

HYDRAULIC JUMP CHARACTERISTICS FOR DIFFERENT OPEN CHANNEL AND STILLING BASIN LAYOUTS

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ABSTRACT

Hydraulic jump is considered as the best way for dissipating energy present in moving water downstream of hydraulic structures. This paper conducted laboratory experiments to investigate the hydraulic jump characteristics variations for different rectangular open channel layouts. In this paper, the used open channel layouts were five bed slopes of 0.0175, 0.0349, 0.0524, 0.0699, and 0.0875, and a sill with three different heights was placed along a model of the stilling basin at three different longitudinal distances. The characteristics of the hydraulic jump, which was formed downstream vertical gate, were measured for variable discharges. Results of experiments show that, the hydraulic jump ratios, jump length and initial depth ratio, L_j/y_1 , jump length and sequent depth ratio, L_j/y_2 , jump depths ratio, y_2/y_1 , y_2-y_1 , and relative energy loss and initial energy ratio, DE/E_1 increase with initial Froude's number for different bed slopes. On the other hand, results show that, the sill has significant effect on the energy dissipation. A new equation was developed to design stilling basin, i.e. the sill height, H , and the longitudinal distance, L_B .

Key words: Rectangular Channel; Hydraulic Jump; Energy Dissipation; Bed Slope.

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List of Symbols

- F_1 Initial Froude's number [–]
 g Gravitational of acceleration [m/s^2]
 y_1 Initial depth [m]
 y_2 Sequent depth [m]
 S Channel bed slope [–]
 L_j Length of jump [m]
 H Sill height [m]
 L_B The sill longitudinal distance downstream the gate [m]

1. INTRODUCTION

Water kinetic energy downstream the vertical gate must be dissipated to prevent scouring of downstream river bed, which may result in failure of downstream structures. Chern [1] applied the model of smoothed particle hydrodynamics (SPH) for investigating the hydraulic jump characteristics in various corrugated beds. It was found that, the dissipated energy on sinusoidal beds is more than that on other beds. The analysis of results shows that, using corrugated beds increases the energy dissipation of hydraulic jump in open channels. It was deduced that, the SPH model is used for studying the variation of the effect of the hydraulic jump characteristics with using corrugated beds. Kordi [2], studied the transitional expanding hydraulic jump. The results show that, the sequent depth, y_2 for the classical jumps is bigger than required sequent depth to form an expanding jump. The expanding hydraulic jump length was found to be 1.25 times of that corresponding of the free jump. The forming classical hydraulic jump in a horizontal bed, and wide rectangular open channel with a smooth bed has been studied extensively, [3,4,5, and 6]. Hager [7] analyzed the hydraulic jump theoretically and experimentally. Hughes [8] studied the Hughes [8] 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. The observed reductions were related to both the bed roughness degree and the initial Froude's number. The observed hydraulic jump characteristics were consistent with the theory. The proposed approximation equation for the theoretical hydraulic jump was found to be compared with the observed hydraulic jump characteristics. Afzal [9] investigated the stream-wise flow structure of turbulent hydraulic jump, which was taken placed over a rectangular channel rough bed. It was found that, the hydraulic jump over a rough bed can be deduced using classical theory of the smooth bed hydraulic jump, using the effective upstream Froude's number instead of the Froude's number. Abdel-Azim [10] studied the effect of both negative and positive bed slopes on the hydraulic jump. The analysis of results showed that, both the initial Froude's number and the bottom slope have major effects on the depth ratio of the hydraulic jump while the initial depth ratio has minor effect on the depth ratio of the hydraulic jump. Chyan-Deng [11], and Smith [12] Studied the hydraulic jump in an slopped rectangular contracted channel. They developed theoretical equations for the sequent depth and sequent area ratios for hydraulic jumps in the contraction taking into consideration the effects of bottom slope and the contracting width. Beirami [13] studied the hydraulic jumps in inclined bed channels. It was showed that, the negative bed slope reduces the sequent depth ratio, while the positive bed slope increases the sequent depth ratio. Gandhi [14] studied the supercritical flow

characteristics in rectangular channel. Neveen [15] investigated effect of channel bed slope on the hydraulic jump characteristics. Small bed slopes was used for that purpose, (0.0027, 0.004, 0.0054, 0.0081, and 0.011). Alikhani et al. [16] studied the hydraulic jump which is formed in stilling basin having vertical end sill. Experiments used model with 1/30 scale for stilling basin and a dam spillway to deduce the forced hydraulic jump design criteria for single continuous sill, which was set up at the stilling basin end. The height of the end sill and its longitudinal distance downstream the vertical gate was established to reduce basin and jump lengths. Debabeche and Achour [17] studied the hydraulic jump formed through a triangular channel and the effect of a continuous sill on its characteristics.

The purpose of this paper is to investigate the characteristics of hydraulic jump, that was formed downstream vertical gate in rectangular open channel. Bigger bed slope values than that in the pervious work were used for this purpose. Also, a new equation was developed for stilling basin design.

2. THEORY

The theory here is built on the principle of momentum, i.e. the rate of change of momentum between the beginning and the end of the hydraulic jump must equal to the total force exerted on the moving water mass within the jump. Also, the dimensional analysis theory was used. The following functional relationship between the paper variables is used to characterize the hydraulic jump which was taken placed downstream vertical gate and the sill height and position in a rectangular channel, Fig. (1).

$$f(y_1, y_2, V_1, L_j, S, g, \rho, \mu, H, L_B) = 0 \tag{1}$$

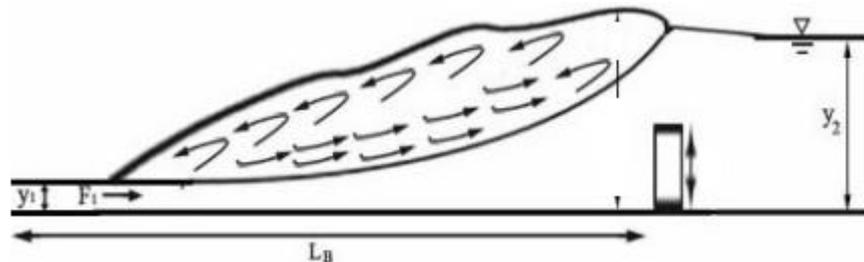


Figure (1) Hydraulic jump with sill

Where; y_1 is the initial depth, V_1 is the initial velocity, y_2 is the hydraulic jump sequent depth (which was considered as the flow depth just downstream the sill), L_j is the hydraulic jump length, S is the bed slope, g is the gravitational acceleration, ρ is water density, μ is water viscosity, H is the sill height, and L_B is the stilling basin length.

For open channel with horizontal bed ($S = 0$) and turbulent flow, the effect of Reynolds number is neglected, and the dimensionless groups may be written as:

$$f\left(\frac{H}{y_1}, \frac{y_2}{y_1}, \frac{L_B}{y_1}, F_1\right) = 0 \quad | \tag{2}$$

For a classical hydraulic jump, the sequent depth ratio is given by Belanger [18] Equation, as:

$$\frac{y_2}{y_1} = \frac{1}{2} \left[-1 + \sqrt{1 + 8F_1^2} \right] \quad (3)$$

The hydraulic jump sequent depth ratio on sloped bed is given by the Chen-Feng Li [19] equation, as:

$$\frac{y_2}{y_1} = \frac{1}{2} \left[-1 + \sqrt{1 + 8F_1^2 / \cos \theta - 4C} \right] \quad (4)$$

Where;

$$C = \frac{y_2}{y_1^2} [V_v \tan \theta / (y_1 - y_2)]$$

V_v = the water volume with the jump

3. THE EXPERIMENTAL WORK

Laboratory experiments were carried out in a recirculation self contained tilting glassy sided flume in the Hydraulics Laboratory of Shoubra Faculty of Engineering, Benha University. The dimensions of the flume are 2.5 m long, 9 cm width and 30 cm height. A control valve was used to regulate the discharge. A screw jack which, located at the upstream end of the flume is used to adjust the flume bed slope. The flume bed slope was directly determined by using a slope indicator, and the flume was rotated freely about a hinged pivot. The tail-water surface depth was regulated by a downstream adjustable gate. The sidewalls along the entire length of the flume are made of glass with metal-frames, to make visual investigations of the flow patterns is allow. The flume horizontal bed was made of steel and it is provided with a PVC pipe to drain the water from the flume. An electric centrifugal pump was used fed water into the flume from an external water source. The water discharged into the flume through two pumps with different discharges. A series of experimental runs at different values of discharge were carried out and the formed hydraulic jump downstream the flume sluice gate. For each experimental run the initial depth y_1 , sequent depth, y_2 and the hydraulic jump length, L_j were measured. The gate opening was changed through the experiments. This paper used five positive bed slopes, S 0.0175, 0.0349, 0.0524, 0.0699, and 0.0875. The flow discharge was measured by using a pre-calibrated orifice meter. The flow depth was measured using a point gauge with accuracy of ± 0.1 mm, Fig. (2).

4. RESULTS AND DISCUSSION

First of all, the used flume was calibrated, where five runs were conducted for horizontal flume bed. It was found that, the obtained results are convenient with Belanger's equation. Results of the experimental runs were carried out to study the different characteristics of the hydraulic jump such as sequent depth ratio, y_2 / y_1 , jump height, $y_2 - y_1$ and relative length of the jump, L_j / y_1 , relative energy loss, E_L / E_1 with Froude's number for different bed slopes. Also, other runs were conducted for designing the stilling basin.

4.1 The Sequent Depth Ratio, y_2 / y_1

Experimental runs were carried out to study the relationship between the hydraulic jump sequent depth ratio, y_2 / y_1 and Froude's number, F_1 and bed slopes, S , Fig. (3). This figure shows that, the sequent depth ratio, y_2 / y_1 increases as the Froude's number F_1 and the channel bed slope S , increase. This information is useful for designing a hydraulic structure of a stilling basin. For example; increasing 96% in $F_1^2 \sqrt{S}$ results in 46% increasing in the sequent depth ratio. The following formula was fitted, and it may be used in estimating the value of the sequent depth ratio for given initial Froude's number, F_1 and channel bed slope, S ;

$$\frac{y_2}{y_1} = -0.02(F_1^2 \sqrt{S})^2 + 0.898(F_1^2 \sqrt{S}) + 2.03 \quad R^2 = 0.922 \quad (5)$$

4.2 The Hydraulic Jump Height, $(y_2 - y_1)$

The effect of the initial Froude's number, F_1 and the channel bed slope, S on the hydraulic jump height, $y_2 - y_1$ was investigated in this section. Fig. (4) shows that, the hydraulic jump height has directly proportional relationship with each initial Froude's number and the channel bed slope. For example; increasing of $F_1^2 \sqrt{S}$ by 96%, results in 37% increasing in the hydraulic jump height. A fitted formula was estimated to calculate the jump height for given Froude's number, F_1 and bed slope, S ;

$$y_2 - y_1 = -0.0313(F_1^2 \sqrt{S})^2 + 0.94(F_1^2 \sqrt{S}) + 3.93 \quad R^2 = 0.956 \quad (6)$$

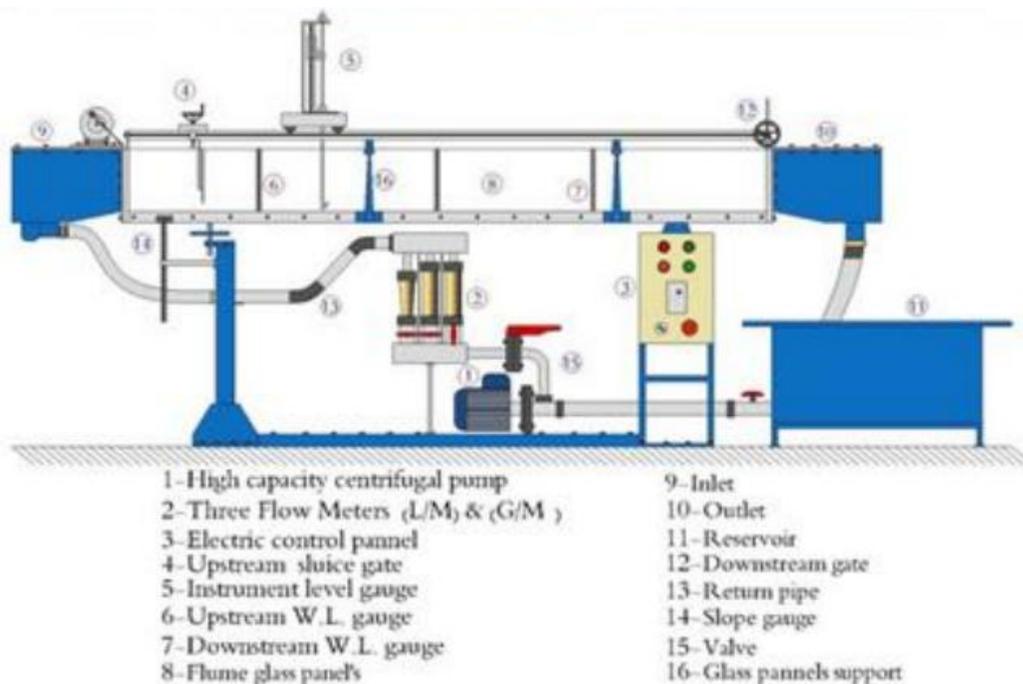


Figure (2) Schematic layout of experimental setup

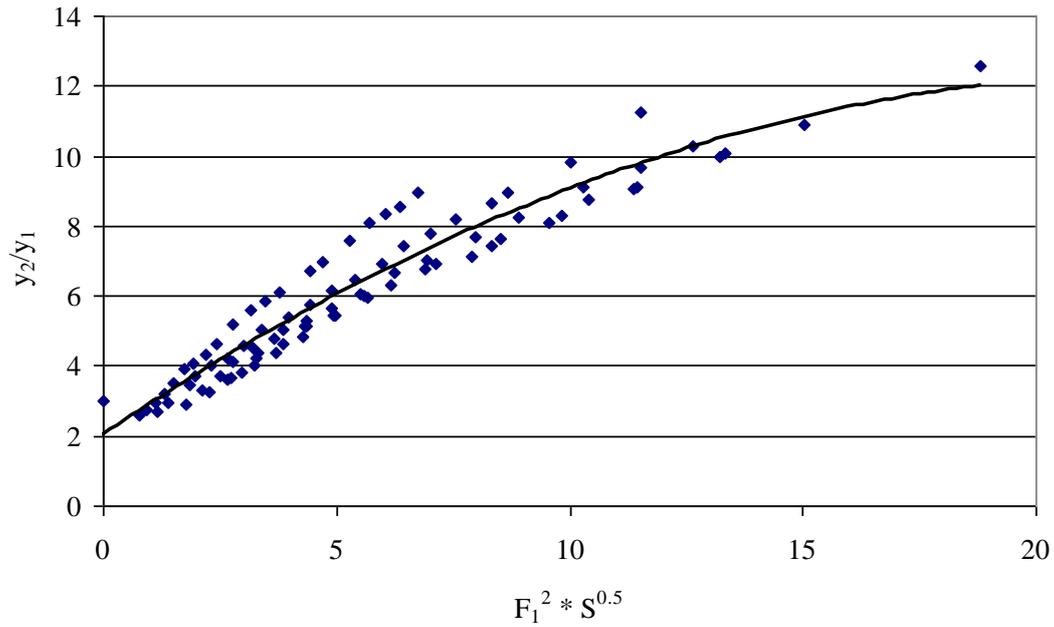


Fig. (3) Determination of y_2/y_1 by knowing intial Froude's number, F_1 and bed slope, S

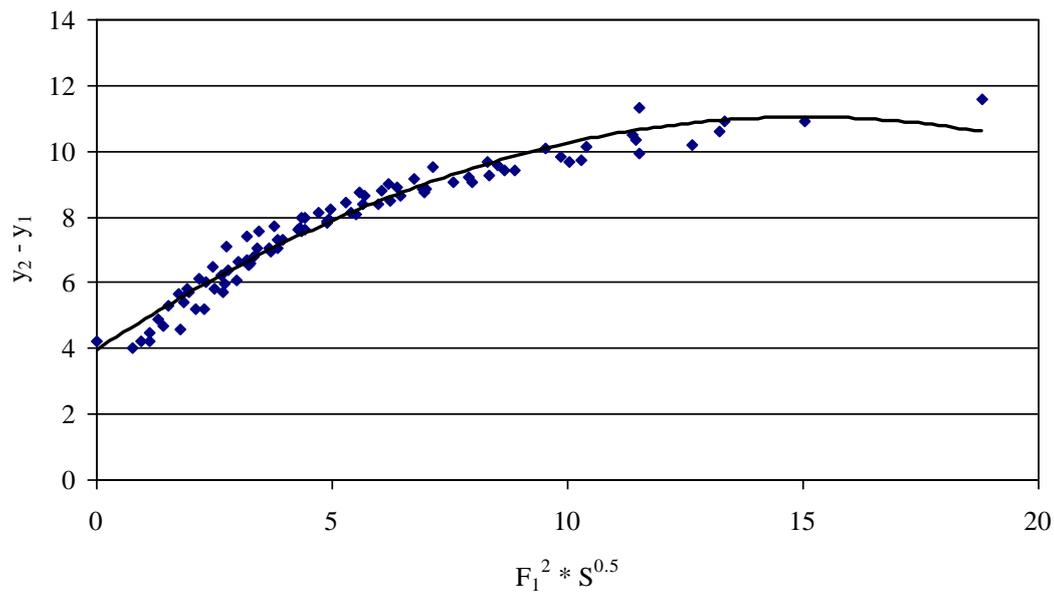


Fig. (4) Hydraulic jump height, $(y_2 - y_1)$ variation with intail Froude's number, F_1 and bed slopes

4.3 The Hydraulic Jump Length, L_j

Other experimental runs were carried out to investigate the variation of the hydraulic jump length with the initial Froude's number and bed slopes. Figs. (5 and 6) show the fitted relationship between each of the hydraulic jump length ratios, L_j / y_1 and L_j / y_2 with Froude's number and bed slope. Fig. (5) shows that, the Froude's number

has linear relationship with L_j / y_1 , and the bed slope has no effect on L_j / y_1 . The linear relationship between F_1 and L_j / y_1 is;

$$\frac{L_j}{y_1} = 10.391 F_1 - 16.863 \quad R^2 = 0.998 \quad (7)$$

The hydraulic jump length ratio, L_j / y_2 variations with the Froude's number and the bed slope are shown in Fig. (6). Also, the following equation may be used for calculating L_j / y_2 by known F_1 and the channel bed slope, S ;

$$\frac{L_j}{y_2} = -2 \times 10^{-5} (F_1^2 / \sqrt{S})^2 + 0.0142 (F_1^2 / \sqrt{S}) + 3.886 \quad R^2 = 0.87 \quad (8)$$

4.4 The Relative Energy Losses through Hydraulic Jump Length, E_L / E_1

Fig. (7) shows the relationship between the initial Froude's number F_1 and the relative energy loss (E_L / E_1) for different channel bed slopes. It was observed that, relative energy loss increases non-linear with the Froude's number. The bed slope

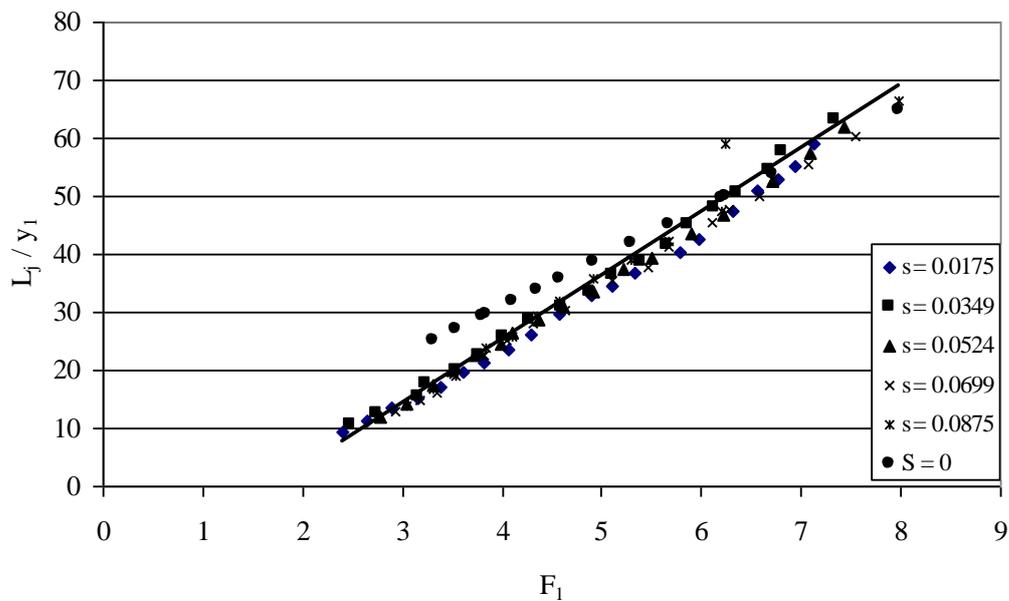


Fig. (5) Variation of L_j / y_1 with initial Froude's number for different bed slopes

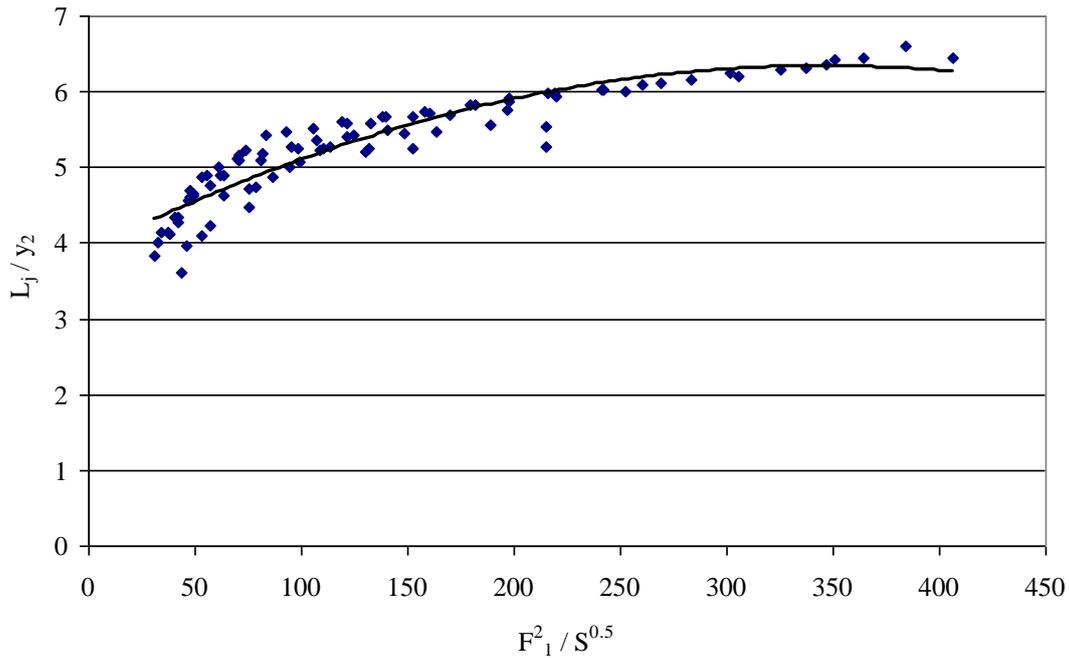


Fig. (6) Variation of L_j / y_2 with the Initial Froude's Number and Bed Slope

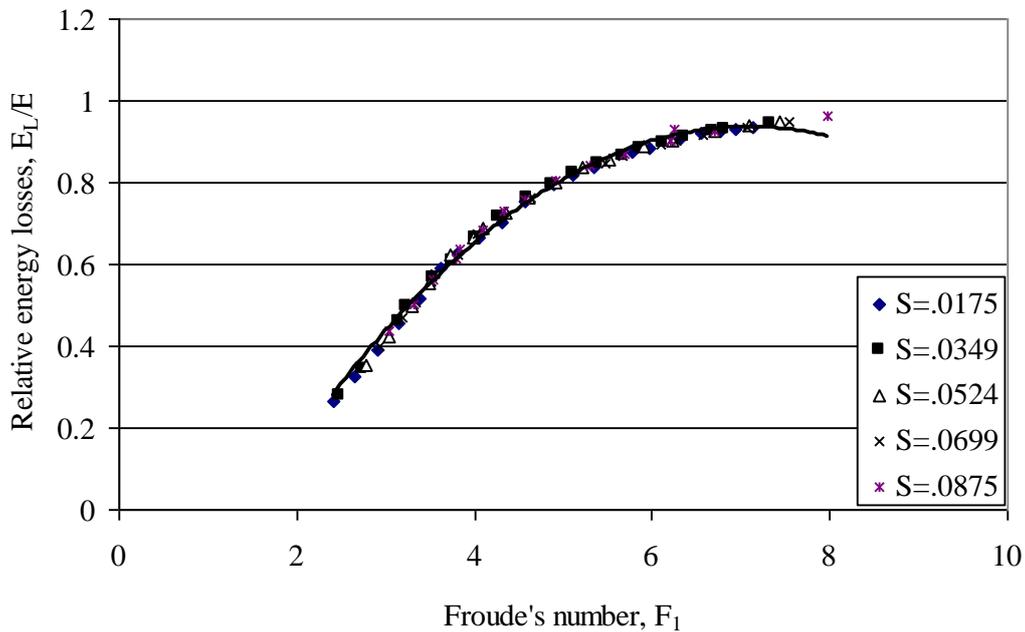


Fig. (7) Relative energy losses relationship with Froude's number for different bed slopes

Approximately has no effect on the relative energy loss, E_L / E_1 . For example; Increasing of F_1 by 59% result in E_L / E_1 increasing by 135%. From the fitted curve an equation may be established and used directly for calculating E_L / E_1 by knowing the initial Froude's number. The equation is;

$$\frac{E_L}{E_1} = -0.0299F_1^2 + 0.0424F_1 - 0.567 \quad R^2 = 0.996 \quad (9)$$

4.5 Design of Stilling Basin, H and L_B

Figs. (8 to 10) demonstrate the ratio of sequent depth, y_2 / y_1 variation with the initial Froude's number F_1 of the hydraulic jump formed due to the end sill for three ratio values for H / L_B . The sequent depth ratio, y_2 / y_1 has an inversely relationship with the sill height ratio, H / L_B comparing with the sequent depth ratios, y_2 / y_1 of the hydraulic jumps from Belengar Equation with the same conditions of flow. Figures show that the sequent depth ratio decreases as the sill height increases for a particular sill longitudinal length, L_B .

The results of this paper agree with the previous studies in proving that, the sill height, H and its position downstream the vertical gate, L_B effect on the sequent depth ratio. Thus, the dimensions of the stilling basin, sill height, H and its location, L_B , may be designed. Through the analysis of the results of the experimental runs, a relationship between the effective dimensionless groups in Equation 1 was fitted to be used for the designing of stilling basin. Fig. (11) shows the relationship between the initial Froude's number, F_1 ratios of H / y_1 and L_B / y_1 , which are considered the main

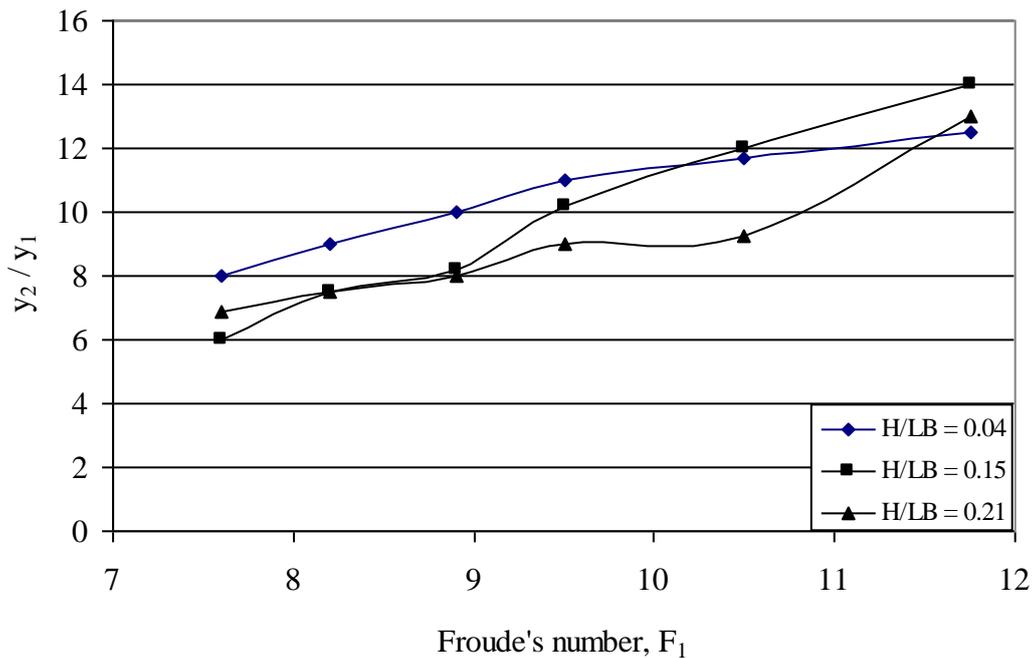


Fig. (8) Sequent depth ratio variation with sill height ratio, for $L_B = 10$ cm

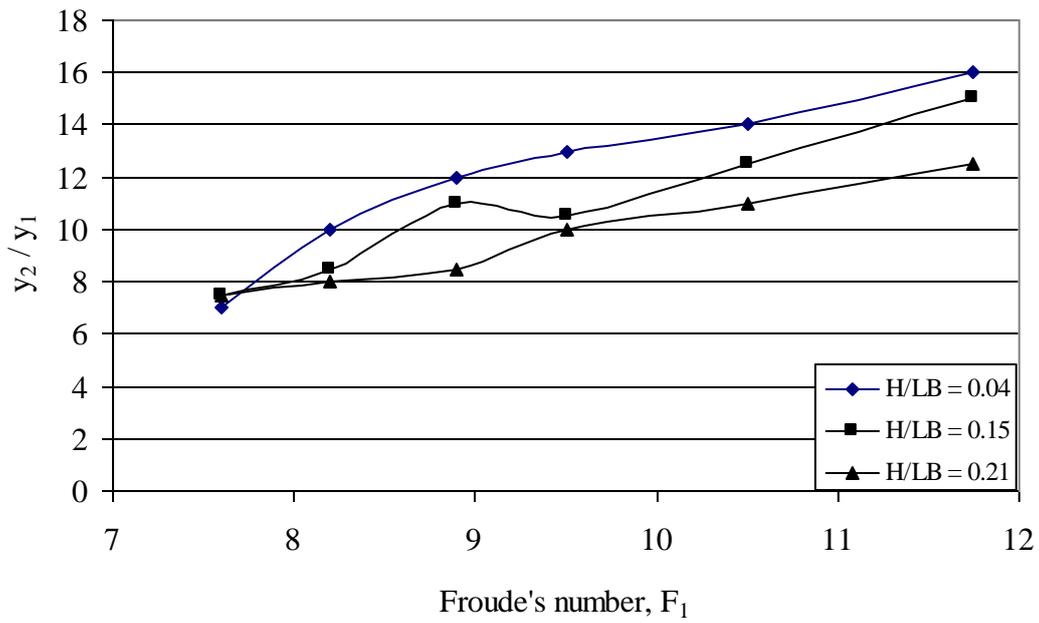


Fig. (9) Sequent depth variation with sill height ratio for $L_B = 15$ cm

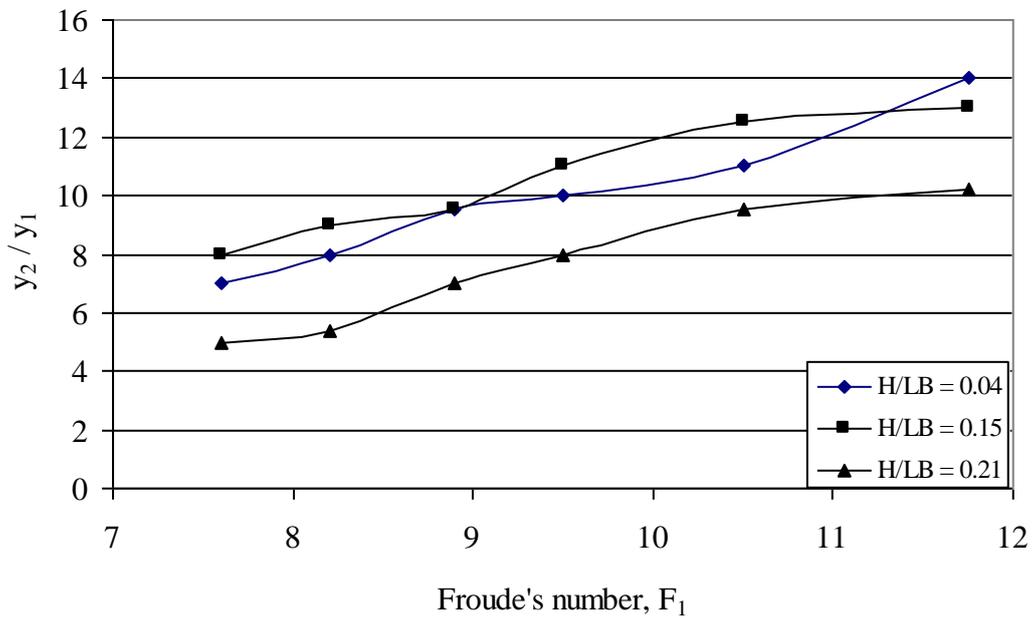


Fig. (10) Sequent depth ratio variation with sill height ratio, for $L_B = 20$ cm

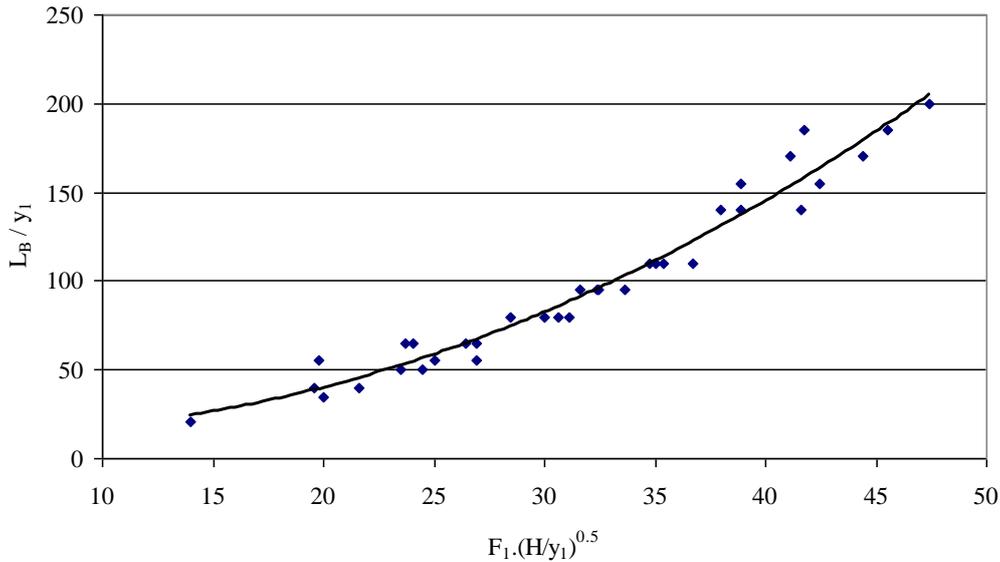


Fig. (11) Sill height, H and stilling basin length L_B estimation Figure

Parameters to express the initial condition, sill geometry and stilling basin and respectively. A fitted formula was estimated between these parameters. Fig. (11) and Equation 10 enable the design of sill height, H and stilling basins, L_B , once, the initial water depth y_1 and initial Froude's number, F_1 are known. By selecting basin length of L_B , the height of the sill, H can be calculated. The calculated sill height, H should be checked to be less than $1/6 F_1^{1.645}$, Hager [7].

$$\frac{L_B}{y_1} = 0.1018 \left(F_1 \sqrt{\frac{H}{y_1}} \right)^2 - 0.8599 \left(F_1 / \sqrt{\frac{H}{y_1}} \right) + 16.38 \quad R^2 = 0.962 \quad (10)$$

This may require using several estimated values for L_B . Based on previous studies, the initial value for stilling basin length L_B was assumed as;

$$3(y_2 - y_1) \leq L_B \leq 5(y_2 - y_1) \quad (11)$$

This assumption is because, for smaller values of L_B than $3(y_2 - y_1)$, the hydraulic jump will take place downstream of the sill, but, for L_B values larger than $5(y_2 - y_1)$, results in neglecting the effect of the sill.

CONCLUSIONS

The following conclusions are made based on this paper.

1. The results show, that hydraulic jump length ratio, L_j / y_2 or L_j / y_1 in terms of initial Froude's number, F_1 , provide information to estimate hydraulic jump lengths at different channel bed slopes.
2. Furthermore, L_j / y_1 has a linear relation with respect to F_1 , while L_j / y_2 does not.
3. Experimental results of this paper conclude that the sequent depth for a hydraulic jump estimation has to take the channel bed slope into account.
4. The hydraulic jump height, $y_2 - y_1$ and the sequent depth ratio, y_2 / y_1 increases as the initial Froude's number and channel bed slope increase.
5. Equation 10 and Fig. 11 enable for Estimation of the sill height and basin length.

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