Experimental Study of Drowned Hydraulic Jump Characteristics Through Different Counterflow Dimensions

Amad.Deen Abdusalam Alghwail[1*]

[1] civileng_amad@yahoo.com

[1] Department of civil Engineering, Faculty of Engineering/Alkhums, Elmergib University, Libya
*civileng_amad@yahoo.com

ABSTRACT

Hydraulic jump is a phenomenon that occurs whenever the flow profile changes from supercritical to subcritical. In this transition, the water surface suddenly raised, surface rollers are formed, intense mixing occurs, air is entrained, with a considerable amount of water energy is dissipated. This paper presents the results of an experimental investigation on the characteristics of the formed drowned hydraulic jump on a horizontal slotted bed, (counterflow). In the current study, the counterflow was used as an energy dissipation method. Experiments were carried out to study the effect of different counterflow dimensions, represented in slot position, inclination angle of slot and slot width on both the length and the submergence ratio of the drowned jump. Graphical presentations were given, describe the relations between the percentage reduction in the length of the hydraulic jump and Approach Froude number due to variation of slot dimensions, for a Froude number ranges from 8.74 to 13.45. The results show that both the percentage reduction in the jump length and the submergence ratio increase as Froude number increases.

Keywords: Drowned Hydraulic Jump, Energy Dissipation, Counterflow, Froude Number

1 Introduction

Hydraulic jump is a phenomenon that occurs whenever the flow profile changes from supercritical to subcritical. In this transition, the water surface suddenly raised [1], surface rollers are formed, intense mixing occurs, air is entrained, with a considerable amount of water energy is dissipated. Hydraulic jump can be classified in two types according to their bed characteristics. The first type is a classical hydraulic jump with a smooth bed, and the second one is a forced hydraulic jump. The first type has been extensively studied by some Authors [2-6].

Conditions in a channel, such as downstream controls, that can change where the conjugate depths form, in addition, tailwater depth can play a very effective role on the location of the hydraulic jump in a channel, and changes in this depth can move the formed jump either upstream or downstream. In a situation where a downstream control, such as sluice gate, forces the tailwater elevation to a depth above the original conjugate depth (subcritical conjugate depth), as shown in Figure 1. so the jump is pushed upstream. In this case, the sluice gate inhibits the movement of the jump upstream so that the upstream conjugate cannot be attained. This leads to a situation known as a drowned or submerged hydraulic jump [7].

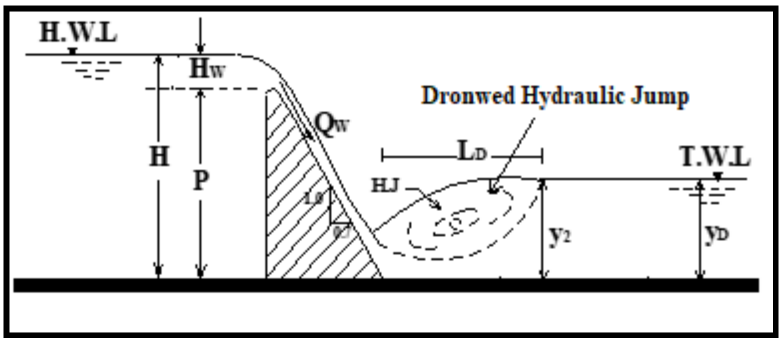


Figure 1: *Formation of a drowned hydraulic jump*

1.1 Dissipation of Water Energy and Hydraulic Jump

Hydraulic structures such as dams and barrages, spillways, sluice gates are commonly constructed in streams having erodible bed materials. In severe weather conditions, dam spillway is used to prevent the dam from being overtopped. A large amount of water to be released through spillway from the reservoir over a short space of time, resulting in flow of very high discharge and velocity. This normally takes the form of highly turbulent supercritical flow in the spillway and its immediate downstream of the channel. The high flow velocity leads to a bed shear stress greatly higher than in the absence of the structure, causing significantly increased sediment transport downstream of the structure. The channel bed level becomes eroded as a result and this is commonly known as the local scour.

Numerous of comprehensive studies, whether experimental or theoretical have been conducted to investigate the problem of water energy dissipation of hydraulic structures, with the aim of dissipating a larger amount of water energy, in order to protect the downstream bed of such structures against scour process, consequently, avoiding potential structural damage risks. Creation of hydraulic jump in open channel is a useful phenomenon. It is generally used to dissipate of excess kinetic energy downstream hydraulic structures, such as drops, spillways, chutes and gates, increasing weight on an apron and thus reduce uplift pressure under control structures.

Dissipation of water energy downstream hydraulic structures has been dealt with in different ways of approach, based on the two following concepts:

(1) Provoking large velocity gradient lead to increasing turbulence in the stream.

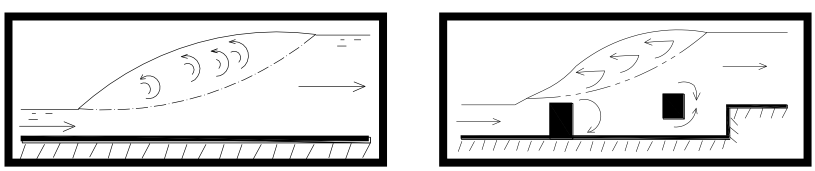
(2) Creating extended and turbulent interfaces between the flowing water and the surrounding air.

Accordingly, several methods and techniques have been utilized, either to improve and increase the efficiency of the existing dissipators or to find new ones, that satisfy both high effectiveness and minimum cost of construction. These methods or techniques might be classified as follows:

(1) Energy dissipation by using stilling basins, (2) Energy dissipation by counter flow and (3) Energy dissipation on slopping surfaces.

Tailwater is generally characterized by small velocities resulting in a subcritical flow condition. The flowing water either over weirs, under sluices or through pipes is characterized by a high velocity jet. When a supercritical flow issuing downstream hydraulic structures, impacts the slow tailwater, a free hydraulic jump zone is formed having a large velocity gradient, Figure 2-A. When the flow level at the tailwater is too low, the free jump will be shooting, extending to a larger length; then the velocity gradient becomes small, consequently, the stilling basin must be lengthened so that jump and eddies zones will finish within the length of the stilling basin, which increases the construction costs.

To restrain the free jump, energy dissipators must be applied, to help reducing the size of stilling basins by moving the hydraulic jump forward, Figure 2-B, the formed jump in this case is then called a forced jump. The efficiency of such energy dissipation methods can have a significant impact on the overall cost of a project. As a result, there have been great efforts amongst engineers and researchers towards developing efficient but also cost effective solutions, Therefore, most of the classical methods of water energy dissipation, are mainly aimed at creating a forced jump, whether perfect or drowned.



(A): *Free jump* **(B):** *Forced jump*

Figure 2: *Formation of free and forced hydraulic jump*

2 Experimental Study

Experimental work was conducted in the experimental set-up, specially prepared to study the effect of the main parameters concerned with the cross jet on the characteristics of the formed hydraulic jump considering the three cases: free perfect jump, without cross jet, forced perfect jump, with cross jet and drowned jump, with cross jet.

The model was installed in the experimental set up prepared at the laboratory of fluid mechanics, **Faculty of Engineering, Elmergib University**. Figure 3 shows the components of the experimental set-up which consists of the following parts [8]:

2.1 The Testing Flume

The testing flume comprises a rectangular section of channel (1) with inlet (2) and discharge (3) tanks. The testing flume is rested on a pair of rigid pedestals (4). A service module (5) incorporating a sump tank (6) and submersible pump (7) provides a source of water which is continuously recirculated through the channel section making a closed circuit of water supply. Laboratory experiments are carried out on a rectangular open channel flume 5 m long and rectangular cross section 25 cm high by 7.6 cm wide. The sides are fabricated form 10 mm transparent Perspex sheets which are bonded to a bed fabricated form painted aluminium alloy. The end tanks are constructed from glass reinforced plastic with a smooth gel coat on the inside. Water enters the working section via inlet tank (2). The sides of the inlet tank are profiled with a smooth contraction towards the working section. To reduce the turbulence of the water entering the inlet tank and to produce a smooth flow of water, the pipe supplying the inlet tank (8) has diffused outlet and is covered by perforated plate and glass marbles.

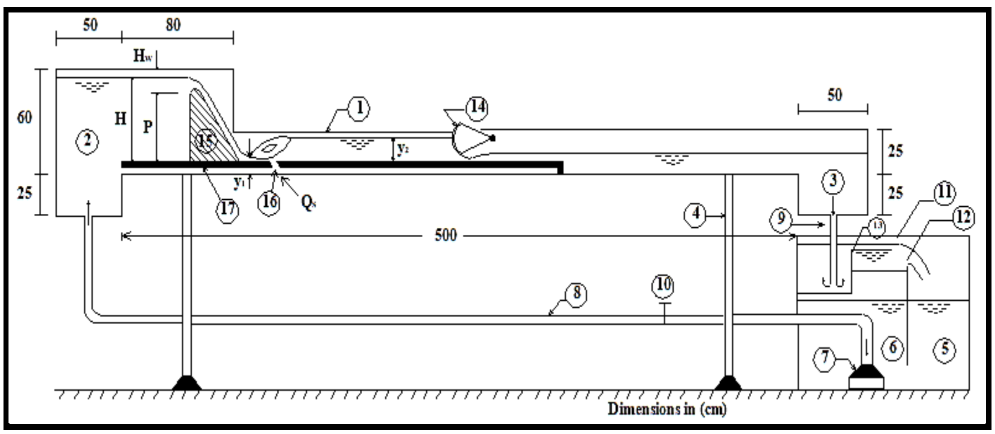


Figure 3: *General layout of the experimental set-up*

Legend: -

- **(1)** *Testing flume.*
- **(2)** *Inlet tank.*
- **(3)** *Discharge tank.*
- **(4)** *Pedestal.*
- **(5)** *Service module.*
- **(6)** *Sump tank.*
- **(7)** *Submersible pump.*
- **(8)** *Supplying pipe.*
- ***(9)*** *Discharge pipe.*
- ***(10)*** *Control valve.*
- ***(11)*** *Moulded channel.*
- ***(12)*** *Rectangular weir.*
- ***(13)*** *Screen.*
- ***(14)*** *Control gate.*
- ***(15)*** *Spillway model.*
- ***(16)*** *Slot.*
- ***(17)*** *structure floor.*

Water exiting from the flume enters the discharge tank (3) where it returns by gravity, through the discharge pipe (9), to the service module (5).

The service module is constructed from glass reinforced plastic. Water is drawn from the sump tank in the base of the service unit by the submersible pump (7). The water is delivered to the flume through the supplying pipe (8) which has a flow control valve (10). Water returns from the flume discharge tank to a moulded channel (11) on the top of the service module. The water then flows over rectangular weir (12) to the sump tank by gravity. The moulded channel has a screen (13) to damp any disturbance caused by the discharge pipe, so that water surface being smooth before falling over the weir. A radial gate (14) is installed in the working channel to control the water depth downstream of the spillway.

2.2 Dissipation Model

The tested model is made of Perspex sheets; it comprises of the following two components:
The inclined surface, of the spillway, is represented by an inclined plate (15) joining the crest of the ogee weir to the testing flume bottom. It has 10 mm thick, 1.0 (Vertical) to 0.7 (Horizontal) slope and 43.5 cm height, as shown in the above slope of the back face of the spillway was chosen according to the previous studies conducted by some Authors [9-12]. Such a given slope prevents separation of flow from the inclined surface.
The slot (16) was formed through a Perspex sheet (17) of 15 mm thickness, represents the structure floor. Slot's angle, width, and position are selected according to the considered values listed in Table 1. It should be noticed that the slot angle gives the direction of the cross jet flow with respect to the horizontal direction, as shown in Figure 4. Photo 1 shows the different components of the experimental set up [8].

Photo 1: *Components of the experimental set up*

2.3 Measuring Devices

2.3.1 Water Depths Measurement

The headwater depth H was measured using a Piezometric tube, fixed on a vertical scale of 0.50 mm accuracy and connected to the bottom of the testing flume by a rubber tube. The contracted depth y_c or the initial water depth y_1 was measured using a point gauge provided with a Vernier to obtain an accuracy up to 0.10 mm. The gauge reading at the channel bed line was taken firstly, then the gauge is adjusted on the water surface at the contracted section. The difference between the two readings gives the initial water depth, $y_1(y_1 = y_c)$.

Because of the frequented wave surface at the end of the hydraulic jump, Piezometric tube was used to measure the tailwater depth y_2. The Piezometric tube is fixed on a vertical scale, of 0.50 mm accuracy. The Piezometric tube is connected to the bottom of the flume by a rubber tube, as shown in photo 2.

Photo 2: *Piezometric tube*

2.3.2 Discharge Measurement

The discharge was measured by a sharp edged rectangular weir of width 17.0 cm and height 5.0 cm. The measuring weir is connected to the moulded channel which has 70 cm long and 25.0 cm wide. The head above the weir was measured using a point gauge having Vernier of accuracy up to 0.10 mm. Photos 3 and 4 show the components of the measuring weir.
The weir was calibrated using the volumetric method [13]. As a result, the obtained discharge equation may be expressed as;

$$Q = 0.27485 * h^{1.578} \tag{1}$$

Where: Q =discharge, $(lit/\sec)$ and h =head over weir.

Photo 3

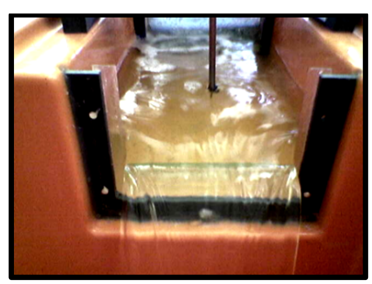


Photo 4

Photos 3 and 4: *Components of the measuring weir*

3 The Experimental Procedure

3.1 Case of Perfect Free Jump

(1) The pump is turned on and the control valve (10) is opened to a certain limit to obtain constant values of the discharge passing over the weir spillway, where Q_W = 0.5, 1.0, 1.50, 2.0 and 2.50 $(lit/\sec)$, corresponding to a headwater depth H = 45.70, 46.98, 48.05, 48.98 and 49.85 cm, respectively.

(2) For each discharge, the contracted section is singed and the contracted depth y_c and it's distance from the weir toe x_c were measured.

(3) Using the tailgate, the position of the hydraulic jump is adjusted so that the front of jump, immediately being at the contracted section to obtain a perfect jump. In this case, the initial depth of jump y_1 equals the contracted depth y_c.

(4) The tailwater depth y_2 was measured using the Piezometric tube and the length of the jump L_J was measured using a horizontal scale.

3.2 Case of Drowned Jump

(1) Considering constant values of both slot width b = 0.15 cm and inclination angle $\theta = 15^\circ$, the slot location was fixed at distances x_s = 5, 10, 15, 20, 25 and 30 cm.

(2) Considering x_s = 5.0 cm, the pump is turned on and the control valve is adjusted to give the same headwater depth H used in case of free jump. In this case, the discharge passing over the weir spillway Q_W remains constant as considered in case of free jump (step 1).

(3) Due to the effect of the discharge issuing from the slot Q_S, the tailwater depth increases creating a drowned jump. After that, the tailwater depth y_2 and the length of the drowned jump L_D, were measured.

(4) Using the tailgate, the tailwater depth was gradually reduced until the jump front is being immediately at the contracted section. Here the initial depth y_1 (or the contracted depth y_c) is still at the same value found in case of free jump, since Q_W is not changed.

(5) The tailwater depth y_2 and the length of forced jump L_J are then measured.

(6) The head on the rectangular weir (12) is measured and the total discharge Q_T is then estimated using Equation. (1). The discharge issuing from the slot Q_S is then found, $Q_S = Q_T - Q_W$.

(7) Steps from (2) to (6) are repeated for other values of the headwater depth H.

(8) Considering another values of the slot distance x_s steps from (1) to (7) are repeated.

(9) Fixing the slot location at distance x_s =15.0 cm and considering slot width b =0.15 cm, the inclination angle of the slot θ is taken equal to 15°, 30, 45°, 60°, 75°, 90°.
For each of the above values of θ, the procedure is repeated from step (2) to (7).
(10) Fixing the slot location at distance x_s =15.0 cm, and considering the inclination angle of slot θ=45°, the width of slot b is varied as b =0.15, 0.20, 0.25, 0.30 cm.
(11) Considering each of the above values of slot width b steps from (2) to (7) are repeated.
It should be noticed that, a sufficient time was allowed to satisfy a steady state condition of flow before recording the measured values.

3.3 Range of Froude Number

In the present study, Froude number ranges from 8.74 to 13.45. In this range, the jump is well established, the roller and jump action is fully developed to cause appreciable energy loss. However, the water surface downstream of the jump is rough and wavy.

3.4 Range of Discharge

The discharge passing over weir ranges from 500 cm3/sec to 2500 cm3/sec, while the discharge passing through slot ranges from 72.50 to 412.40 cm3/sec. The total discharge ranges from 500 to 2912.40 cm3/sec. The relative slot discharge ranges from 0.039 to 0.439 cm3/sec.

3.5 Range of Experiments

In this work, seventeen experiments were carried out in the laboratory. For each experiment, five runs corresponding to five values of Froude number were carried out, then the total number of experiments equals, 5x17=85 runs.

3.6 Main Parameters Involved in The Current Problem

Referring to Figure 4, the parameters affect on the hydraulic jump characteristics may be grouped
as follows;

3.6.1 Boundary Parameters

(i) The height of the inclined surface p.
(ii) The width of the tailwater channel B.
(iii) The distance of slot position x_s.
(iv) The width of slot b.
(v) The inclination angle of slot θ.

3.6.2 Flow Parameters

(i) The headwater depth H.

(ii) The head over the weir crest H_W.

(iii) The conjugate depths, y_1 and y_2.

(iv) The mean velocity of flow at the contracted section v_1.

(v) The discharge passing over the weir Q_W.

(vi) The discharge passing through the slot Q_S.

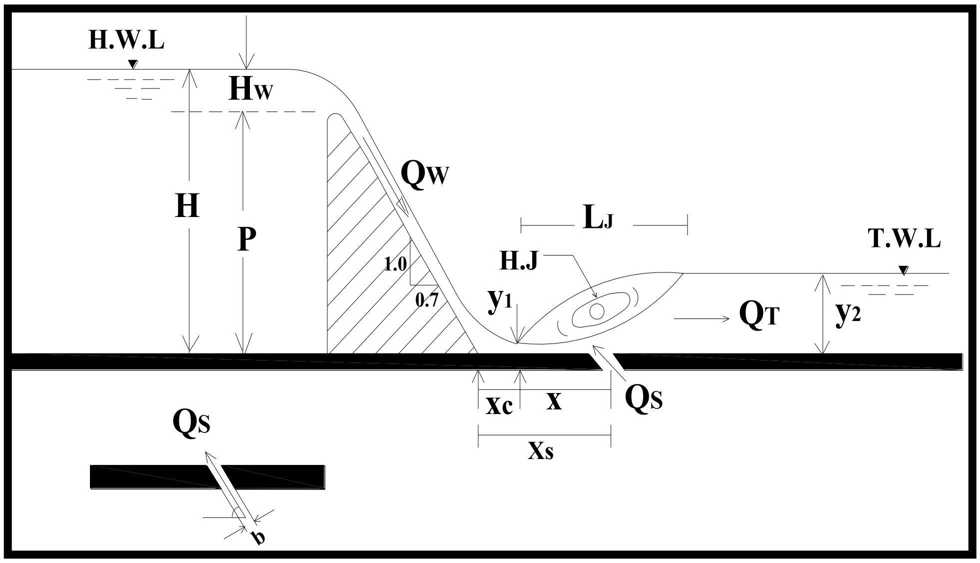


Figure 4: *Details of dissipater model*

All over the experimental work, the height of the inclined surface p was kept constant at 43.50 cm. For each experiment, the headwater depth H was changed five times since H = 45.70, 46.98, 48.05, 48.98 and 49.85 cm. Since $H = p + H_W$, therefore the head over the weir crest H_W equals 2.2, 3.48, 4.55, 5.48 and 6.35 cm, respectively. The width of tailwater channel also was kept constant in the experiments. It should be noticed that the mean velocity v_1, includes the effect of both H and Q_W.

4 Analysis of Results

The main parameters involved in the current problem are; the distance of slot location x_s the angle of slot with the horizontal θ the width of slot b and Froude number of the incoming flow (supercritical) F_1. Different values of x_s, θ, b and F_1 were experimentally investigated as indicated in Table 1.

Table 1: *The tested values of the considered parameters*

Parameter	Fixed parameters			Variable parameters		
	x_s, cm	θ°	b, cm	x_s, cm	θ°	b, cm
Distance of slot location, x_s, cm	-	15	0.15	5 10 15 20 25 30	-	-
Inclination angle of slot, θ°	15	-	0.15	-	15 30 45 60 75 90	-
Width of slot, b cm	15	45	-	-		0.15 0.20 0.25 0.30

The case of free jump, in which the cross jet is not existed, was also investigated to be a reference data used to indicate the effect of the above parameters on the hydraulic jump characteristics and to compare the results obtained from the case of forced jump formed due to the cross jet flow.

Comparison is based on the obtained results considering the case of the prefect hydraulic jump, either free or forced, and the case of drowned jump as shown in Figure 5. Referring to Figure 5, cases of perfect free, perfect forced and drowned jump have the same conditions of flow upstream the contracted section, wherever $x_s > x_c$; the head water depth H, the head over the weir crest H_W and discharge passing over the weir Q_W.

Downstream the contracted section, the above cases have different conditions; the total discharge Q_T and the tailwater depth y_2. In case of free jump, where $Q_S = 0$, the total discharge Q_T equals to the weir discharge Q_W or $Q_T = Q_W$ while $Q_T = Q_W + Q_S$ in case of forced perfect or drowned jumps, where Q_S is the discharge passing through the slot.

Analysis of results in this paper was only focused on effect of the considered parameters on the drowned jump.

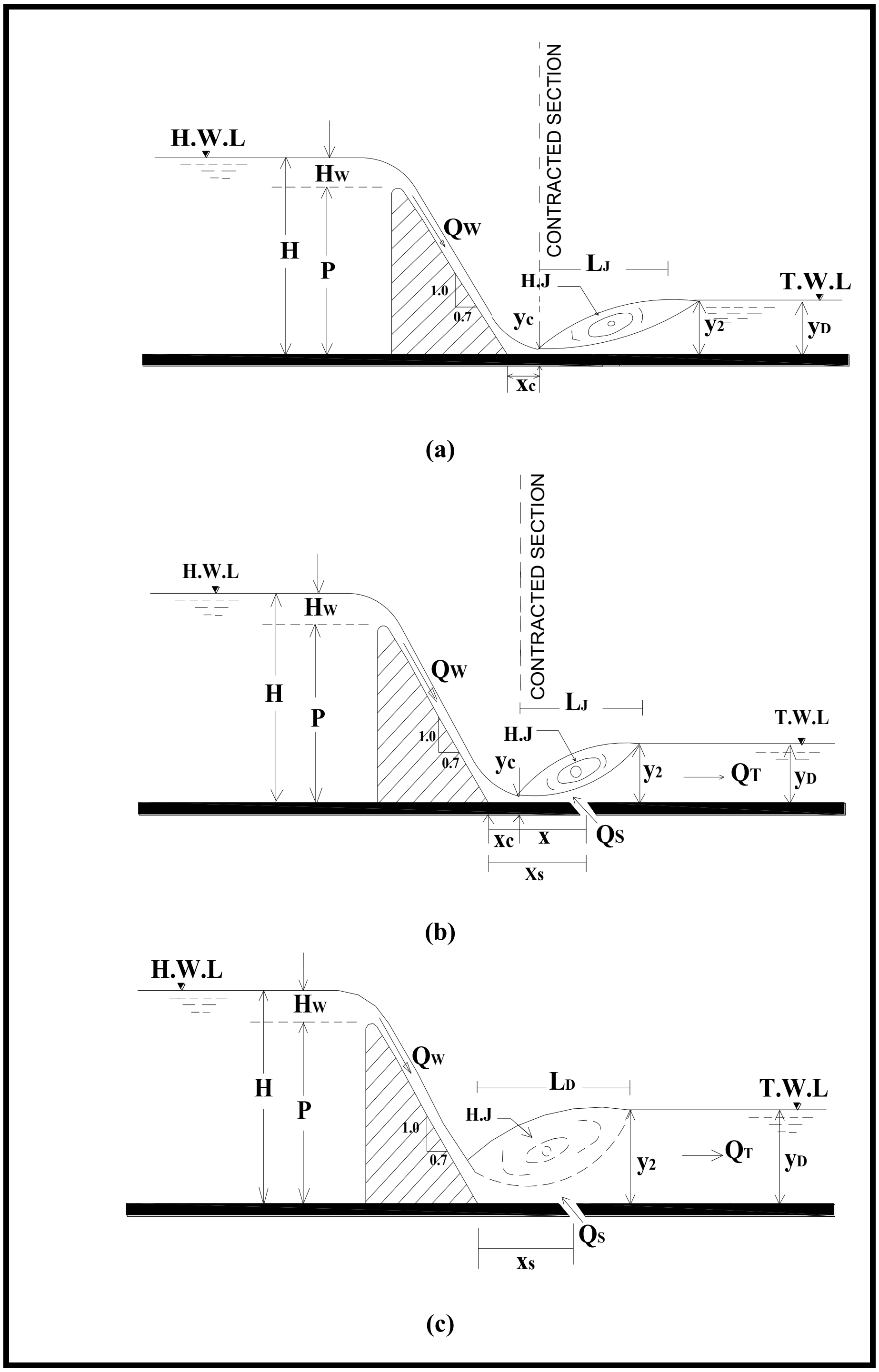


Figure 5: *Definition sketch for the formed hydraulic jump; (a) Free perfect jump, (b) Forced perfect jump and (c) Drowned jump*

4.1 The Effect of Counterflow on The Drowned Jump

The effect of the cross jet on the drowned jump is examined using the same tested values of slot position x_s, inclination angle θ and slot width b given in Table 1. As illustrated in section 3, after establishing a free perfect jump, once the cross jet is allowed to act, the tailwater depth y_2 increases and the jump becomes drowned.

Both the length of the drowned jump L_D and the submergence ratio S_D are affected by the variation of slot position x_s, inclination angle of slot θ and slot width b. Here , the submergence ratio S_D is defined as the ratio between the tailwater depth for a free jump y_2 to the same depth creating drowned jump y_D or;

$$S_D = y_2 / y_D \tag{2}$$

To indicate the effect of cross jet on the drowned jump , the length of drowned jump L_D is compared to the length L_f which expresses the sum of contraction section distance x_c and length of free perfect jump L_J or; $L_f = x_c + L_J$

The resulting relative difference Δ_L between the length L_f and L_D is expressed as a percentage value, where;

$$\Delta L\% = \frac{L_f - L_D}{L_f} \times 100 \tag{3}$$

The effect of variation of slot location x_s angle θ and width b on both the submergence ratio S_D and the percentage reduction ΔL % of length L_f is discussed below.

4.1.1 Effect of Slot Location x_s

To show the effect of slot location, the distance x_s is varied as x_s = 5, 10, 15, 20, 25 and 30 cm while the inclination angle of slot θ and the width of slot b are kept constant at 15° and 0.15 cm, respectively. Table 2 indicates both measured and calculated data, describing the effect of slot position x_s on the characteristics of the drowned jump, while Figure 6 shows the relation between the percentage difference ΔL % and Froude number F_1 considering the tested values of slot location x_s. Both Table 2 and Figure 6 show that the reduction in free jump length ΔL % increases as F_1 increases for all values of x_s. On the other hand, the maximum values of ΔL % are obtained when x_s = 15 cm, while the minimum value occur when x_s = 5 cm. The maximum value of ΔL % is 34.62% occurs when x_s = 15 cm and F_1 = 13.45, while the minimum value equals 18.75% when x_s = 5 cm and F_1 = 9.22.

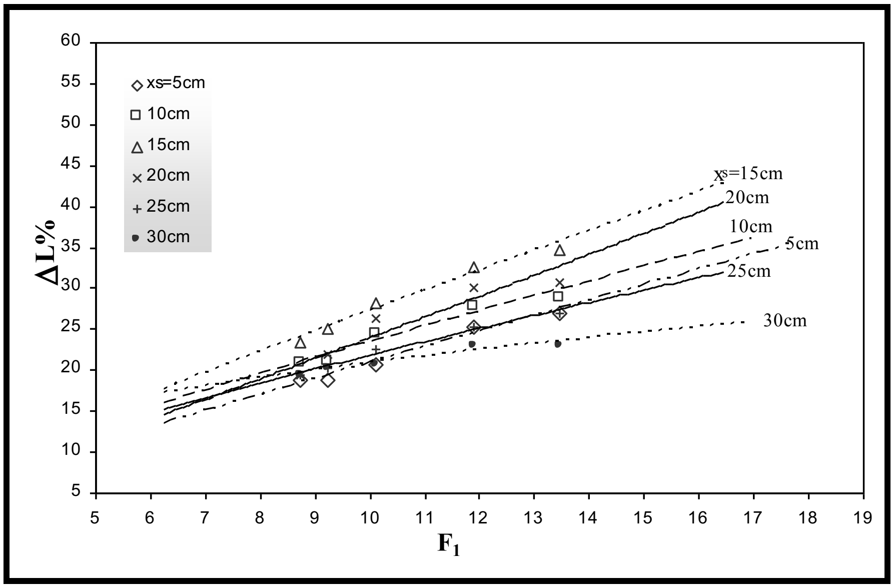


Figure 6: *Relation between percentage difference ΔL % and Froude number F_1 due to variation of slot location x_s*

It is found also from Table 2, that the submergence ratio S_D increase as F_1 increases and has the maximum values when x_s = 15 cm. Generally, the submergence ratio S_D ranges from 1.01 to 1.74.

4.1.2 Effect of the Inclination Angle of Slot θ

Considering the effect of the variation of angle of inclination θ on the drowned jump, the slot location x_s and slot width b are kept constant at 15 cm and 0.15 cm, respectively. In the same time the inclination angle θ was varied as θ=15, 30, 45, 60, 75, 90°. Table 3 and Figure 7 show the resulting effect, on the drowned jump due to variation of angle θ. It is found that, the percentage difference ΔL % increases as Froude number F_1 increases. The maximum values of ΔL % equals 40.38% is obtained when θ = 45° and F_1 = 13.45.

As for the submergence ratio S_D, it has the same trend of ΔL %, since it increases when F_1 increases, and has its maximum value 1.88 when F_1 = 13.45 and θ = 45°.

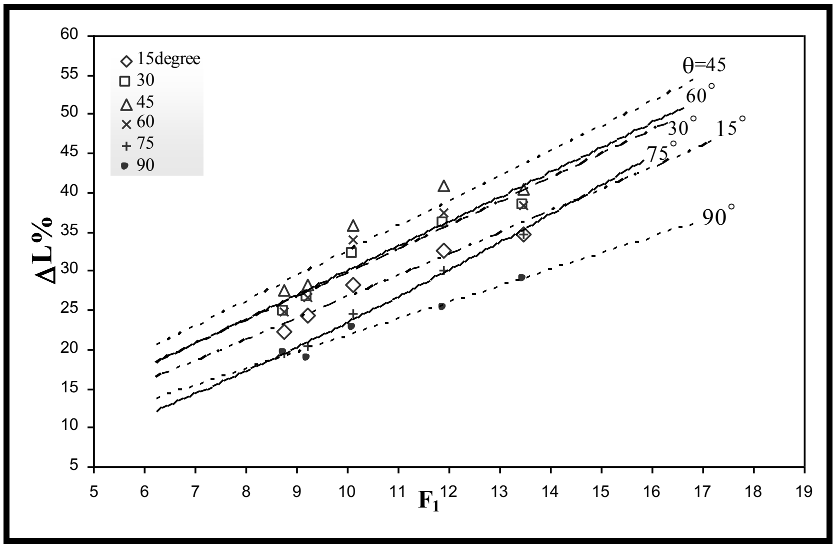


Figure 7: *Relation Between ΔL % and F_1 Due to Variation of Inclination Angle of Slot θ*

4.1.3 Effect of Slot Width b

In this case, the slot location x_s and slot inclination angle θ are kept constant at 15 cm and 15°, respectively, while the slot width b is varied as b = 0.15, 0.20, 0.25, and 0.30 cm. Table 4 and Figure 8 show the data describing the resulting effect, on the percentage difference ΔL % and the submergence ratio S_D due to variation of slot width b.

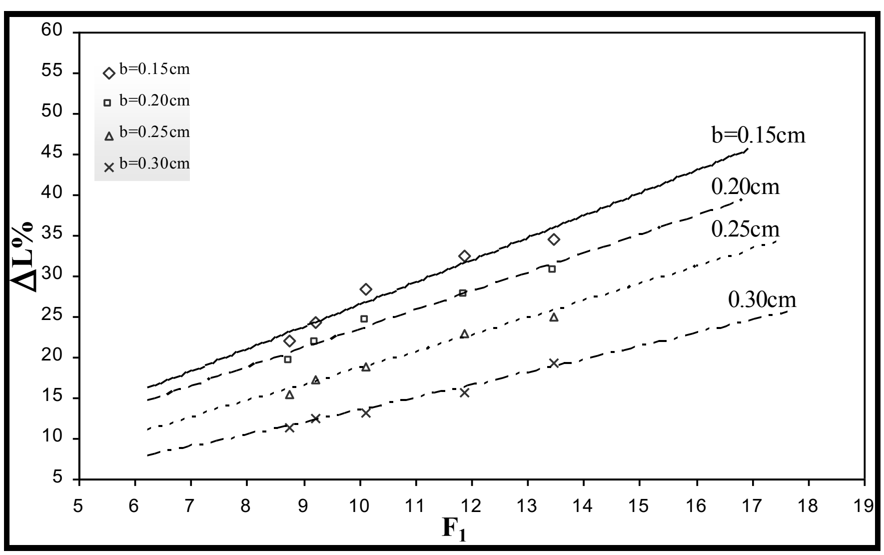


Figure 8: *Relation Between ΔL % and Froude Number F_1 Due to Variation of Slot Width b*

It is found from Table 4 and Figure 8 that both ΔL % and S_D increase as F_1 increases and the maximum value of ΔL % and S_D are obtained when b = 0.15 cm. This refers to that when the slot width increases, an overhead jump occurs and falling in the downstream of the slot which increases the length of drowned jump L_D. Therefore, the slot width b = 0.15 cm gives the minimum values of L_D compared to other slot widths.

5 Conclusions

A comprehensive experimental study had been conducted in the present work, to investigate some characteristics of the formed drowned hydraulic jump, when the counter flow used to dissipate the energy of the flow falling over an ogee weir spillway. The obtained results insure that control of the hydraulic jump formed downstream of an ogee weir spillway, is possible using the reversed cross jet dissipator (counterflow). The suggested cross jet dissipator can be used to convert the repelled hydraulic jump not only to a perfect jump but also to a drowned jump and hence reduces the length of solid floor to a large extent.

Graphical presentations were given for a drowned hydraulic jump, for a Froude number ranges from 8.74 to 13.45.

The characteristics of the drowned hydraulic jump are represented by three variables, namely; the length of drowned jump L_D, the reduction in free jump length ΔL % and the submergence ratio S_D.

Based on the analysis and discussion of the experimental results, obtained in the present study, the following conclusions may be given as follows:

(1) In general, the results show that both the percentage reduction in the jump length and the submergence ratio increase as Froude number increases.

(2) The maximum value of ΔL % is 34.62 % occurs when x_s = 15 cm and F_1= 13.45, while the minimum value equals 18.75% when x_s = 5 cm and F_1= 9.22.

(3) Both ΔL % and S_D increase as F_1 increases and the maximum values of ΔL % and S_D are obtained when b = 0.15 cm.

(4) The submergence ratio S_D has the same trend of ΔL %, since it increases when F_1 increases, and has its maximum value 1.88 when F_1 = 13.45 and θ = 45°.

(5) The cross jet flow can shorten the length of the solid floor, by creating a drowned jump instead of a free perfect jump, to about 65% with a submergence ratio of about 1.74.

(6) The value of the counterflow width b (the slot), should not exceed the value of b = 0.15 cm, otherwise an overhead jump will occurs and falling in the downstream of the slot which increases the length of drowned jump L_D. Therefore, the slot width b = 0.15 cm gives the minimum values of L_D in comparison to other slot widths.

x_s	F_1	x_c	L_J, cm	L_f	L_D	y_2	y_D	$\Delta L\%$	$\Delta y\%$	S = y_2
5	13.45	3.00	23.00	26.00	19.00	5.00	8.10	26.92	62.00	1.62
	11.88	6.50	35.00	41.50	31.00	7.50	9.10	25.30	21.33	1.21
	10.10	8.00	45.00	53.00	42.00	9.60	10.30	20.75	7.29	1.07
	9.22	11.00	53.00	64.00	52.00	11.25	11.53	18.75	2.49	1.02
	8.74	13.50	61.00	74.50	60.50	12.75	12.85	18.79	0.78	1.01
10	13.45	3.00	23.00	26.00	18.50	5.00	8.50	28.85	70.00	1.70
	11.88	6.50	35.00	41.50	30.00	7.50	9.50	27.71	26.67	1.27
	10.10	8.00	45.00	53.00	40.00	9.60	10.70	24.53	11.46	1.11
	9.22	11.00	53.00	64.00	50.50	11.25	11.80	21.09	4.89	1.05
	8.74	13.50	61.00	74.50	59.00	12.75	13.20	20.81	3.53	1.04
15	13.45	3.00	23.00	26.00	17.00	5.00	8.70	34.62	74.00	1.74
	11.88	6.50	35.00	41.50	28.00	7.50	9.70	32.53	29.33	1.29
	10.10	8.00	45.00	53.00	38.00	9.60	10.90	28.30	13.54	1.14
	9.22	11.00	53.00	64.00	48.00	11.25	12.10	25.00	7.56	1.08
	8.74	13.50	61.00	74.50	57.00	12.75	13.40	23.49	5.10	1.05
20	13.45	3.00	23.00	26.00	18.00	5.00	8.60	30.77	72.00	1.72
	11.88	6.50	35.00	41.50	29.00	7.50	9.50	30.12	26.67	1.27
	10.10	8.00	45.00	53.00	39.00	9.60	10.70	26.42	11.46	1.11
	9.22	11.00	53.00	64.00	50.00	11.25	11.70	21.88	4.00	1.04
	8.74	13.50	61.00	74.50	60.00	12.75	13.10	19.46	2.75	1.03
25	13.45	3.00	23.00	26.00	19.00	5.00	8.30	26.92	66.00	1.66
	11.88	6.50	35.00	41.50	31.00	7.50	9.30	25.30	24.00	1.24
	10.10	8.00	45.00	53.00	41.00	9.60	10.40	22.64	8.33	1.08
	9.22	11.00	53.00	64.00	51.00	11.25	11.50	20.31	2.22	1.02
	8.74	13.50	61.00	74.50	60.00	12.75	12.90	19.46	1.18	1.01
30	13.45	3.00	23.00	26.00	20.00	5.00	8.20	23.08	64.00	1.64
	11.88	6.50	35.00	41.50	32.00	7.50	9.10	22.89	21.33	1.21
	10.10	8.00	45.00	53.00	42.00	9.60	10.30	20.75	7.29	1.07
	9.22	11.00	53.00	64.00	51.00	11.25	11.40	20.31	1.33	1.01
	8.74	13.50	61.00	74.50	60.00	12.75	12.90	19.46	1.18	1.01

Table 2: *Effect of Slot Locations* x_s *on the Drowned Jump, When* b = 0.15 cm *and* θ = 15°

Table 3: *Measured and Calculated Data for the Drowned Jump Due to Variation of Inclination Angle θ When b = 0.15 cm and x_s = 15 cm*

θ°	F_1	x_c	L_J, cm	L_f	L_D	y_2	y_B	$\Delta L\%$	$\Delta y\%$	$S_B = \frac{y_B}{y_2}$
15°	13.45	3.00	23.00	26.00	17.00	5.00	8.70	34.62	74.00	1.74
	11.88	6.50	35.00	41.50	28.00	7.50	9.70	32.53	29.33	1.29
	10.10	8.00	45.00	53.00	38.00	9.60	10.90	28.30	13.54	1.14
	9.22	11.00	53.00	64.00	48.50	11.25	12.10	24.22	7.56	1.08
	8.74	13.50	61.00	74.50	58.00	12.75	13.40	22.15	5.10	1.05
30°	13.45	3.00	23.00	26.00	16.00	5.00	8.90	38.46	78.00	1.78
	11.88	6.50	35.00	41.50	26.50	7.50	9.90	36.14	32.00	1.32
	10.10	8.00	45.00	53.00	36.00	9.60	11.20	32.08	16.67	1.17
	9.22	11.00	53.00	64.00	47.00	11.25	12.30	26.56	9.33	1.09
	8.74	13.50	61.00	74.50	56.00	12.75	13.50	24.83	5.88	1.06
45°	13.45	3.00	23.00	26.00	15.50	5.00	9.40	40.38	88.00	1.88
	11.88	6.50	35.00	41.50	24.50	7.50	10.60	40.96	41.33	1.41
	10.10	8.00	45.00	53.00	34.00	9.60	11.60	35.85	20.83	1.21
	9.22	11.00	53.00	64.00	46.00	11.25	12.70	28.13	12.89	1.13
	8.74	13.50	61.00	74.50	54.00	12.75	13.90	27.52	9.02	1.09
60°	13.45	3.00	23.00	26.00	16.00	5.00	9.10	38.46	82.00	1.82
	11.88	6.50	35.00	41.50	26.00	7.50	10.40	37.35	38.67	1.39
	10.10	8.00	45.00	53.00	35.00	9.60	11.30	33.96	17.71	1.18
	9.22	11.00	53.00	64.00	47.00	11.25	12.50	26.56	11.11	1.11
	8.74	13.50	61.00	74.50	56.00	12.75	13.60	24.83	6.67	1.07
75°	13.45	3.00	23.00	26.00	17.00	5.00	8.90	34.62	78.00	1.78
	11.88	6.50	35.00	41.50	29.00	7.50	10.30	30.12	37.33	1.37
	10.10	8.00	45.00	53.00	40.00	9.60	11.20	24.53	16.67	1.17
	9.22	11.00	53.00	64.00	51.00	11.25	12.20	20.31	8.44	1.08
	8.74	13.50	61.00	74.50	60.00	12.75	13.30	19.46	4.31	1.04
90°	13.45	3.00	23.00	26.00	18.50	5.00	8.40	28.85	68.00	1.68
	11.88	6.50	35.00	41.50	31.00	7.50	9.70	25.30	29.33	1.29
	10.10	8.00	45.00	53.00	41.00	9.60	10.70	22.64	11.46	1.11
	9.22	11.00	53.00	64.00	52.00	11.25	11.70	18.75	4.00	1.04
	8.74	13.50	61.00	74.50	60.00	12.75	12.90	19.46	1.18	1.01

b	F_1	α	L_J, cm	L_f	L_D	y_2	y_B	$\Delta L\%$	$\Delta y\%$	$S_B = \frac{y_B}{y_2}$
0.15	13.45	3.00	23.00	26.00	17.00	5.00	8.70	34.62	74.00	1.74
	11.88	6.50	35.00	41.50	28.00	7.50	9.70	32.53	29.33	1.29
	10.10	8.00	45.00	53.00	38.00	9.60	10.90	28.30	13.54	1.14
	9.22	11.00	53.00	64.00	48.50	11.25	12.10	24.22	7.56	1.08
	8.74	13.50	61.00	74.50	58.00	12.75	13.40	22.15	5.10	1.05
0.20	13.45	3.00	23.00	26.00	18.00	5.00	8.60	30.77	72.00	1.72
	11.88	6.50	35.00	41.50	30.00	7.50	9.50	27.71	26.67	1.27
	10.10	8.00	45.00	53.00	40.00	9.60	10.70	24.53	11.46	1.11
	9.22	11.00	53.00	64.00	50.00	11.25	12.00	21.88	6.67	1.07
	8.74	13.50	61.00	74.50	60.00	12.75	13.30	19.46	4.31	1.04
0.25	13.45	3.00	23.00	26.00	19.50	5.00	8.40	25.00	68.00	1.68
	11.88	6.50	35.00	41.50	32.00	7.30	9.30	22.89	24.00	1.24
	10.10	8.00	45.00	53.00	43.00	9.60	10.40	18.87	8.33	1.08
	9.22	11.00	53.00	64.00	53.00	11.25	11.90	17.19	5.78	1.06
	8.74	13.50	61.00	74.50	63.00	12.75	13.10	15.44	2.75	1.03
0.30	13.45	3.00	23.00	26.00	21.00	5.00	8.20	19.23	64.00	1.64
	11.88	6.50	35.00	41.50	35.00	7.50	9.50	15.66	26.67	1.27
	10.10	8.00	45.00	53.00	46.00	9.60	10.20	13.21	6.25	1.06
	9.22	11.00	53.00	64.00	56.00	11.25	11.90	12.50	5.78	1.06
	8.74	13.50	61.00	74.50	66.00	12.75	12.90	11.41	1.18	1.01

Table 4: *Data Describing the Effect of Variation of Slot Width* b *on the Drowned Jump When* x_s *= 15 cm,* θ *= 15*$^\circ$

References

[1] Chow VT. Open channel hydraulics. London: McGraw-Hill Book Co. Ltd.; 1959

[2] Peterka AJ. Hydraulic design of stilling basins and energy dissipaters engineering monograph No. 25, U.S. Bureau of Reclamation, Denver Colorado; 1958

[3] Rajaratnam N. Hydraulic jumps. In: *Advances in hydroscience*, vol. 4. Edtion Ven Te Chow; 1967. p. 254.W. S.

[4] McCorquodale JA. Hydraulic jumps and internal flows. In: Cheremisionoff NP, editor. Encyclopedia of fluid, vol. 2. Houston: Gulf Publishing; 1986. p. 120–73

[5] Hager WH. Energy dissipaters and hydraulic jump. 3rd ed. Dordrecht: Kluwer Academic; 1992

[6] Sholichin M, Akib S. Development of drop number performance for estimate hydraulic jump on vertical and sloped drop structure. *Int J Eng Sci* 2011;5(11):1678–87

[7] Chaudhry, M. H. (2008). Open-Channel Flow, Springer Science+Business Media, LLC, New York, NY.

[8] Alghwail, A. D. A., Stević, S., Abourohiem, M. A. (2018). Dissipation of mechanical energy over spillway through counter flow, *GRAĐEVINAR, 70* (5), pp.377-391, doi: **https://doi.org/10.14256/JCE.1691.2016**

[9] Stephenson, D. (1991),” Energy dissipation down stepped spillways”., *Water power & Dam construction* 42 (9), pp. 27-30

[10] Chanson, H. (1994 a). “Comparison of energy dissipation between nappe and skimming flow regimes on stepped chutes”, *ASCE, J. Hydraulic Research*, Vol.32, No.2, pp.213-218

[11] Chamani, M. R. and Rajaratnam N. (1999-b), “Onset of skimming flow on stepped spillways”. *J. Hydraulic Engineering*.125 (9) PP. 969-971.

[12] Chamani, M. R. and Rajaratnam N. (1999-a),’ Characteristics of skimming flow over stepped spillways” *J. Hydraulic Engineering*. 125 (4) PP. 361-368

[13] USBR hydraulic design of stilling basins and energy dissipators, *Engineering Monograph*, p 92. No.25.

[14] Alghwail, A. (2016) Alleviation the scouring problem downstream of dam spillways through a reversed cross-jet flow dissipator. In:ICSE 2016 (8th International Conference on Scour and Erosion), 12-15 September 2016, Oxford, UK.