Original Research Article

Effect of Channel Slope on Hydraulic Jump Characteristics

ABSTRACT

Hydraulic jump primarily serves as an energy dissipater to dissipate excess energy of flowing water downstream of hydraulic structures, such as spillway, sluice gates etc. A review of literature has shown that earlier researcher concentrated more on horizontal channel while very little information is available on sloping channels. Further, they have studied the hydraulic jump characteristics in terms of approach Froude number only. In the present study hydraulic jump in sloping prismatic channel has been studied and analyzed. The experiments were performed for a range of Froude numbers from 2 to 4.6. The results obtained were compared with the result of horizontal channel to determine the effect of slope on hydraulic jump characteristics. The empirical computational model for different hydraulic jump characteristics such as sequent depth ratio, relative height of the jump, relative length of the jump and relative energy loss are developed considering the effect of approach Froude number, and slope of the channel.

Keywords: Open Channel, Hydraulic Jump, Energy Dissipation, Sloping Channel, Spillway, Sluice Gate, etc.

1. INTRODUCTION

Downstream of many types of hydraulic structures such as dams and barrages, spillways, sluice gates and draft tubes of hydraulic turbines, a considerable portion of the kinetic energy in supercritical flow must be dissipated to prevent scour and erosion. [1] Study the effect of a corrugated bed on the hydraulic jump, a smoothed particle hydrodynamics (SPH) model is applied to investigate the characteristics of hydraulic jumps in various corrugated beds. It is found that the sinusoidal bed can dissipate more energy than other beds. As a result, corrugated beds can be used to enhance energy dissipation of hydraulic jump in the open channel. In general, the proposed SPH model is capable of simulating the effect of corrugated beds on hydraulic jump characteristics. [2] Study the transitional expanding hydraulic jump. The results indicate that the post depth Y_2 required to form an expanding jump is distinctly smaller than that for the corresponding classical jumps. The expanding jump length was 1.25 times the corresponding free jump length. A jump formed in a horizontal, wide rectangular channel with a smooth bed is often referred to as the classical hydraulic jump and has been studied extensively ([3]; [4]; [5]; and [6]). If Y_1 and V_1 are, respectively, the depth and mean velocity of the supercritical stream just upstream of the jump, with a Froude number of $Fr_1 = \frac{V_1}{\sqrt{gy_1}}$ where g is the acceleration due to gravity, the subcritical sequent depth Y_2 is given by the well-known Belanger equation [7]

$$\frac{Y_2}{Y_1} = \frac{\sqrt{1+8F_{r1}^2}-1}{2} \tag{1}$$

[8] analyzed the hydraulic jump theoretically and experimental means. [9] studied the hydraulic jump characteristics over several artificially roughened test beds in a horizontal rectangular flume with smooth side walls. Observations showed that boundary roughness reduces both the sequent depth and the length of a hydraulic jump, and that the observed reductions were related to both Froude number and the degree of roughness. The observed hydraulic jump characteristics were consistent with theory, and a proposed approximation for a theoretical hydraulic jump equation was found to compare favorably with the observed characteristics. [10] Investigated the stream-wise flow structure of a turbulent hydraulic jump over a rough bed rectangular channel. The hydraulic jump over a rough bed channel can be directly deduced from classical smooth bed hydraulic jump theory, provided the upstream Froude number is replaced by the effective upstream Froude number. [11] Study the effect of both positive and negative slopes on the hydraulic jump. The analysis of results indicated that both the inlet Froude number and the bottom slope have major effects while the inflow depth ratio has a minor effect on the depth ratio of the jump at the outlet. [12] Study the hydraulic jump in an inclined rectangular chute contraction. They developed theoretical equations for the sequent-area and sequent-depth ratios for

hydraulic jumps in the contraction considering the effects of contracting width and sloping bottom. [13] Studied the hydraulic jumps in sloping channels and showed that the negative slope of the basin reduces the sequent depth ratio, while a positive slope increases the sequent depth ratio. [14] Study the characteristics of supercritical flow in rectangular channel.

This paper presents the results of a study undertaken to determine the effects of bed slop, on the hydraulic jump characteristic sand.

2. THE EXPERIMENTAL WORK

The experiments were conducted in a recirculation self contained tilting glass sided flume in the Hydraulics Laboratory of Faculty of Engineering, Shoubra, Benha University. The flume is 2.5m long, 9cm wide and 35cm deep. A discharge control valve was used to regulate the flow rate. The bottom slope was adjusted using a screw jack located at the upstream end of the flume while at the downstream end; the flume was allowed to rotate freely about a hinged pivot. The slope was directly determined using a slope indicator. A downstream adjustable gate was used to regulate the tail-water surface elevation. The sidewalls along the entire length of the flume are made of glass with metal-frames, to allow visual investigation of the flow patterns. The horizontal bottom of the flume was made of steel and provided with a PVC pipe to drainage the water from the flume. The water entered the flume from an external water source, which was fed by an electric centrifugal pump. The water discharged the flume through two pumps with different capacities; 90, and 160lit/s. Figure 1 illustrates a complete and detailed flume description. A series of runs at different values of discharge were experimented and hydraulic jump was formed by operating the sluice gate and different discharge. For each run initial depth, sequent depth and length of hydraulic jump were measured. The experiments were carried out mainly by using five different gate opening, d_g of 1, 1.5, 2, 2.5, and 3cm. four positive bottom slopes, S_o were used. The used slopes were 0.0027, 0.004, 0.0054, 0.0081, and 0.011. The slopes were selected based on the flume facility. Five different flow rates ranged from 90lit/s to 160lit/s were used for each particular conduit height and bottom slope. The initial Froude number ranged from 1.2 to 4.6. The discharge was measured using a pre-calibrated orifice meter. Depth measurements were taken using a point gauge with an accuracy of ± 0.1 mm. For each run, the initial depth of jump, the flow rate and the depth of water just downstream the conduit outlet were measured.

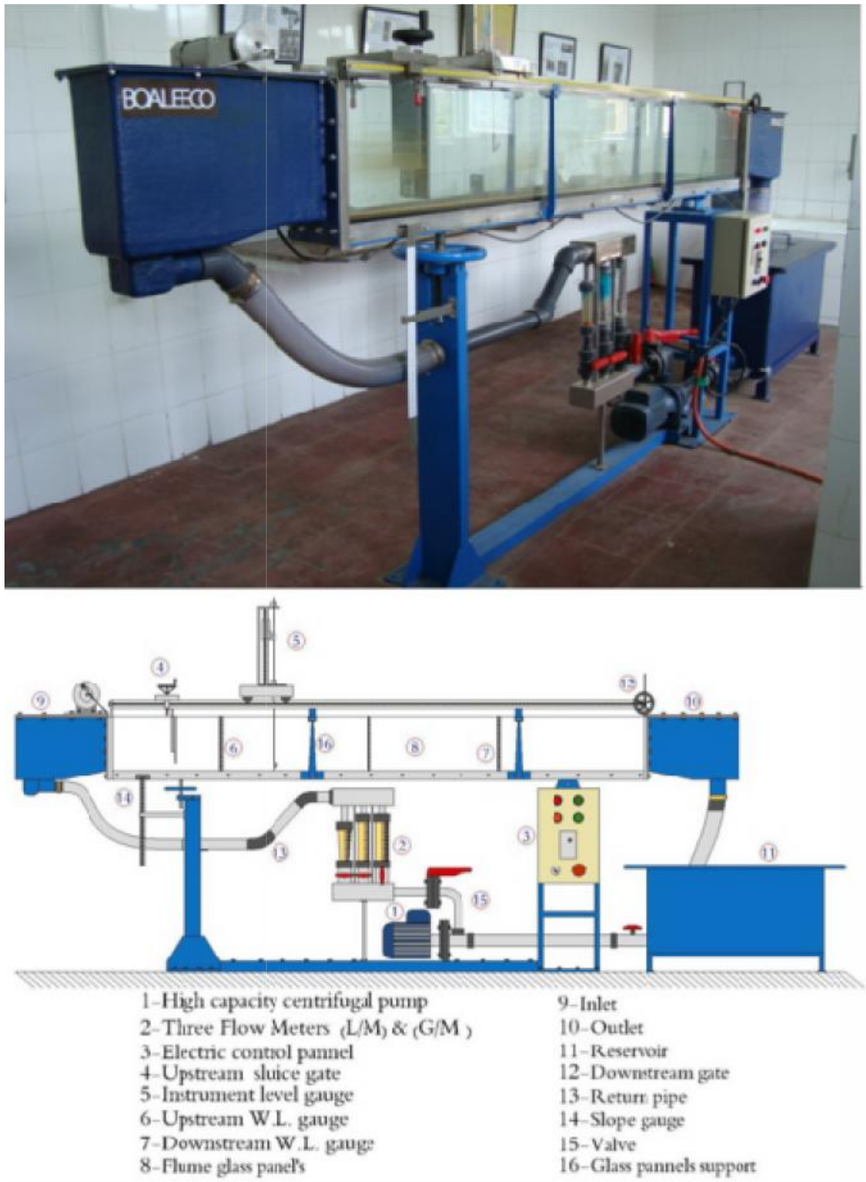


Fig. 1. Schematic Layout of Experimental Setup

3. RESULTS AND DISCUSSION

The variation of different hydraulic jump characteristics such as sequent depth ratio, relative height of the jump, and relative length of the jump, relative energy loss with approach Froude number and slope of the channel is given below. The relative depth (Y_2/Y_1) was measured and plot with respect to Froude number. Figure 2 shows the variation of sequent depth ratio with approach Froude number and slope of the channel. It is observed that sequent depth ratio increases with increase in approach Froude number and slope of the channel bed. It is evident from the figure that approximately 90%, 95% and 99.7% of experimental data are laying within ± 10% of best fit curve. The increase of Froude number by 100% the relative sequent depth increases by 85%. At same Froude number the increase of channel slope causes increase of the relative depth. It is clear that the relative depth (Y_2/Y_1) increases with the increase of the slope at particular inlet Froude number. The lowest value is due to the minimum slope (0.0027) and the maximum value due to the maximum slope (0.011).

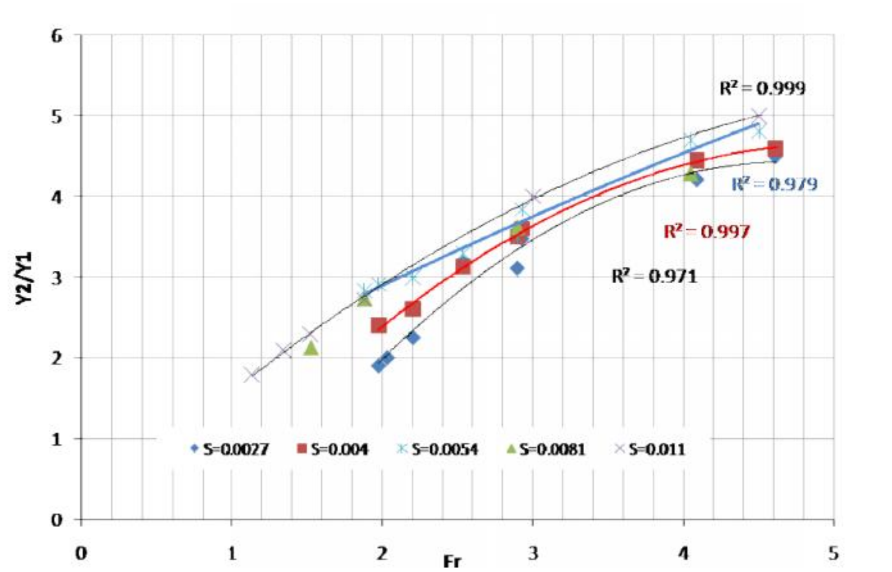


Fig. 2. Variation of Sequent Depth Ratio with approach Froude number and Channel Slope

Figures 3 presents the variations of Y_2/Y_1 with the bottom slope (0.0027, 0.004, 0.0054, 0.0081, and 0.011) for different inlet Froude number. It is clear that the depth ratio increases with the increase of the slope at particular inlet Froude number. The lowest value is due to the maximum negative slope (0.0027) and the maximum value is due to the maximum slope (0.011). This could be explained by the fact that, the weight component acts in the direction of the flow. This in turn results in a reduction of the depth ratio and the rate of reduction increase as the slope decreases. On the other hand, the jump depth ratio at the outlet of the conduit increases by the increase of the inlet Froude number at particular value of the slope.

The mul... linear regressions were app... predict a statistical equation that correlates depth ratio with other independ... ameters (F_{r1}, S_o, Q, dg, and ... e form;

$$\frac{Y_2}{Y_1} = \exp 3 \frac{.66}{} + \ldots 4Q + 9.38S_o - 71.8d_g + 1.57 \frac{6324.1}{Fr^4} - \frac{290}{Fr} \qquad (2)$$

... correlation ... With ... coefficient equals 0.95

$$\ldots 44.23 - \ldots = \ldots \frac{469.58}{Fr} + \frac{59.58}{-Fr} + \ldots \frac{375}{Fr} \qquad (3)$$

With correlation coefficient equals 0.90.

Where: Y_1 is the conjugate depth of flow U.S. the jump, Y_2 is the sequent depth of flow D.S. the jump, Q is the flow discharge, S_o is the slope of the channel, d_g is the gate opening, and F_{r1} is the Froude number at vena contracta.

Figure 4 shows the comparison of sequent depth ratio of present model equations 2, and 3 with the model equations developed by [4]. It is observed that most of the experimental data are lying between the present model and Rajatnam. It proves that the present model gives high accuracy.

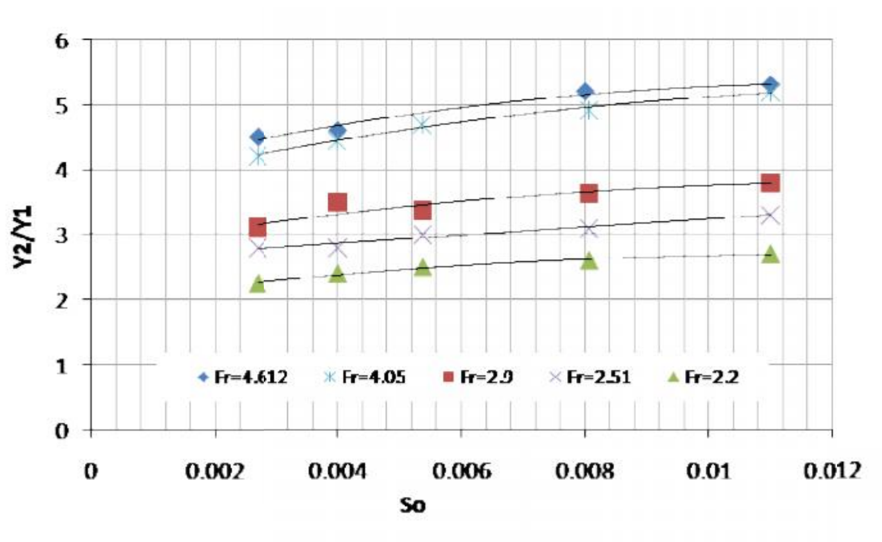


Fig. 3: Variations of Y_2/Y_1 with slope for different values of Froude number

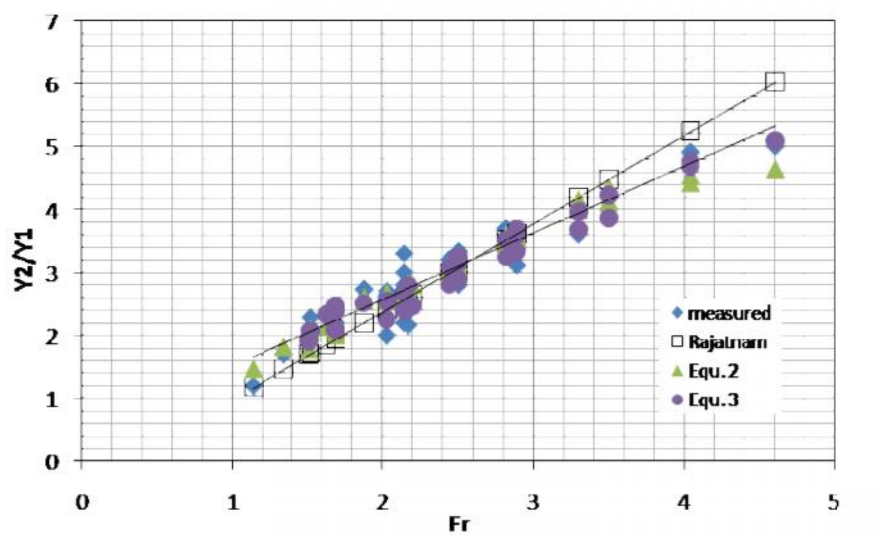


Fig. 4: The relation between the Froude number and the depth ratio

Figure 5 shows the relation between the Froude number and relative energy loss (E_L/E_1) for different slope. It is observed that relative energy loss increases with increase in approach Froude number and slope of the channel bed. It is evident from the figure that approximately 98%, 97%, 93% and 92% of experimental data are lying within ± 8% of best fit curve. The relative slap lengths (length of hydraulic jump added to the distance of it from the gate (L_s/Y_1)) were plotted with different Froude number in figure 6. It is observed that relative slap length of the jump increases with increase in approach Froude number and slope of the channel bed. Figure 7 illustrates the relation between hydraulic jump length (L_{Hj}) and the sequent depth (Y_2) for different slopes. It clears that the hydraulic jump length increase by 80% as increase of sequent depth by 100%.

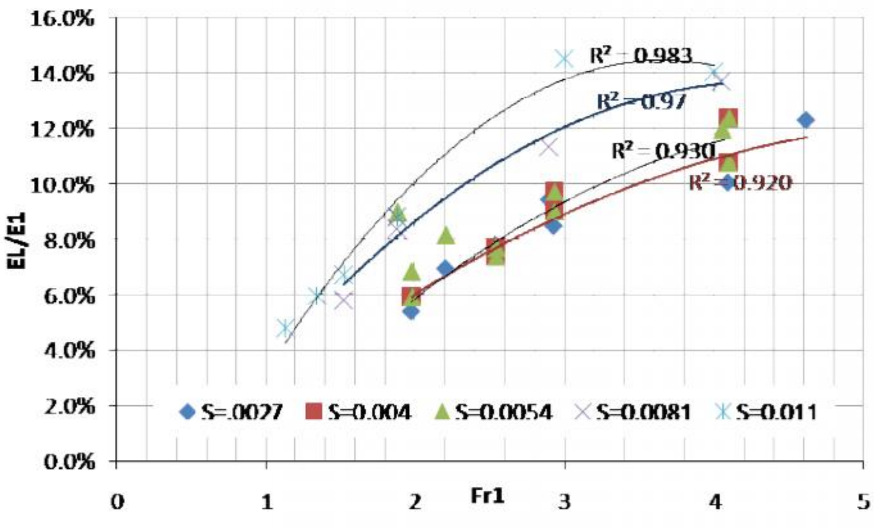


Fig. 5. Variation of Relative Energy Loss with approach Froude number and Channel Slope

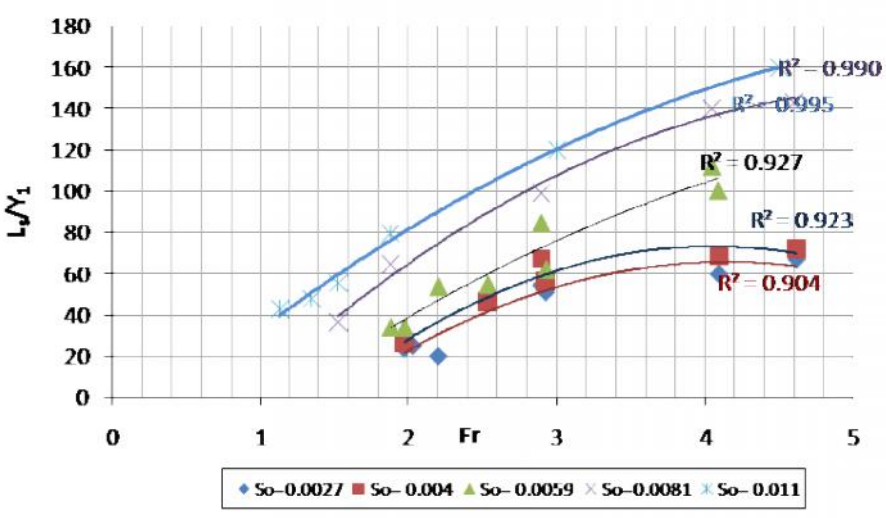


Fig. 6. Variation of Relative slap length with approach Froude number and Channel Slope

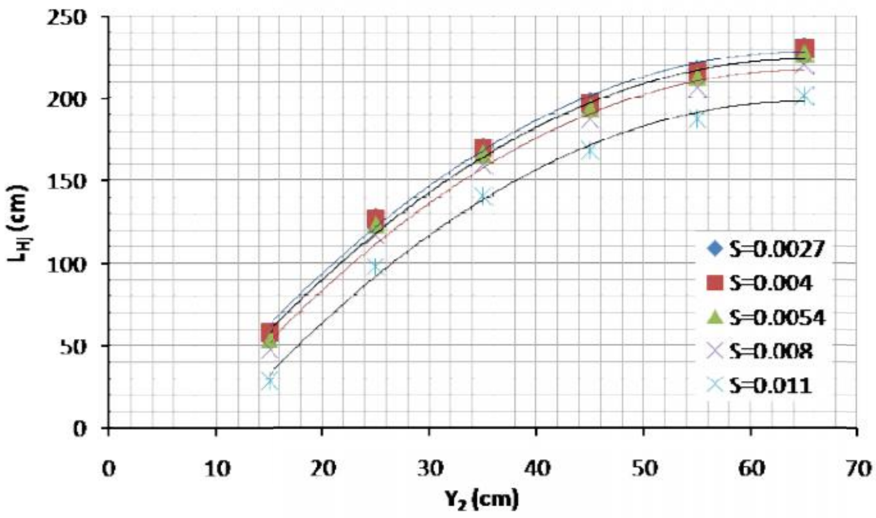


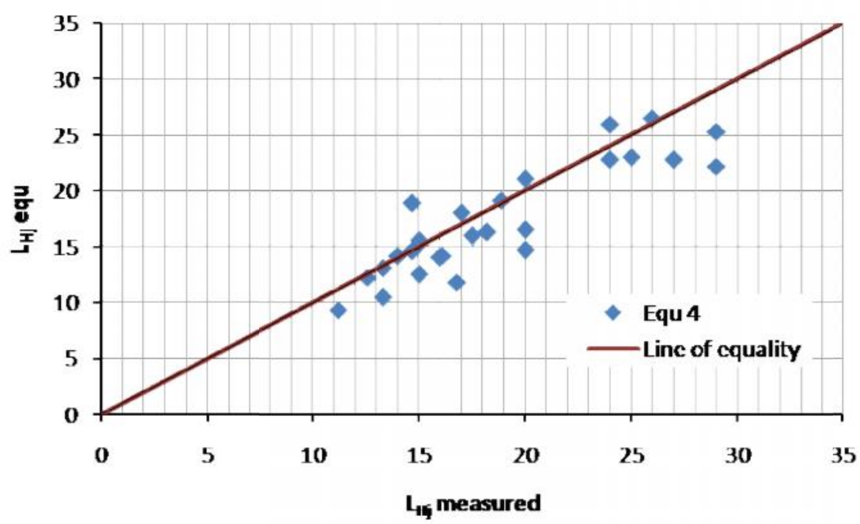
Fig. 7. The hydraulic jump length with approach sequent depth and Channel Slope

In order to derive an equation with the corrected hydraulic jump length L_{hj} and relative Length of slap L_s/Y_1 as the dependent variable, the regression analysis of "Data … er. 9.0" was … to obtain the following equations:

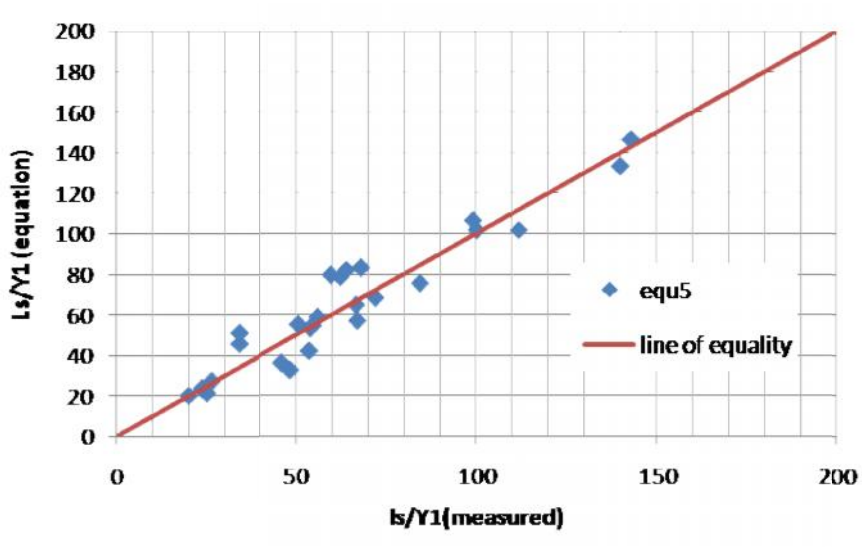
L … 220.3 … - 131358 * S … 52507074 * F_r^4 + 19.9E9 * S_o^3 … 8.71E11 * S_o^4 … 2.88E13 * F_r^5 … 55 S_o … 6339.41/Y_5 … 1007.5/Y_3 + 90063.06/Y_o^2 … (4)

… 4238 + … S_o^3 − 14 … 60843 … 13563852 * S_o^4 − 8S_o^5 − … 18249.97/5 … 17 − … 975.6/ … − + 3276.8/ … $\frac{Ls}{Y}$ = 140711/ … S_o + … 885.8/ … (5)

Figure 7 shows the comparison between Eq.(4) and Eq.(5) for all slope. Clearly good agreement was achieved.



(a)



(b)

Fig. 8. Comparison between actual, and present model for all slopes (a) Equ. 4 and (b) Equ. 5

4. CONCLUSIONS

Hydraulic jumps formed in rectangular closed conduit with different slopes were analyzed based on an extensive experimental investigation. It was found that both the bottom slope S_o, and the inlet Froude number F_{r1}, have major effect on the variations of the jump outlet depth ratio. The jump depth ratio increases with the increase of F_{r1} and increases with the increase of the bottom slope of the conduit. A general prediction model was proposed in different form for jumps formed in conduits. The prediction of the proposed model was compared to the previously developed models. The predicted results agreed well with the experimental observations as well as with those of the previously developed models using the same technique.

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List of symbols

Fr_1	Inflow Froude number [–]
g	Acceleration due to gravity [$m.s^{-2}$]
Y_1	Upstream sequent depth [m]
Y_2	Downstream sequent depth [m]
S	Channel slope [–]
L_{Hj}	Length of jump [m]
Ls	Length of slap [m]
Q	Flow discharge [$m^3.s^{-1}$]