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Variations of Hydraulic Jump Characteristics Due to Different Sill with Slot Layouts

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Downstream many hydraulic structures such as dams, barrage sluice gate etc, changing water flow from supercritical to subcritical flow causes formation of hydraulic jump. The formed hydraulic jump dissipates excess energy of flowing water. This paper carried out experimental runs to study the effect of sills with slot on the hydraulic jump characteristics. The considered hydraulic jump characteristics were the jump sequent depth, jump height, jump length, and energy losses through the jump. In these experimental runs, three sill parameters, which are sill relative slot area, relative sill height, and relative sill distance were used to study their effects on the hydraulic jump characteristics. Five relative slot areas with values of 0 (solid sill), 25, 50, 75, and 100% (no sill), four relative sill heights, of 0 (no sill), 0.75, 1.0, and 1.5 and three relative sill distances were used to show the effect of each parameter on the hydraulic jump characteristics. Results showed that the hydraulic jump sequent depth, height, and energy losses have directly proportional relation with relative sill height but inversely proportional relation with sill relative slot area and relative sill distance. Opposite results were obtained for the jump length. The results were translated into group of curves and equations to obtain any jump characteristic for given sill relative slot area, relative sill height, and relative sill distance. Also, empirical computational models were developed using Buckingham's π-Theorem to calculate any hydraulic jump characteristic for given conditions.

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SYMBOLS

F_1 = Initial Froude number (-)
g = Gravity acceleration (ms^{-2})
η = Ratio of the slot area to the sill area (-)
H_r= Ratio of the sill height, H to the gate opening, GO (-)
L_S= Ratio of the distance of the sill downstream the gate, to the distance of the hydraulic jump end from the gate without sill for the same hydraulic conditions (-)
y_1 = Initial depth (m)
y_2 = Sequent depth (m)
E_1 = Energy upstream the jump (m)
E_2 = Energy downstream the jump (m)
ΔE = Energy loss =E_1- E_2 (m)
L_j = Jump length (m)
H_j = Jump height (m)
I_D = Sequent depth factor (-)
I_H = Hydraulic jump height factor (-)
I_E = Energy loss factor (-)
I_L = The jump length factor (-)

1. INTRODUCTION

Flow downstream of dams, barrage sluice gates, and spillways has supercritical condition with high kinetic energy. This energy must be dissipated to prevent bed scour and erosion. The concept of the methods of kinetic energy dissipation is to achieve subcritical flow condition at the downstream channel. As much as possible kinetic energy of flow must be dissipated by converting it into heat energy which is dissipated into atmosphere. Hydraulic jump is a phenomenon well known to hydraulic engineers as energy dissipater. Previous studies showed that the initial Froude number is the most effective factor upon which the hydraulic jump characteristics depend. The initial and sequent hydraulic jump flow depths have relationship known as sequent depth ratio of Belanger [1] in the rectangular channel. The forming classical hydraulic jump in a horizontal bed and wide rectangular open channel with a smooth bed has been studied extensively, McCorquodale [2], and Hager [3]. Also, the hydraulic jump in open rectangular channels studied by Valiani [4] and Svendsen et al. [5]. Review on analytical and experimental studies by Herbrand [6], Hager [7], Smith [8], and Bremen and Hager [9 and 10], Agarwal [11], and Gandhi [12-14] are mainly devoted to the sequent depth ratio and the relative energy loss. Hughes [15] and Afzal [16] studied the characteristics of hydraulic jump in horizontal rectangular open channel with artificially roughened beds and smooth side walls. Also, it was found that, both the hydraulic jump length, and the sequent depth are reduced due to boundary roughness. Variations of the formed hydraulic jump characteristics with different solid end sill layouts were studied by Mahmoud R. [17].

The purpose of this paper is to investigate the variations of hydraulic jump characteristics due to different sill with slot layouts. Where, no researchers in the previous work studied this concept. The used sill parameters were the slot relative area, sill relative distance, and the sill relative height. Also, fitting curves and equations were developed for this purpose.

2. EXPERIMENTAL FLUME

This paper carried out experimental runs using horizontal experimental open flume in the Hydraulic Laboratory, which is located in the Branch Building of Shobra Faculty of Engineering, Benha University. The experimental flume measuring section of base unit is 2.5 m long and has transparent side walls. This can be extended to 5 m by adding an additional element. The flume has cross section with dimensions of width 90 and height 300 mm. The important elements of the flume are specially shaped inlet area by means of which a homogenous flow is obtained, a high capacity centrifugal pump for setting up the water circuit, a flow rate measuring device and a manual inclination adjustment mechanism designed to compensate flow losses or to simulate natural, sluice gate was fitted in the flume shortly after the inlet with the downstream end sluice gate fully lower. The sluice gate should then be raised to form a hydraulic jump a short distance downstream of the sluice gate, Fig. 1.

3. EXPERIMENTAL PROGRAM

More than 180 experimental runs were carried out to study the effect of the sill with slot parameters on the hydraulic jump characteristics. The sill parameters were the relative sill height, H_r which is the ratio of the sill height, H to the gate opening, GO, the relative slot area, η, which is the ratio of the slot area to the sill area, and the relative sill distance L_S, which is the ratio of

Fig. 1. Schematic layout of experimental setup

the distance of the sill downstream the gate to the distance of the hydraulic jump end from the gate without sill for the same hydraulic conditions. The studied hydraulic jump characteristics were the sequent depth ratio, y_2/y_1, the jump height ratio, H_j/y_1, The energy losses ratio, $\Delta E/E_1$, and the jump length ratio, L_j/y_1. Table 1 show the experimental program for achieving the paper purposes;

4. RESULTS AND DISCUSSION

The experimental program was divided into four groups. In the first group, seven runs were carried out through horizontal bed, and without sill to check the validity of the flume results. The second, third, and forth groups carried out experimental runs to study the effect of the relative slot area, relative sill height, and relative sill distance on the jump characteristics respectively.

4.1 Group 1 Flume Validation

The obtained results of the group 1 showed that, the measured sequent depth ratio, y_2/y_1 values were compatible with Belanger's linear relationship between initial Froude number, F_1, and y_2/y_1 for a hydraulic jump in a rectangular channel, see Table 1. The difference between the present and Belanger relationship was found to be within 10%.

4.2 Group 2 Effect of the Relative Sill Area, η on the Hydraulic Jump Characteristics

First of all, all the considered hydraulic jump characteristics increase with F_1, as shown in Fig. 2 as an example, for η = 0.5, H_r = 1.5 and L_S = 1. On the other hand, the obtained results of this group's runs show that, each of y_2/y_1, H_j/y_1, and $\Delta E/E_1$ decrease as η increases but L_j/y_1 increases with η, at given F_1, H_r and L_S. For example; for F_1 = 5.85, H_r = 1.5 and L_S = 1, increasing in η, by 200% results in decreasing 59, 83, 17% in y_2/y_1, H_j/y_1, and $\Delta E/E_1$ respectively, and 21% increasing in L_j/y_1, Fig. 3.

4.3 Group 3 Hydraulic Jump Variations Characteristics with the Relative Sill Height, H_r

Through the analysis of the experimental results of the group 2 and Fig. 4, it was found that at given F_1,η and L_S, y_2/y_1, H_j/y_1, and $\Delta E/E_1$ increase as H_r increases but L_j/y_1 decreases as H_r increases. For example; the values of y_2/y_1, H_j/y_1, and $\Delta E/E_1$ increase by percents of 15, 18, and 33% respectively, and L_j/y_1 decreases by percent of 8% as H_r increases by 100% at values of F_1 = 5.85, η = 0.5 and L_S = 1.

Table 1. Experimental program

H_r	η (%)	L_S (%)
0	100	No sill
0.75	0	50
		100
		150
	25	50
		100
		150
	50	50
		100
		150
	75	50
		100
		150
1	0	50
		100
		150
	25	50
		100
		150
	50	50
		100
		150
	75	50
		100
		150
1.5	0	50
		100
		150
	25	50
		100
		150
	50	50
		100
		150
	75	50
		100
		150

Table 2. Comparison of the present study with Belanger relationship

F1	Present study	Belanger
2.508465	3.236696	3.082568
3.218362	4.405139	4.078832
5.847136	7.472834	7.784202
6.503759	9.451743	8.711284
8.076341	11.69789	10.93261

4.4 Group 4 Variations of Hydraulic Jump Characteristics with the Relative Sill Distance, L_S

Fig. 5 shows that, L_S has inversely proportional relationship with each of y_2/y_1, H_j/y_1, and $\Delta E/E_1$ but directly proportional relationship with L_j/y_1 at constant values of F_1,η and H_r. For example; y_2/y_1, H_j/y_1, and $\Delta E/E_1$have decreasing percents of 9.3, 11, and 3.4% and increasing 8% in L_j/y_1 as L_S increases by 100% at F_1 = 5.85, η = 0.5 and H_r =1.5.

4.5 Empirical Computational Model

Through using Buckingham's π-theorem and the curve fitting of the experimental results between dimensionless sill parameters groups and the hydraulic jump characteristics, the following general curves, Figs. (6,7,8, and 9) and empirical equations, Equations (5,6,7, and8) were developed. The sill parameters were represented as sequent depth factor I_D, hydraulic jump height factor, I_H, energy loss factor, I_E and the jump length factors, I_L on the x- axis and y_2/y_1, H_j/y_1, $\Delta E/E_1$ and L_j/y_1 were represented on the y- axis respectively. Figs. (6,7,8, and 9) and Equations (5,6,7, and 8) may be used in estimation of the hydraulic jump sequent depth, height, energy loss, and jump length respectively for given values of η, H_r, and L_S.

Where

$$I_D = 0.52F_1 - 2.7\eta + 1.016\ (H_r / L_S) + 1.355 \tag{1}$$

$$I_H = 0.52F_1 - 2.7\eta + 1.016\ (H_r / L_S) + 0.355 \tag{2}$$

$$I_E = 0.0591F_1 - 0.413\eta + 0.0899\ (H_r / L_S) + 0.3361 \tag{3}$$

$$I_L = 1.695F_1 + 4.58\eta + 1.935\ (H_r / L_S) - 1.494 \tag{4}$$

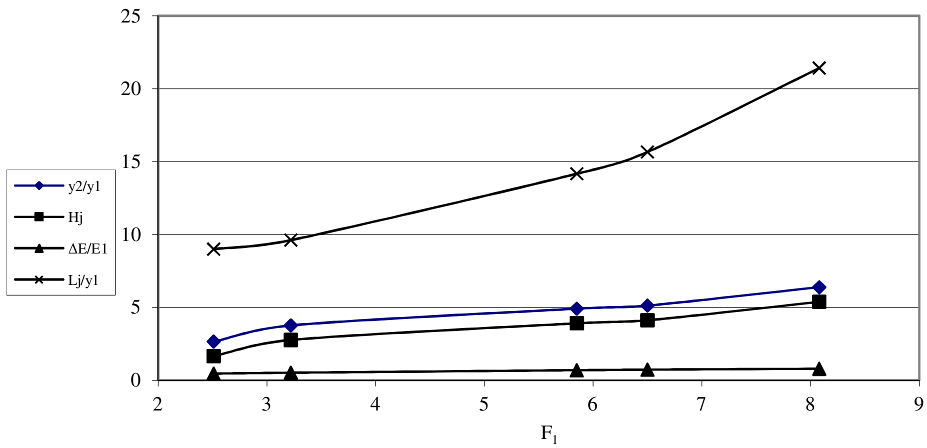

Fig. 2. Variations of the hydraulic jump characteristics with F_1 for η = 50%, H_r = 1.5 and L_S =1

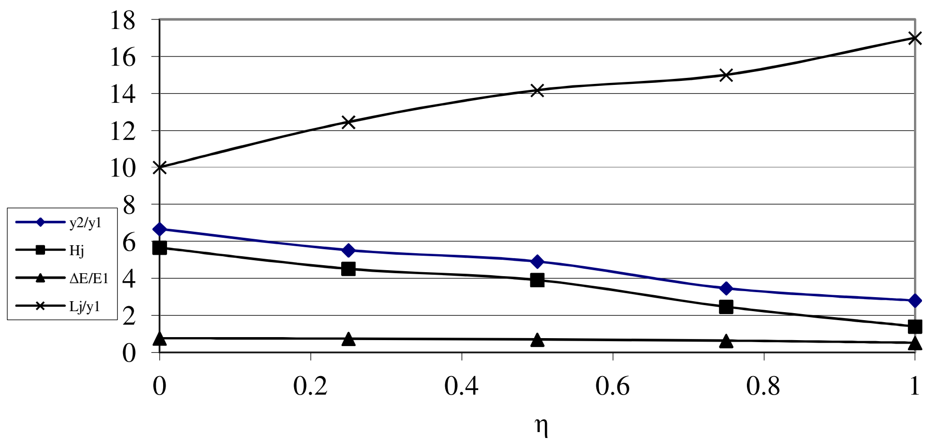

Fig. 3. Variations of the hydraulic jump characteristics with η, for F_1 = 5.85, H_r = 1.5, and L_S = 1

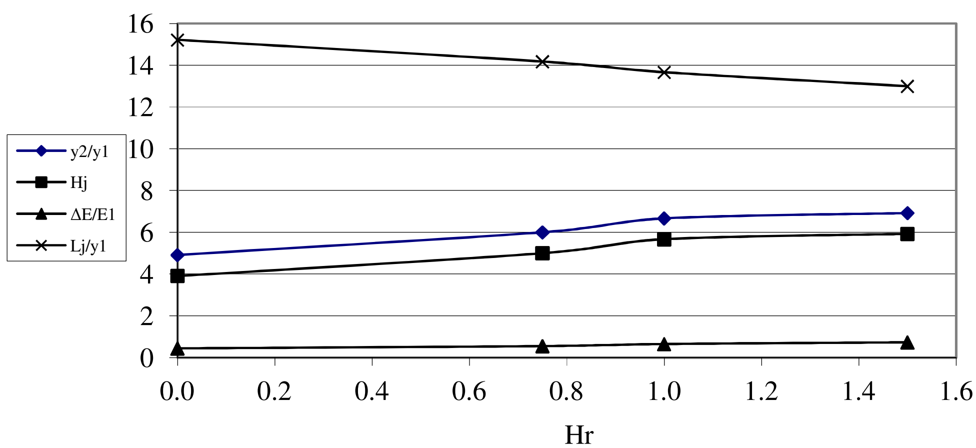

Fig. 4. Vaiations of the hydraulic jump characteristics with Hr, for F1 = 5.85, η = 0.5, and LS = 1

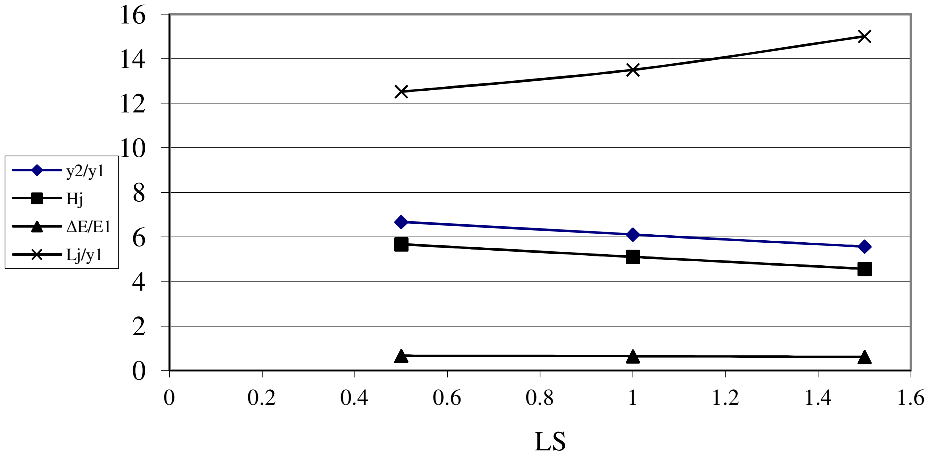

Fig. 5. Variations of the hydraulic jump characteristics with LS, for F1 = 5.85, η = 0.5, and Hr = 1.5

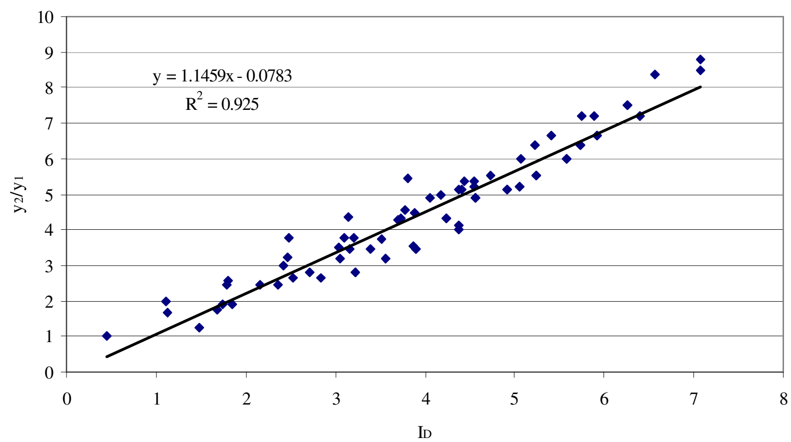

Fig. 6. Effect of sill parameters on y_2/y_1

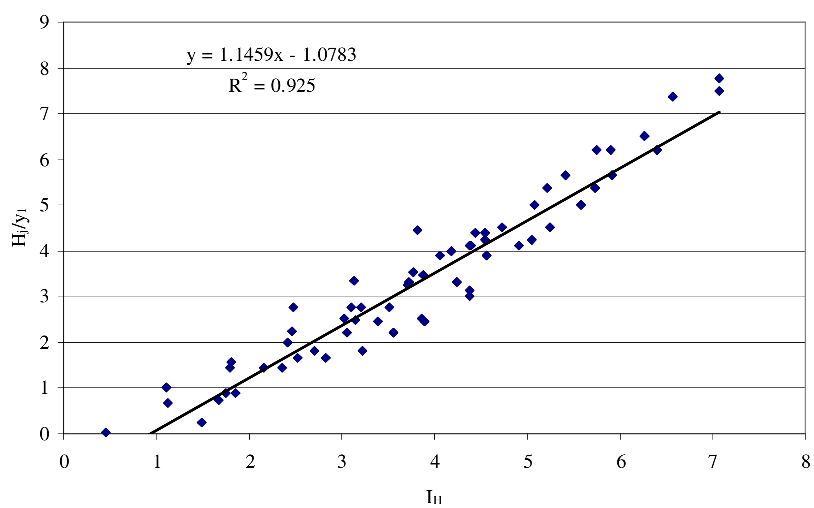

Fig. 7. Effect of sill parameters on H_j

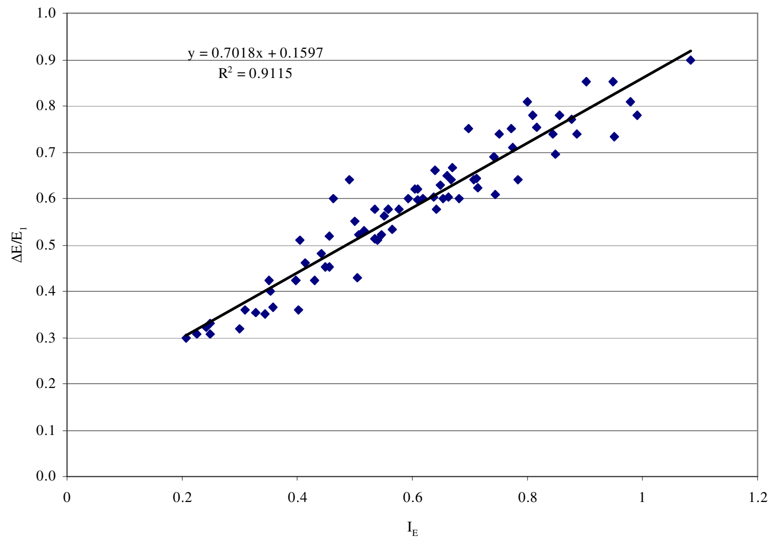

Fig. 8. Effect of sill parameters on Δ E/E_1

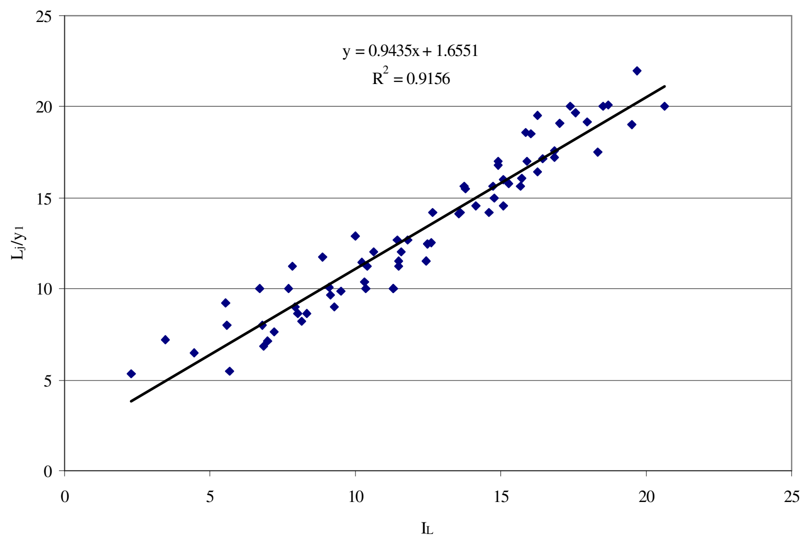

Fig. 9. Effect of sill parameters on L_j

$$y_2 / y_1 = 0.596\, F_1 - 3.0939\, \eta + 1.164\ (H_r / L_S) + 1.474 \tag{5}$$

$$H_j / y_1 = 0.596\, F_1 - 3.0939\, \eta + 1.164\ (H_r / L_S) - 0.672 \tag{6}$$

$$\Delta E / E_1 = 0.0415 F_1 - 0.29 \eta + 0.063\ (H_r / L_S) + 0.396 \tag{7}$$

$$L_j / y_1 = 1.599 F_1 + 4.321 \eta + 1.826\ (H_r / L_S) + 0.246 \tag{8}$$

5. CONCLUSION

The purpose of this paper is to study the variations of the hydraulic jump characteristics with different sill with slot layouts. Based on the analysis of the recorded results, the fitted curves and equations, the following conclusions are reached:

1- Each of y_2/y_1, H_j/y_1, and $\Delta E/E_1$ decrease as η increases but L_j/y_1increases with η, at constant F_1, H_r and L_S.

2- At given values of F_1,ɳ, and L_S, y_2/y_1, H_j/y_1, and $\Delta E/E_1$ increase as H_r increases but L_j/y_1 decreases as H_r increases.
3- L_S has inversely proportional relationship with each of y_2/y_1, H_j/y_1, and $\Delta E/E_1$ but it has directly proportional relationship with L_j/y_1 at given F_1,ɳ, and H_r.
4- The fitted curves and developed equations may be used in estimation of y_2/y_1, H_j/y_1, $\Delta E/E_1$ and L_j/y_1 for any given values of ɳ, H_r, and L_S.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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