7.6}$.

It seems that the case of C_{s7} has a better hydraulic effect on the rates of energy dissipation than the presence of the case of S_{s5}. But economically, the case of S_{s5} is less expensive than the case of C_{s7}, and the percentages of energy dissipation are not by a large difference.

The presence of regular rows of baffle blocks in the stilling basin causes the collision of the flow with the blocks, which reverses the direction of the hydraulic jump and increases the dissipation of water energy.

In cases of rows of baffle blocks are arranged in a staggered way, the flow paths increase and the chances of collision of flow with the baffle blocks increase, so the value of the reverse force increases and the energy dissipation increases.

The fluctuation of the water surface decreases in the presence of scattered baffle blocks in the stilling basin as the flow finds paths between the blocks in each row, and the number of paths increases if there are staggered rows of baffle blocks.

Figures (14, 15, 16, and 17) show the flow paths between rows of square and circular baffle blocks, respectively.

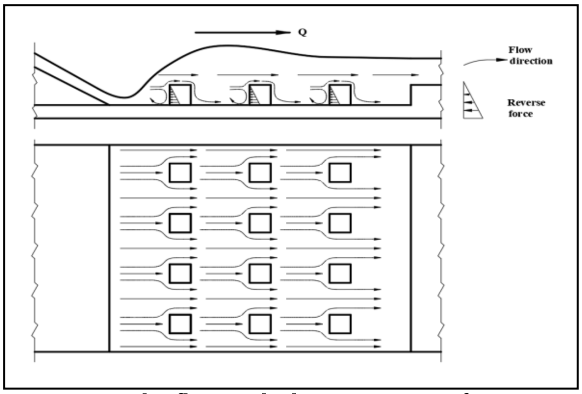


Fig. 14. The flow paths between rows of square baffle blocks.

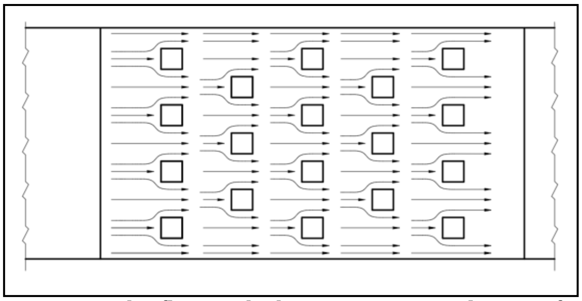


Fig. 15. The flow paths between staggered rows of square baffle blocks.

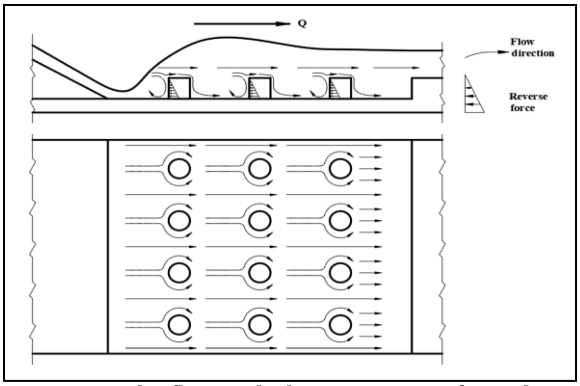


Fig. 16. The flow paths between rows of circular baffle blocks.

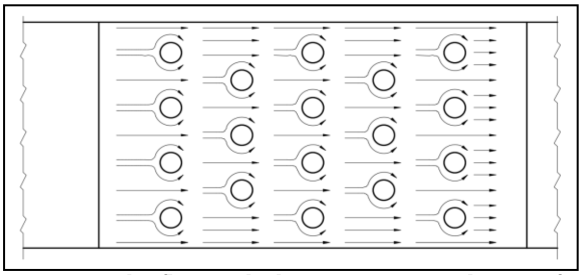


Fig. 17. The flow paths between staggered rows of circular baffle blocks.

As previously mentioned in the literature review, Hayder [8] conducted laboratory experiments to investigate the HJ characteristics using five rows of semicircular baffle blocks in a staggered way. Fig. 18 shows the relationship between F_{r1} and $\Delta E/ E_1$ for cases of S_{s5}, and C_{s5}) and compares it to the results of Hayder at the same value of the Froude number.

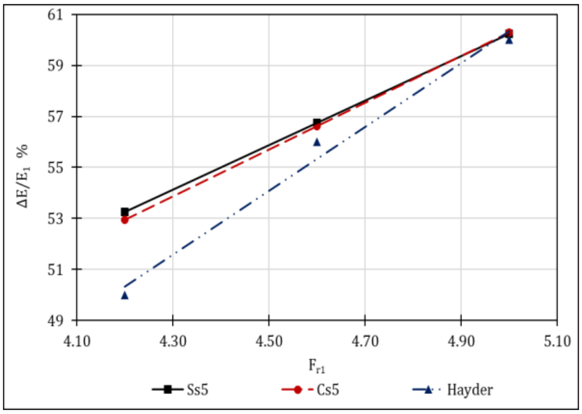


Fig. 18. Relationship between $\Delta E/E_1$ and F_{r1} for cases of S_{s5}, C_{s5}, and Hayder.

The comparison showed that the results are nearly similar despite the different characteristics of the models used, such as the shape of the spillway, the shape of the baffle block sector, their dimensions, and the number of baffle blocks in each row. While the current study cases gave better energy dispersion ratios at the same flow condition.

(C) Hydraulic Jump length.

The HJ length in a horizontal channel is considered as the distance between the jump toe and the maximum surface of water [18]. According to Hager (1992), the HJ length cannot be easily well-defined in actual experiments, thus it can be measured from the jump toe to a point where the surface fluctuations become less violent and begin to disappear [19].

Figures (19, 20 and 21) present the relationship between (F_{r1}) and the jump length normalized by the supercritical depth of the HJ (L_j/y_1) for cases of stilling basin containing different arrangements of square and circular cross-section baffle blocks respectively.

The results showed that the case of S_7 showed better performance in decreasing the relative HJ length compared to other cases of square baffle blocks. Comparing between different cases of circular baffle blocks, the case of C_2 performed better effect in decreasing the relative HJ length.

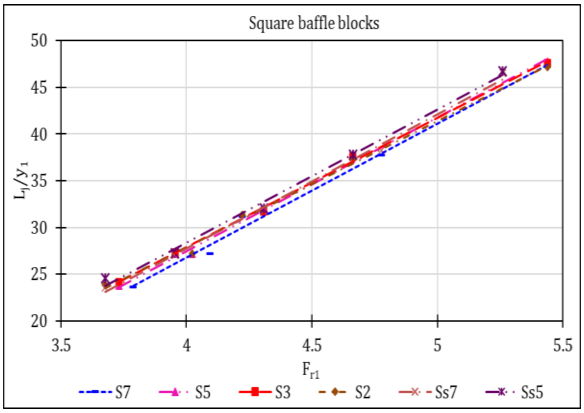


Fig. 19. Relationship between L_j/y_1 and F_{r1} for square baffle blocks.

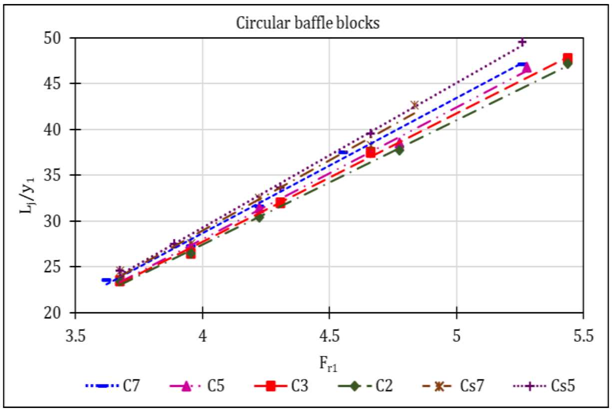


Fig. 20. Relationship between L_j/y_1 and F_{r1} for circular baffle blocks.

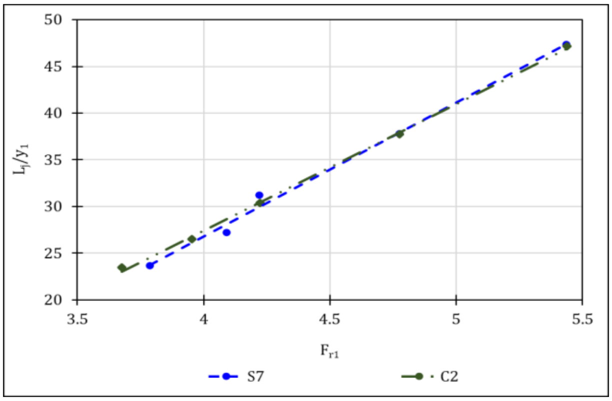


Fig. 21. Relationship between L_j/y_1 and F_{r1} for the cases of S_7 and C_5.

It was found that the toe of the HJs formed on the spillway body at different beginnings due to the different rates of immersion of the spillway as a result of each case, which makes the results of the HJ length not inversely proportional to the percentages of energy dissipation.

4. **Conclusions**

The effect of a HJ stilling basin with various arrangements of baffle blocks covering the basin floor downstream of the spillway on the HJ characteristics and energy dissipation was numerically simulated using Flow-3D software.

The study indicated that the Flow-3D software delivers high-accuracy simulation of the phenomenon of energy dissipation.

The numerical results showed that the presence of scattered baffle blocks in the stilling basin increases the energy dissipation, while decreasing the jump length and the length of the stilling basin as a result. The energy dissipation increases as the initial Froud number increases for the same case of obstacles, and this is consistent with the results mentioned in the research of (Hayder 2017) [8].

By comparing the effects of the different configurations of baffle blocks on the percentages of energy dissipation, it was found that the case of a stilling basin containing five rows of square baffle blocks in a staggered way and followed by a positive step with the same height was better than other cases of square baffles. The case of seven rows of circular baffle blocks in a staggered way has the best effect on increasing relative energy loss compared to all other studied cases, and the energy dissipation increased by about 7% compared to the case of pooled stilling basin without obstacles.

The effect of the presence of different formations of obstacles on the HJ length was also studied. The case of installation of two rows of circular baffle blocks in the stilling basin has better effect on decreasing relative HJ length.

5. Recommendations

To complete the benefit of this study, other future studies are recommended:

1. Studying the effect of the same study variables on the phenomenon of energy dissipation in the case of the presence of a gate instead of a spillway with the introduction of the immersion rate as one of the influencing factors.

2. Studying the effect of the presence of continues slices instead of scattered baffle blocks in the stilling basin downstream of the heading-up structures on the phenomenon of energy dissipation.

3. Studying the effect of these obstacles on the phenomenon of scour downstream of the spillways and gates.

4. Using other software to determine the most accurate one to simulate the phenomenon of energy dissipation.

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