Analysis of Hydraulic jump characteristics In Double Opposite Intake Canals

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Abstract

An intermediate regulator regulates the water demand flow to meet the maximum water requirements. The shortage in water demands fulfills the needs of agricultural drains after required water treatment. The upstream water levels at the two sides in the longitudinal direction of the regulator determine the flow direction through this structure. Since the movement of water is in two directions, the stilling basin must be symmetrical. The effect of double square baffles with different heights and widths located at the mid-distance of the stilling basin on the submerged hydraulic jump characteristics downstream gates are investigated. Various components, such as relative baffle heights and widths, were studied experimentally under different flow conditions. The experiments were conducted on a 16 m long, 66 cm wide, and 64 cm deep flume. One-dimensional momentum and continuity equations are applied to the control volume to deduce the theoretical equation of the relative depth and energy loss of the submerged jump. The dimensional analysis was used to define the affecting dimensionless variables under the studied phenomenon. The square baffle shape model with a relative width equal to unity is the optimal width from the jump characteristics point of view. In addition, as the relative height of the baffle increases, the performance of the hydraulic jump characteristics enhances within the experimental limits of this study (the relative baffle height ≤ 3.01). The average decrease of the jump's relative depth and length is (22%–25.8%), respectively, and the average increase of the relative energy loss is 20.8% at the inlet Froude number equals 4. The average percentage error between theoretical and experimental data was ±10% and ±8% for the relative depth and energy loss of the submerged hydraulic jump, respectively.

Keywords Submerged jump- Baffles- Gates- Stilling basin- Energy dissipation.

List of symbols

Q	*Inlet discharge*	Y_3	*back up water depth*
Fr_1	*Inlet Froude number*	Lj	*length of SHJ*
V_1	*average velocity at vena contracta*	Y_t	*dept at sec 2*
V_4	*average velocity at sec 2*	Y_t/Y_1	*relative depth of SHJ*
G	*gate opening*	Lj/Y_1	*relative length of SHJ*
SHJ	*submerged hydraulic jump*	d_1, d_2	*water depths above tested baffles*
L	*total length of the stilling basin*	ds	*water depth at sudden expansion*
B	*expanded basin width*	γ	*specific weight of the water*
b	*contracted basin width*	W_b	*tested baffle widths*
E_1	*water energy at sec 1*	W_{bo}	*relative baffle widths*
E_2	*water energy at sec 2*	h_b	*tested baffle heights*
$\Delta E/E_1$	*relative energy loss of SHJ*	h_{bo}	*relative baffle heights*
Y_1	*water depth at sec 1*		

1. Introduction:

According to water scarcity, agricultural drainage water is reused. The water flowing through a secondary channel fluctuates according to water levels in the main channel and the drainage. Double opposite gates are installed at the two sides of the regulator, so the bed protection is a mirror designed around the midline of the stilling basin in the lateral direction. This study confirms the effect of a reversible flow that meets the water requirements for the agricultural zones through the gate management of operating double opposite intakes. Each time the flow reverses itself, the flow is controlled by only the working gate. When water crosses the gate, high potential energy is converted to high kinetic energy. This high energy affects the hydraulic structure badly; thus, it should be dissipated. A hydraulic jump is used as a perfect energy dissipator downstream of the gate. It may be free jump or submerged, according to the tailwater depth. Submerged jumps have been studied by many contributors. Govinda Rao et al. (1963); Rajaratnam (1965); D.long et al. (1991); F.Ma et al. (1999); Leutheusser et al. (2001); Dey et al. (2008). Chanson et al. (2004) found that one of the most important technical uses of the hydraulic jump is to disperse flow energy downstream in hydraulic structures. The rate of energy dissipation or head loss over a hydraulic jump is determined by the inflow Froude number and the jump height. Hager (2013) stated that hydraulic jumps may be formed in prismatic or non-prismatic channels and may be forced or non-forced. According to position and the initial depth of the jump, the jump may be free or submerged. stilling basin supported by baffles to shorten the length of the basin for the specific flow condition. Baffles have taken attention for many years. Pillai et al. (1989); Bejestan et al. (2009); N. Rajaratnam (2011); A. Habibizadeh et al. (2012); Dilrooban et al. (2014); Ali et al. (1995) conducted experimental research to establish the correct position of the baffle sill downstream of the heading-up structure, which is a function of sill height and normal flow depth. Wu et al. (1995) experimented to investigate the influence of continuous baffles with varying heights and positions on energy dissipation in a rectangular flume under submerged flow conditions. According to the submergence ratio and entering Froude number values, the studies revealed two flow states: deflected surface jet and reattached wall jet. To minimize bed channel erosion, a deflected surface jet is suggested. Negm et al. (2002) investigated the optimum roughened length of prismatic stilling basins. The roughness parameter that produces the shortest jump length and therefore the shortest length from a stilling basin hydraulic point of view is determined and defined. Izadjoo et al. (2007) investigated the influence of a corrugated bed with a trapezoidal form on the flow characteristics of a hydraulic jump. The trapezoidal corrugated bed lowered the conjugate depth and length of the jump by 20% and 50%, respectively, when compared to the smooth bed. A. Bestawy et al. (2013) investigated the effect of various baffle arrays on the scour of downstream spillways. In general, models with concave surfaces cause the flow to shift direction more than those with low turbulence intensity in the recirculation zone downstream of baffle piers and waste more energy than other types. Moussa et al, (2018) investigated the effect of right and slanted faces on the scour downstream of the gate and its performance at both upstream and downstream sills with a constant height above the apron of Naga Hammadi Barrage. It was concluded that the sill had a greater impact on the characteristics of the submerged flow than the absence of the sill.

According to Negm et al. (2021), sudden expansion is constructed according to topography. The presence of the sudden expansion dissipates more energy. Many researchers studied the sudden expansion of the basin. Herbrand (1973); Ram et al. (1998); Negm et al. (2006); Daneshfaraz et al, (2017); LUO et al. (2018) Bremen et al. (1993) examined the fundamental characteristics of transitional jumps produced in expanded channels. An established equation for sequent depth ratio in channels with abrupt expansions with varied positions of the jump upstream of the expansion section based on logical principles and experimental data was produced. Matin, et al., (2008) developed a mathematical prediction equation to discover a mathematical expression for determining the subsequent depth ratio in an expanding, sloping rectangular channel using known factors such as Fr_1, expansion ratio, and channel slope. Gandhi et al. (2014) investigated the features of the jump generated in a sudden expanding basin with and without baffle blocks and an end sill experimentally. It is found that utilizing the appurtenances increases the jump efficiency, modifies its features, and causes the flow pattern to be symmetric. Karimi et al. (2017) investigated the effects of a sudden expanding basin and incoming flow characteristics on severe pressure fluctuations. It was discovered that abrupt expansion had a significant influence on reducing pressure fluctuations. Torkamanzad et al. (2019) investigated the influence of an asymmetric expansion basin with roughness on energy dissipation and jump properties. It was discovered that the new basin outperformed the traditional one. The efficiency of energy dissipation was much improved, and the subsequent length was reduced. The flow batten was also found to be symmetric. According to the above review, it is obvious that an examination of the subject of reverse flow through a double opposite gate connecting two streams has not been studied before. Thus, the present study aims to focus on this phenomenon, as shown in Fig. 2.

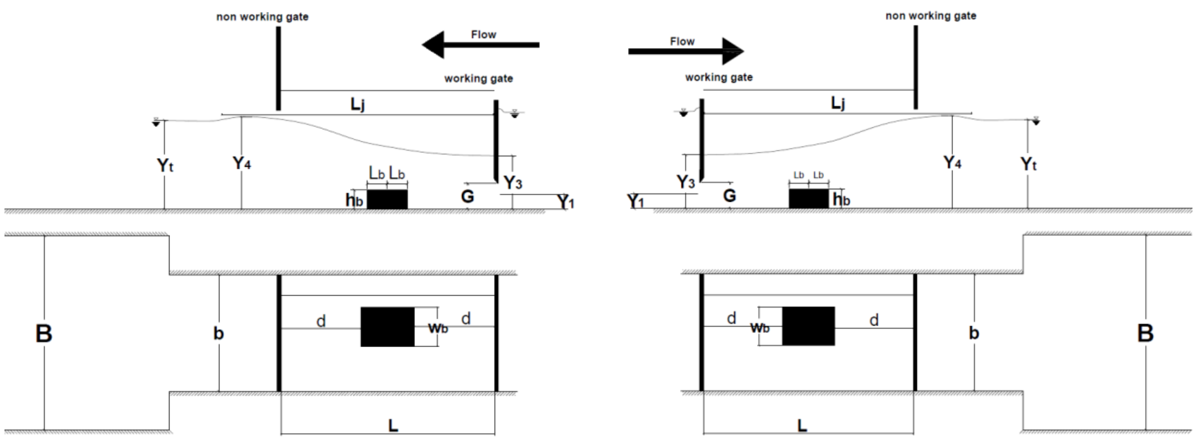

Fig 1. Sketch of the experimental model, regular flow and reverse flow directions.

2. Experimental setup:

A recirculating flume 16m long, 65.5cm deep, and 66cm wide was utilized to examine 120 laboratory experiments. To enable visual inspection, the model was built of clear Perspex with a thickness of 1cm. The reduced section measures 48 cm wide by 160 cm long. The stilling basin suddenly contracted to 66cm in width. The model's bed is made of solid material. The two gates facing each other are 80 cm apart. The input gates are separated by 40cm from the sudden expansions. The basin runs with a single gate when the flow reverses, and the non-working gate does not influence the flow. The basin was fitted with two adjacent square baffles with a height of 2.5 cm. Four various lengths (3,4,5,6) cm have been tested with three different widths (100%-75%-50%) of the basin width, respectively. Baffles are fixed in the middle of the double gates. A pre-calibrated v-notch weir was used to measure discharge. A point gauge is used to survey the water's surface profile. The submerged jump's length is measured downstream of the roller length when the flow depth is practically constant. A tailgate controls the submergence ratio (S). In a steady condition, the depth of supercritical flow (Y_1), depth of subcritical flow (Y_t), backup water depth (Y_3), length of jump (Lj), and flow rate (Q) were all recorded. Table 1 displays the range of the experimental results:

Table.1. Experimental parameters.

Symbol	Definition	Value
Q (lit/s)	Discharge	18.8-30.9
Fr_1	Inlet Froude number	1.79-8.30
S	Submergence ratio	5
e	Expansion ratio	1.4
G (cm)	Gate opening	3-4-5-6-7
h_b (cm)	Baffle height	3-4-5-6
W_b (cm)	Baffle width	33-24.7-16.5

3. Dimension analysis:

Dimensional analysis was applied to define the dimensionless parameters for SHJ, as shown in Fig. 2. Using the principles of dimensional analysis, equation 1 may be written in the form:

$$\left(\frac{Y_t}{Y_1}, \frac{Lj}{Y_1}, \frac{\Delta E}{E_1}\right) = f\,(W_{bo}, Fr_1, h_{bo}) \qquad (1)$$

4. Theoretical study:

As illustrated in equation (2), the 1-D momentum and continuity equations are both used to formulate a theoretical equation for estimating the relative depth of SHJ produced in an abruptly expanding stilling basin with double intermediate baffles. The control volume, as shown in Fig. 3, is specified at the beginning of the jump and ends just downstream of the constricted part. The following assumptions underpin the current analysis: The flow is steady (a), while the liquid is incompressible (b); The channel is horizontal with smooth boundaries (c); hydrostatic pressure distribution at the start and finish of the jump (d); uniform velocity distribution at the beginning and end of the control volume (e); the effects of air entrainment and turbulence are neglected (f); and the boundary of the baffles is smooth (g). Table (2) shows the all-elements effect at the control volume (1- 2).

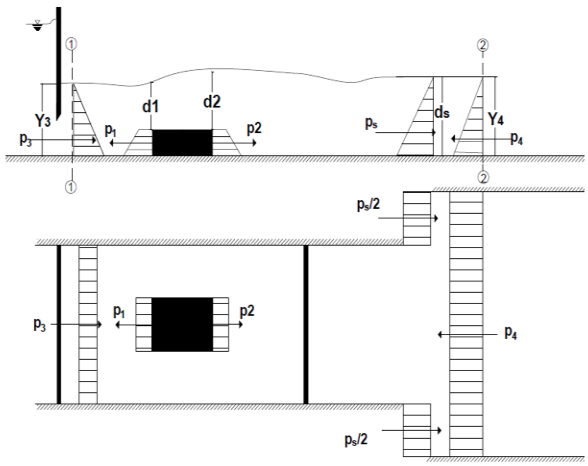

Fig.2 Definition Sketch showing the momentum forces.

Table.2. pressure forces at the control volume 1-2

Symbols	Definition	Control volume 1-2
P_1	Upstream hydrostatic pressure force on the first baffle	$\frac{h_b}{2}[\gamma\ d_1+\gamma\ (d_1+h_b)]*W_b$
P_2	Downstream hydrostatic pressure force on the second baffle	$\frac{h_b}{2}[\gamma\ d_2+\gamma\ (d_2+h_b)]\ *W_b$
P_3	hydrostatic pressure force at vena contracta	$0.5\gamma * Y_3^2*b$
P_4	hydrostatic pressure force at the end of the control volume	$0.5\ \gamma\ *Y_4^2*B$
Ps	side pressure force	$0.5\ \gamma d_s^2\ *(B-b)$
Pnet	The hydrostatic net force on the baffles	$P_1- P_2$

Based on the above, the momentum equation could be written as in equation (2) as follow:

$$P_3-P_{net}-P_s-P_4=\frac{\gamma}{g}Q(V_2-V_1) \qquad (2)$$

By substituting in eq (2):

$$0.5\ \gamma * Y_3^2*b - \frac{h_b}{2}[\ \gamma\ d_1+\gamma\ (d_1+h)]\ *W_b + \frac{h_b}{2}[\ \gamma\ d_2+\gamma\ (d_2+h)]*W_b - \gamma\ d_s^2\ *(B-b) - 0.5\ \gamma\ *Y_4^2*B\ =\ \frac{\gamma}{g}Q\left[\frac{1}{(Y4*B)} - \frac{1}{(Y1*b)}\right] \qquad (3)$$

Dividing eq (3) by ($2\gamma\ y_1^2/\ b$) and simplify to obtain**:**

$$S = \sqrt{2W_{b0}\, h_{b0}\, \Sigma d_{net0} + (e-1)d_{s0}^2 + Y_0^2 e + 2Fn_1^2\left(\frac{1}{eY_o} - 1\right)} \quad (4)$$

In which, $e = \frac{b}{B}$, $Y_o = \frac{Y_4}{Y_1}$, $h_{b0} = \frac{h_b}{b}$, $d_{s0} = \frac{d_s}{Y_1}$, $W_{b0} = \frac{W_b}{Y_1}$ and $\Sigma d_{net0} = \frac{[d_1 - d_2]}{Y_1}$

Once the flow is reversed due to different flow conditions, the theoretical equation will be the same.

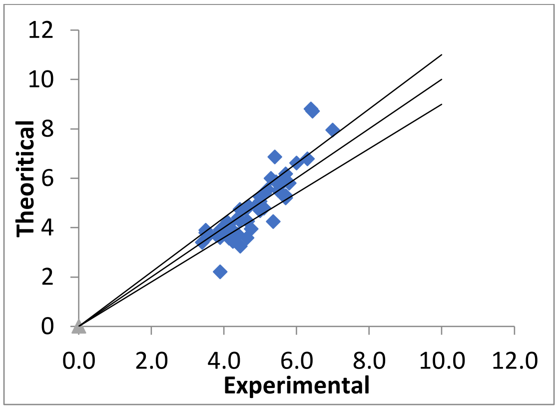

Fig.3 Comparison of the experimental and theoretical relative depth of the jump

The theoretical values of the relative depth of the submerged jump for the tested baffles obtained by solving equation (4) are plotted against the corresponding experimental values as shown in Fig. 3. The data in the figure is slightly asymmetrically distributed around the line of equality. The average percentage error is ±10%. Almost all of the results lie between lines of (±10%) percentage errors.

The Relative Energy loss

By applying the energy equation between sec (1) and sec (2), the energy loss is given as follows:

$$E_1 = Y_3 + \frac{V_1^2}{2g} \quad (5)$$

$$E_2 = Y_t + \frac{V_4^2}{2g} \quad (6)$$

$$\Delta E = (E_1 - E_2) \quad (7)$$

$$\Delta E/E_1 = \left(Y_3 + \frac{V_1^2}{2g} - Y_t - \frac{V_4^2}{2g}\right) / \left(Y_3 + \frac{V_1^2}{2g}\right) \quad (8)$$

From the continuity equation:

$$V_t = \frac{V_1 Y_1 b}{Y_4 B} \quad (9)$$

Take $\frac{B}{b} = e$, $\frac{Y_4}{Y_1} = Y_0$, $V_t = \frac{V_1}{Y_0 e}$, $\frac{Y3}{Y1} = S$

Multiply eq 8 by $\frac{Y_1}{Y_1}$ to get;

$$\frac{\Delta E}{E_1} = \frac{2S + Fr_1^2 - 2Y_0 - \frac{Fn_1^2}{Y_0{}^2 e^2}}{2S + Fn_1^2} \quad (10)$$

The relative energy losses for the baffles from the experiments and those obtained by solving the momentum equation (1) for different heights and widths are plotted as shown in Fig. 4b.

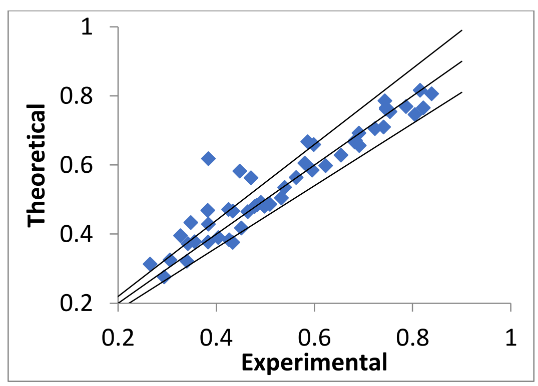

Fig.4 Comparison of experimental and Theoretical relative energy of the jump

The data in Fig. 4 is slightly asymmetrically distributed around the line of equality. The average percentage error is ±8%. Almost all of the results lie between lines of (±10%) percentage errors.

5. Analysis and discussion of results:

The square baffles with four different dimensions (3,4,5,6) cm and three different relative widths (100%-75%-50%) are examined experimentally at different flow conditions. The baffles are examined at the mid-distance of the double gates. The experiments are examined under submergence ratio (S = 5) and different values of the inlet Froude number. The relationships between the relative depth, length, and energy loss of SHJ and the inlet supercritical Froude number are plotted for different square baffles, as shown in the figures below.

The best results came with the highest square baffles within the experimental data, where relative width equals unity, which gives the minimum relative depth, length, and maximum relative energy loss.

5.1. Effect of square baffle relative heights

5.1.1. Relative jump depth

Figures 5–6, 7-8, and 9 introduce the relationship between the initial Fr1 and the relative depth of the jump for different baffle relative heights at S = 5. From these figures for all different relative widths, any increase in the initial Froude number leads to a cross-ponding increase in the relative depth of the hydraulic jump. Moreover, at a constant Froude number, when the relative width increases, the relative depth of the hydraulic jump decreases. For all baffle relative heights, the best case, which gives the minimum relative depth, occurs when the baffle width equals the total contracted width of the channel for tested S = 5.

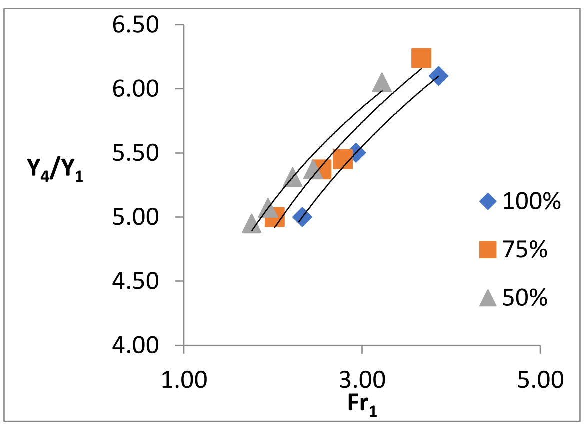

Fig.5 The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}=0.91

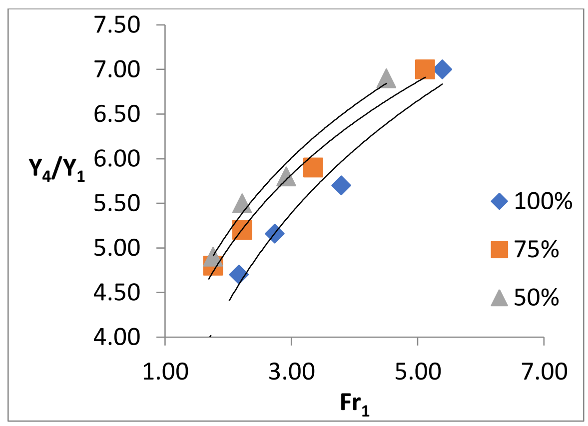

Fig.6 The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}=1.3

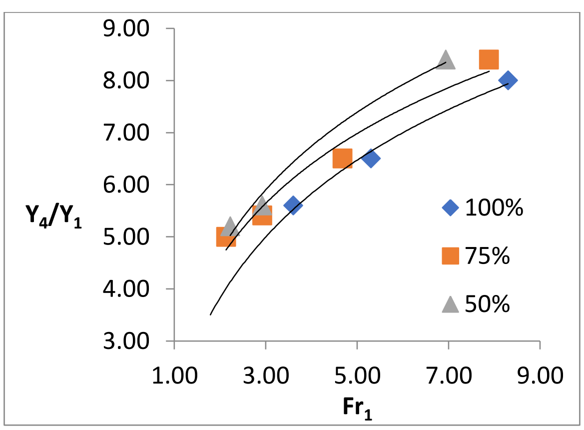

Fig.7 The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}=1.64.

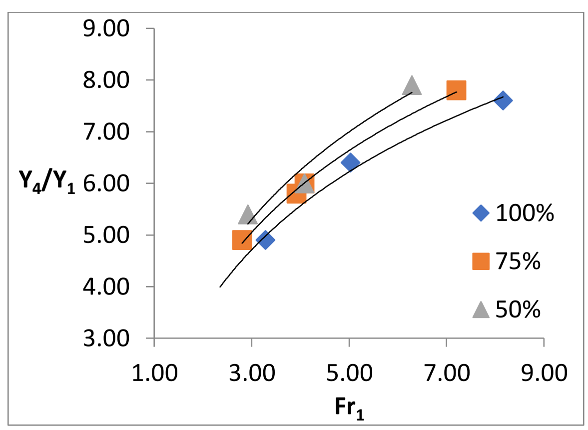

Fig.8 The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}=2.17

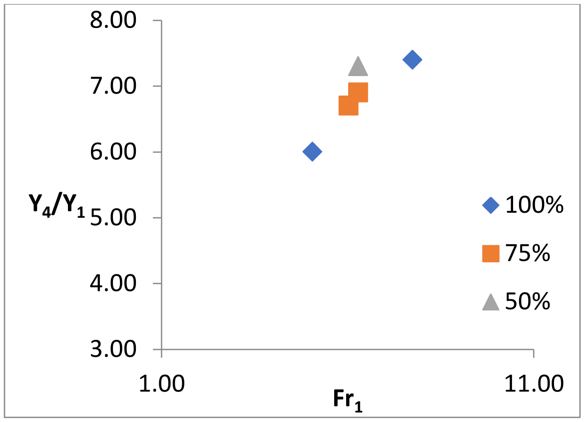

Fig.9 **The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}=3.01**

5.1.2. Relative energy loss:

Figures (10-11-12-13-14) depict the relationship between Fr_1 and $\Delta E/E_1$ for different baffle relative heights at S = 5. From these figures, for all baffle relative heights, the increase in Fr_1 results in an increase in $\Delta E/E_1$. Furthermore, at a specific Froude number, as the relative width increases, so does the relative energy loss of the hydraulic jump. When the relative width of the baffle equals unity for the tested submerged ratio, the maximum relative energy loss occurs.

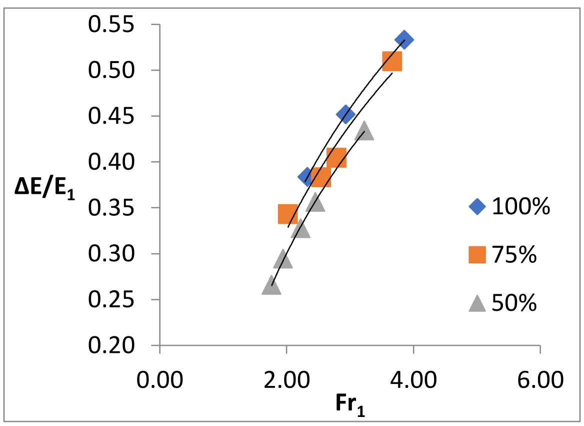

*Fig.10 **The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}= 0.91***

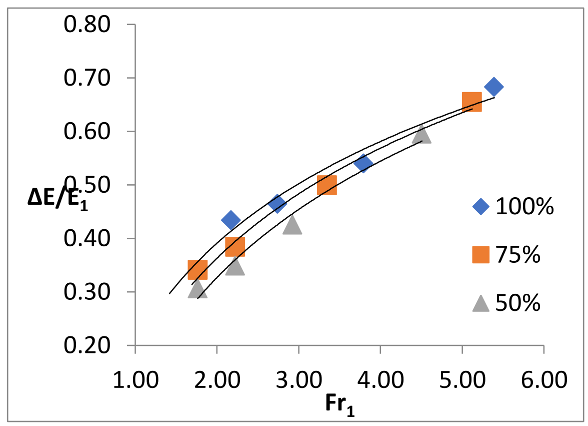

*Fig.11 **The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}= 1.3***

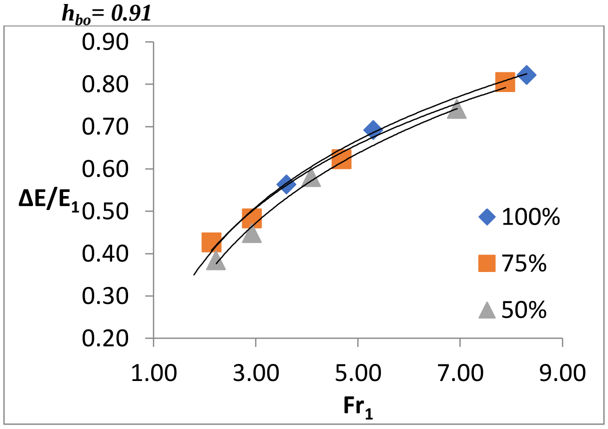

Fig.12 **The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}= 1.64**

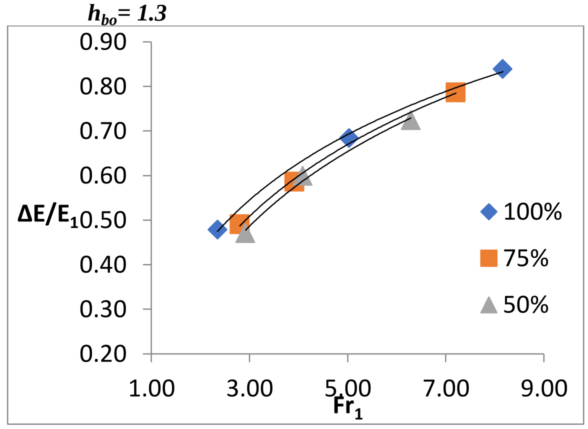

Fig.13 The relationship between $Y_4/Y_1$and Fr_1 for average hbo= 2.17

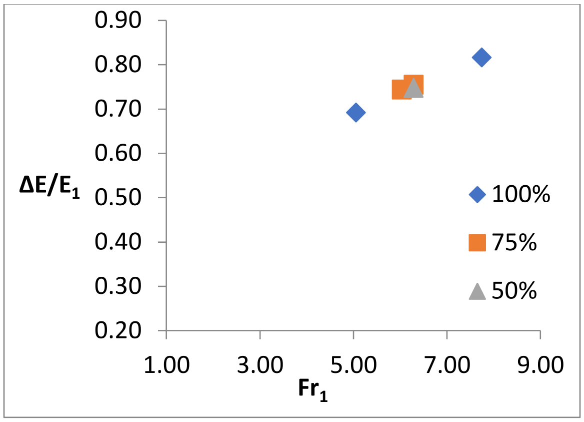

Fig.14 **The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}=3.01**

5.1.3. Relative jump length:

Figures (15-16-17-18-19) show the relationship between Fr_1 and Lj/Y_1 for various baffle relative heights at S = 5. There is a proportional relationship between the initial Froude number and the relative length of the hydraulic jump. In addition, for any given Froude number, the relative length of the hydraulic jump reduces as the relative width increases. For the tested submergence ratio, the best condition with the least relative depth occurred when the baffle width equaled the total contracted width of the channel.

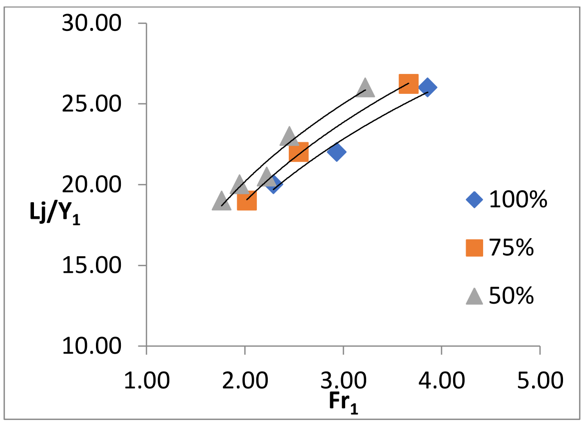

Fig.15 ***The relationship between $Y_4/Y_1$and Fr_1 for average h_{bo}= 0.91***

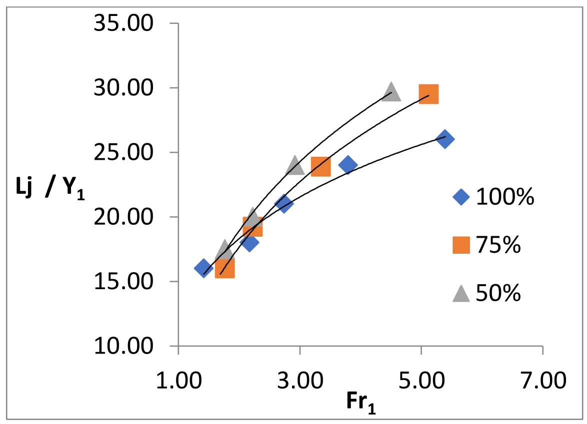

Fig.16 ***The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}= 1.3***

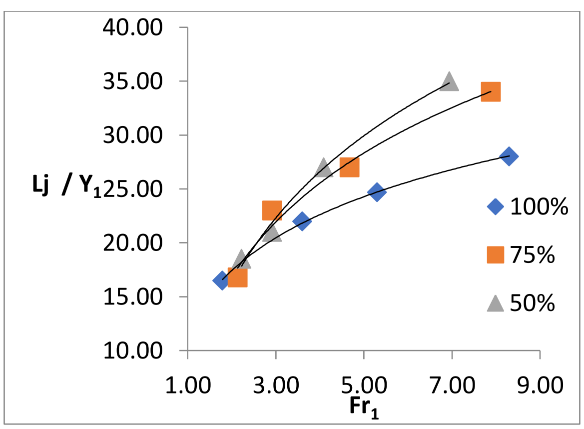

Fig.17 **The relationship between $Y_4/Y_1$and Fr_1 for average**

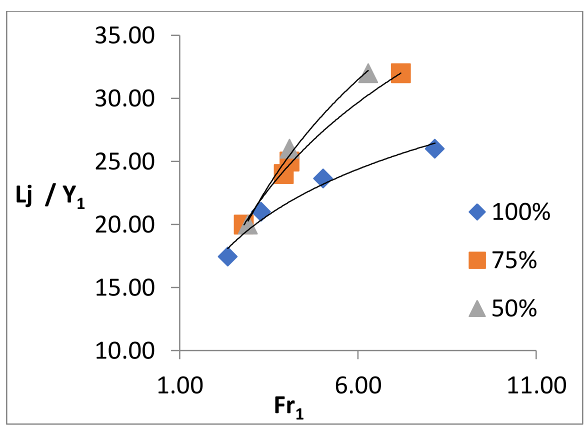

Fig.18 The relationship between $Y_4/Y_1$and Fr_1 for average h_{bo}=

h_{bo}= 1.64 2.17

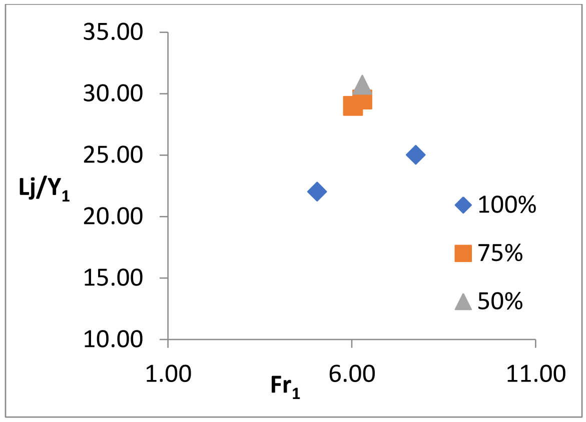

Fig.19 **The relationship between Y_4/Y_1 and Fr_1 for average h_{bo}=3.01.**

The reason for increasing the energy loss of the jump as the baffle width increases for the same submergence ratio is that the dissipated energy is a function of the impact force between the incoming flow and the baffle. In other words, this impact force is a function of the velocity and the upstream baffle surface area. Since the baffle height is constant, the impact force becomes a function of the baffle width and the inlet velocity of the flow. The effect of the velocity on the baffle is approximately the same, so the impact force is proportional to the baffle width. Consequently, as the energy loss increases, the relative length of the jump and the relative depth decrease.

5.2 Effect of square baffle relative heights:

5.2.1. Relative depth:

Figures (20-21-22) depict the relationship between the Fr_1 and the relative depth of the jump for different baffle relative widths at S = 5. It is shown that any increase in the initial Froude number leads to a cross-ponding increase in the relative depth of the hydraulic jump for all various relative heights. Furthermore, for a specific Froude number, the relative depth of the hydraulic jump reduces as the relative height increases. For tested S = 5, the best condition with the least relative depth occurred when the baffle's relative height equals 3.01 within the experimental results.

(Negm et al.) [32] The presented study plots a smooth case graph. Negm et al.'s results at the submergence ratio (S = 5) are noticeably higher than the results of this investigation. This is due to the differences in the model's arrangement in the two scenarios. Negm et al. collected data from a gradually expanding stilling basin, whereas the current investigation was conducted in an abruptly expanding basin, yielding minimal values of SHJ relative depth. Furthermore, the current study's expanded ratio (e = 1.4) is less than Negm's used expansion ratio (e = 1.67).

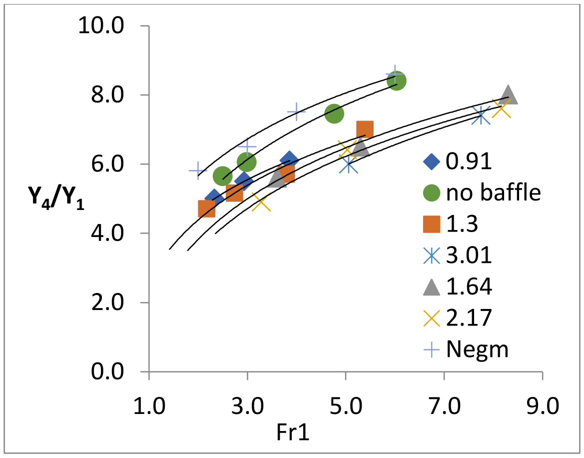

Fig.20 ***The relationship between Y_4/Y_1 and Fr_1 for W_{bo} = 100%.***

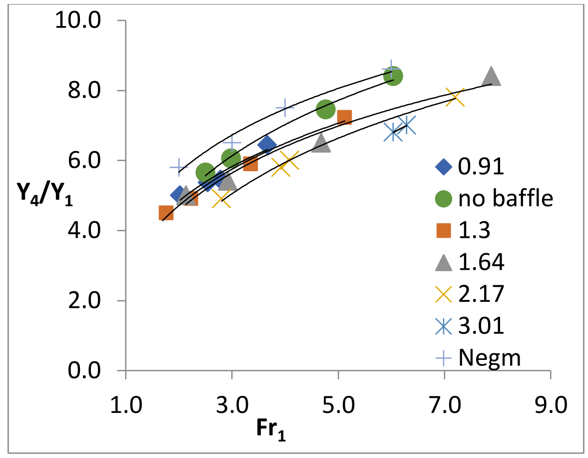

Fig.21 ***The relationship between Y_4/Y_1 and Fr_1 for W_{bo} =75%.***

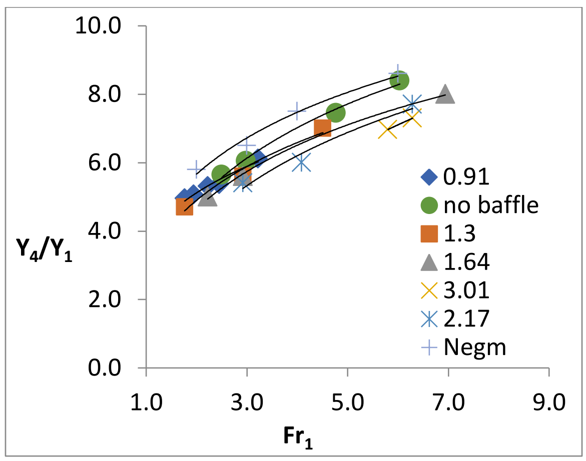

Fig.22 **The relationship between Y_4/Y_1 and Fr_1 for W_{bo} =50%.**

5.2.2. Relative energy loss

Figures 23–24–25 show the relationship between the Fr_1 and the jump's relative energy loss at S = 5. There is a positive relationship between the initial Froude number and the relative energy loss of the hydraulic jump for all tested relative heights. Furthermore, the relative energy loss of the hydraulic jump grows as the relative height increases for any equal Froude number. The optimum condition with the least relative energy loss occurred when the baffle relative height equaled 3.01 for tested S = 5.

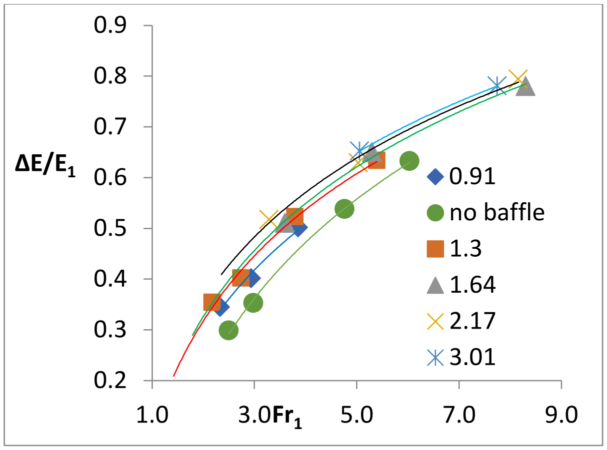

Fig.23 ***The relationship between Y_4/Y_1 and Fr_1 for W_{bo} =100%.***

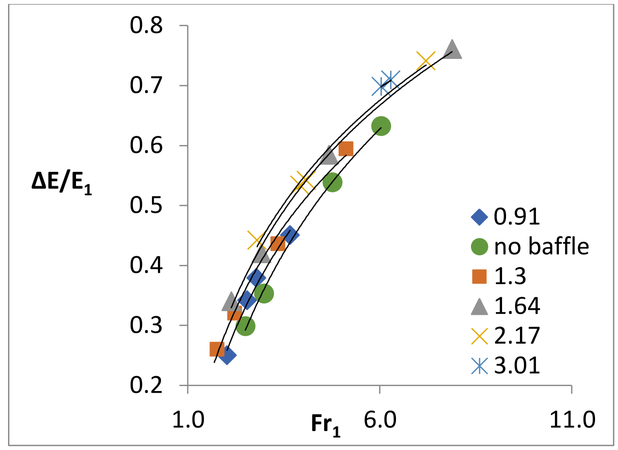

Fig.24 ***The relationship between Y_4/Y_1 and Fr_1 for W_{bo} =75%.***

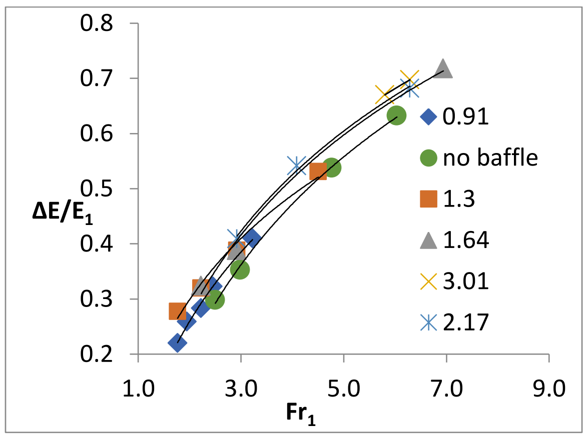

Fig.25 **The relationship between Y_4/Y_1 and Fr_1 for W_{bo} =50%.**

5.2.1. Relative jump length

Figures 26–27–28 show the relationship between the Fr_1 and the jump's relative depth for various baffle relative widths at S = 5. Any increase in the initial Froude number causes a corresponding rise in the relative length of the hydraulic jump for all different relative heights. Furthermore, the relative depth of the hydraulic jump decreases as the relative height increases at a constant Froude number. The best condition within the experimental values that gives the least relative length is when the baffle's relative height equals 3.01 for tested S = 5.

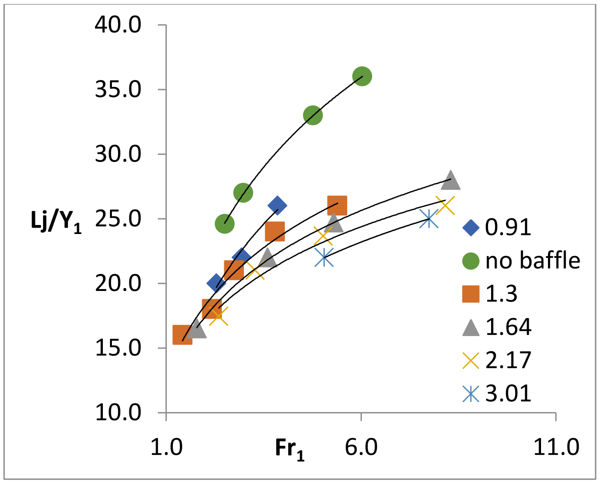

Fig.26 ***The relationship between relative jump and Fr₁ at relative width 100%.***

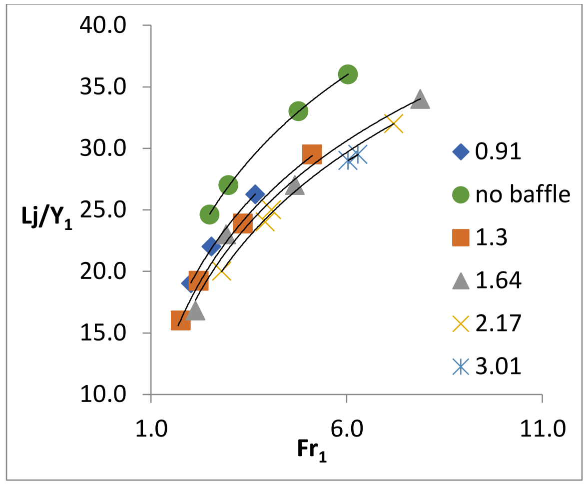

Fig.27 ***The relationship between relative depth and Fr_1 at relative width is 75%.***

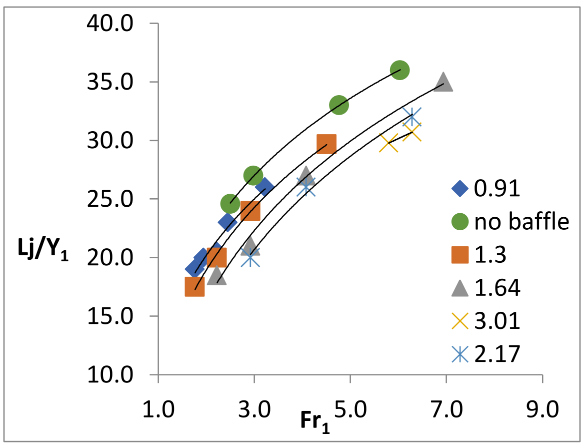

Fig.28 **The relationship between relative depth and Fr_1 at relative width 50%.**

6. Conclusion:

This study manages the high and low water demands by exchanging the water between the canals and open agricultural drains. Experimental and theoretical investigations of reverse flow in a horizontal canal with a double gate at the two sides of the regulator are applied.

According to the findings of this study:

- For all experimental data, the relative energy loss, length, and depth increase as the Froude number increases.
- Any baffle, regardless of its height, within the experimental data increases the energy dissipation and decreases the submerged jump length and depth.
- The proposed theoretical equations for predicting subsequent depth ratio and relative energy loss are acceptable based on the measured data.
- Square baffles with a relative width equal to unity give the best results, which maximize the energy loss and decrease the relative length and depth of the jump.

- Square baffles with a relative height equal to 3.01 and a relative width equal to 100% dissipate the average extra energy by 20.8% and decrease both the average relative depth and jump length by 22% and 25.8%, respectively.

Consent for publication:

The authors provide their permission for the material in the work to be published.

Declarations:

Competing interests, there are no conflicting financial or non-financial interests that the authors are aware of.

Ethics approval and consent to participate, are not applicable

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Data availability:

The corresponding author will provide the dataset upon reasonable request, which was utilized and/or analyzed during the current investigation.

Authors' contributions:

Each component of the study had an equal contribution from the authors. The final manuscript was reviewed and approved by all writers.

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