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Using a broad crested sill to control hydraulic jump in a triangular channel

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Abstract

In this paper, the results of an experimental study on the effect of a broad crested sill in forming a controlled hydraulic jump in a triangular channel are presented. The experiments were carried out in a horizontal symmetrical triangular channel with the central angle of 94.4°. A broad crested sill was installed at the end of the classical hydraulic jump to ensure that the jump will be build up where adequate tail water is not available. The results are compared with the previous experimental and theoretical studies and empirical equations are developed by means of experimental results to predict the sequent depth ratio and the length of the jump and surface rollers.

Keywords: hydraulic jump, triangular section, sequent depth ratio, hydraulic structures.

1. Introduction

A hydraulic jump is a natural phenomenon that occurs when a higher velocity supercritical flow upstream is met by a subcritical downstream flow with a decreased velocity and sufficient depth. When liquid at high velocity discharges into a zone of lower velocity, a rather abrupt rise occurs in the liquid surface. The rapidly flowing liquid is abruptly slowed and increases in height, converting some of the flow's initial kinetic energy into an increase in potential energy, with some energy irreversibly lost through turbulence to heat. In practical applications, jumps are created in the environment with specific purposes such as erosion prevention. Erosion in stream beds is often caused by a high velocity water flow which leads to sediment transport. This process can be prevented by decreasing the velocity of the flow into the stream bed with the introduction of a hydraulic jump. Often in these cases, a hydraulic jump is created by devices such as a weir or sluice gate where the turbulent flow enters the stream. An extensive literature has been developed for this type of engineering by Hager (1995), Vischer (1995), Chanson (2004), Khatsuria (2005) and Abdul Matin et al. (2008). The mixture of chemical constituents in a solution is another practical use for hydraulic jumps. Introducing a hydraulic jump rapidly increases the turbulence of the flow, allowing sufficient constituent mixing without the use of any additional mechanisms. The wastewater industry sometimes uses hydraulic jumps as a way to mix solutions, minimizing the need to implement more expensive mechanical mixing systems.

For a prismatic horizontal channel, the flow conditions downstream of a hydraulic jump are functions typically of the discharge, upstream depth and channel shape (Henderson, 1966). Despite the characteristics and the effect of end sills on classical hydraulic jump (CHJ) in common channel shapes such as rectangular cross sections are widely studied, a few works have been done regarding to hydraulic jump in triangular channels. Hydraulic jump in a triangular channel has some advantages with respect to the energy dissipation and the lower tail water condition relative to the other cross sections for the same hydraulics conditions (Hager and Wanoschek, 1987). It should be also noted that the triangular section does not satisfy the requirements of a stilling basin but it has some significant practical applications when used as irrigation ditch section (Achour, 1989). So, it will be useful to develop a controlled hydraulic jump in triangular canal to raise the water surface and deliver the required flow.

In the case of jumps formed in nonrectangular channels the flow expands in the horizontal in addition to the vertical direction and the front of the jump is in the form of two oblique wings which may either meet at the center of the channel or be extended across by a partial normal front. This means that the flow pattern is three-dimensional compare to the rectangular channel which is almost two-dimensional (Debabeche and Achour, 2007). In symmetrical triangular channel the inflow Froude number F_1, may be expressed by $F_1=[2Q^2/(gm^2Y_1^5)]^{1/2}$ in which Q, Y_1, g and m are the discharge, the inflow jet depth, the acceleration due to the gravity and the side slope 1 vertical to m horizontal of the channel walls respectively.

As reported by Rajaratnam (1967), Stevens was probably the first to propose the way to predict the sequent depth ratio of hydraulic jump in nonrectangular channels in 1933. Argyropoulos (1961) conducted an experimental study of hydraulic jump in a triangular channel. The depth of flume was 41.0 cm with a semi central angle of 23.7° and a length of 5.25 m. Further experiments with a triangular channel of smooth plywood with semi central angle of 30° were carried out by Rajaratnam (1964). The results showed that the theoretical results using momentum equation over estimate the sequent depth ratio of the jump. A variation of about 5% between the calculated and the measured sequent depth ratio of the jump in a triangular channel was also observed by Hager and Wanoschek (1987). Here the experiments were carried out in a triangular channel with a vertical wall and a tilted wall which have a half central angle of 44.7°. The results were then extrapolated to the jump in a triangular section with central angle of 90°.

Hager and Wanoschek (1987) derived an asymptotic solution for the momentum equation in a triangular channel as Eq. (1):

$$Y = (1.5F_1^2 - 1)^{1/3} \tag{1}$$

in which $Y=Y_2/Y_1$ is the sequent depth ratio and Y_2 is the sequent depth of the jump.

They also derived a relationship for the length of the surface roller and the jump length as Eq. (2):

$$\frac{L}{Y_2} = 2.4Am^{0.5}F_1^{0.4/m} \quad ; \quad 0.4 < m \le 1 \tag{2}$$

in which $L=L_r$ if A=3/4 and $L=L_j$ if A=1.0 and m is side slope of the tilted walls.

The results of Hager and Wanoschek (1987) showed that the sequent depth ratio of the jump in triangular canal is lower, the relative energy dissipation is higher, the length of the jump is shorter up to two times, the volume of the jump is about 30% higher and the sensitivity to slight discharge variation is lower than the rectangular channel whit similar conditions.

Achour and Debabeche (2003) studied the effects of a thin crested sill on the characteristics of jump in a triangular channel and presented empirical equations for sequent depth ratio and sill height.

Debabeche and Achour (2007) also focused on the characteristics of minimum-B jump and derived empirical equations as Eqs. (3), (4) and (5):

$$Y = 1 + \alpha Ln\left(\frac{F_1 + 4}{5}\right) \tag{3}$$

$$Y = 1 + \beta S \tag{4}$$

$$S = \gamma Ln\left(\frac{F_1 + 4}{5}\right) \tag{5}$$

in which $S=s/Y_1$ is the relative sill height and α, β and γ are constants coefficients depend on the type of sill (broad crested or thin crested).

Hamidifar *et al.* (2009) studied the characteristics of hydraulic jump in a triangular channel and proposed empirical equations for the sequent depth ratio and the jump length.

2. Materials and methods

In the present study, experiments were carried out in the central laboratory of water researches in the Dept. of Irrigation and Reclamation Eng., University of Tehran. A rectangular flume of 9.0 m long, 0.5 m width and 0.6 m height was used for the experiments. A triangular section was then set up at the beginning part of the flume (3.6 m) by placing two symmetrical tilted wall with 94.4° central angle and 0.25 m vertical height and side slopes of 1:1(vertical: horizontal).

Both the rectangular and the triangular channels were made of Plexiglas. In order to obtain a high velocity inflowing jet, a pressure box of height equal to the prescribed opening was installed at the entrance of the triangular channel. Due to difficulty in measuring the initial water depth, it was assumed that the initial depth of the jump is equal to the opening of the pressure box.

Toe of the jumps were fixed at a distance of about 5 cm from the outlet of the pressure box for all the experiments by means of tail water tuning using a sluice gate at the end of the flume. Discharge was varied between 1.6≤Q≤6.8 l/s which produced the inflow

Froude number between $2.6 \leq F_1 \leq 12.5$ for two pressure box openings equal to 2.5 and 4.3 cm.

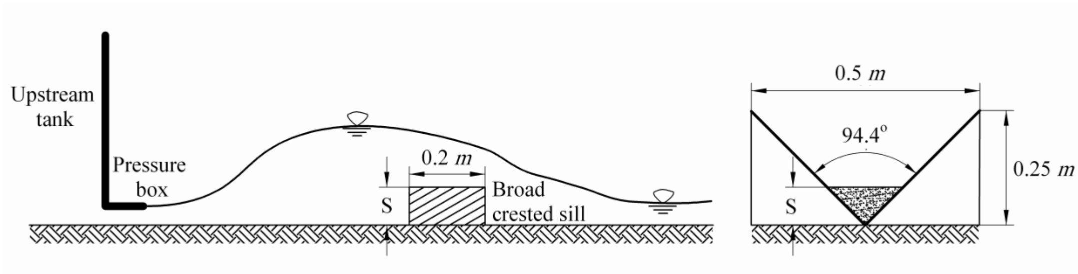

Figure 1. Schematic view of the experimental setup

After that the prescribed discharge was achieved, the tailwater depth was adjusted to satisfy the particular condition for the jump toe. The discharge was measured by using a thin-crested rectangular weir at the upstream reservoir which was located at the entrance of the flume. The flow depths and water surface profile was recorded using a point gauge with a precision of ±0.1 mm. Schematic view of the experimental setup is shown in Fig. (1).

Each series of the experiments consists of two different tests. The first test was carried out to study the classical hydraulic jump in triangular sections. In these tests the characteristics of CHJ was recorded. After that a 20 cm long wooden end sill was set up at the end of CHJ as a base and the tailgate was opened to lower the tailwater. Then the sill was heightened by a number of 4.0 mm thick Plexiglas sheets to build up the same hydraulic jump upstream of the end sill. In these conditions the height of the sill was recorded.

3. Results and discussion

Hydraulic jump in a triangular channel is a three dimensional phenomenon. As reported by Hager and Wanoschek (1987), a backflow zone develops at the sloping side walls, leading to an extensive secondary current. Fig. (2) shows the experimental variation of Y versus F_1. In Fig. (2) calculated values of Y from the equations proposed by Hager and Wanoscheck (1987) and Achour and Debabeche (2003) are also presented in order to make a comparison between the results. It is clear that the sequent depth ratio grows with increasing the inflow Froude number, F_1. As it can be seen from the Fig. (2), the measured sequent depth ratios from the present study are less than those predicted by the mentioned equations for all the values of F_1. It means that the theoretical relationship of Hager and Wanoscheck (1987) over estimate the sequent depth ratio as a result of neglecting the friction loss effects in developing the equations.

Variation of the relative sill height versus the sequent depth ratio is plotted in Fig. (3). The linear equation presented by Achour and Debabeche (2003) is also plotted in the Fig. (3) to make a comparison between the results. A new power form equation which is in a good agreement with the experimental data is developed as Eq. (6):

$$Y - 1 = 0.939 S^{1.136} \quad ; \quad R^2 = 0.99 \qquad (6)$$

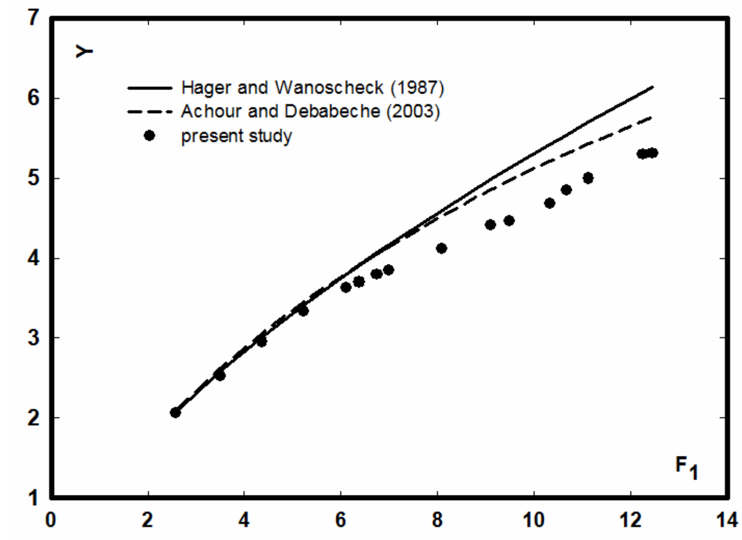

Figure 2. Variations of the sequent depth ratio with jet Froude number

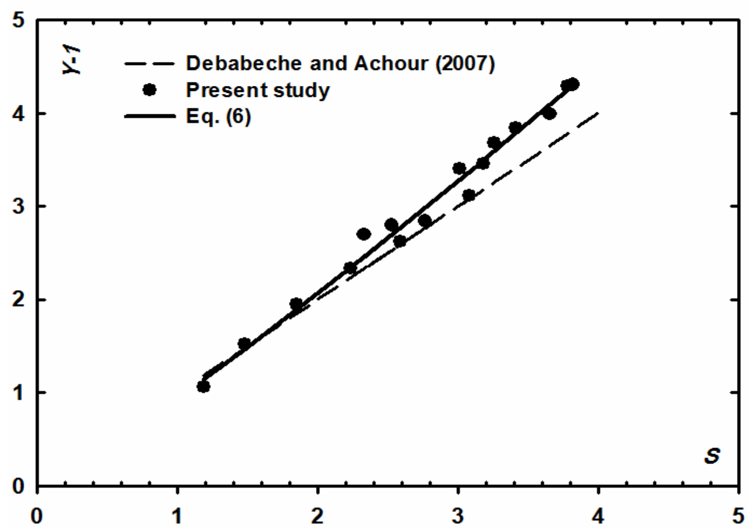

Figure 3. Variations of the relative sill height versus the sequent depth ratio

Fig. (4) shows variations of relative sill height S, against F_1. As it can be seen from this figure, the equation was proposed by Debabeche and Achour (2007) somewhat overestimates the sill height. It was found that the sill height may be related to F_1 with a power form equation as Eq. (7):

$$S = 0.632 F_1^{0.724} \quad ; \quad R^2 = 0.98 \tag{7}$$

The distance between the toe of the jump and division surface between backflow and the channel main flow is defined as the length of the rollers L_r. The length of the jump L_j, is also defined as the horizontal distance from the jump toe to the maximum water surface. Variations of L_r and L_j versus F_1 are plotted in Figs. (5) and (6) respectively.

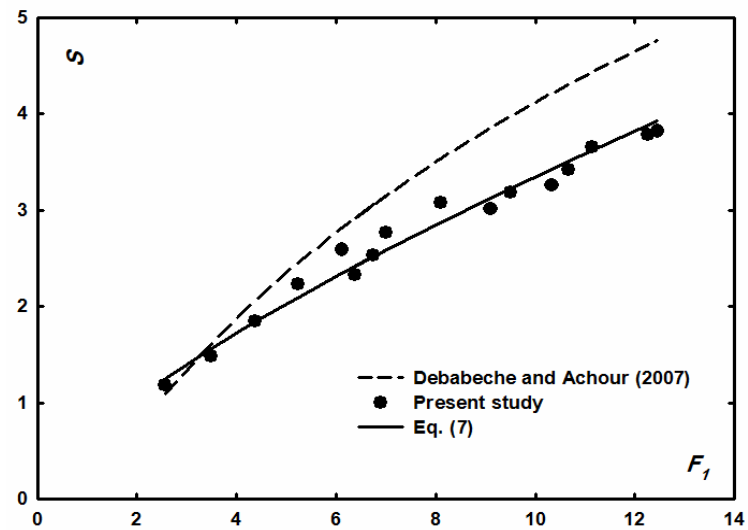

Figure 4. Variations of relative sill height with F_1

As shown in these figures, both L_r/Y_2 and L_j/Y_2 are increased with increasing the F_1 and have a power form trend with respect to F_1 as:

$$\frac{L_r}{Y_2} or \frac{L_j}{Y_2} = \mathrm{aF_1^b} \tag{8}$$

Where coefficients of a and *b* are given in Table 1.

Table 1.
Values of constants *a* and *b*

	a	*b*	R^2
Length of the rollers	2.246	0.360	0.95
Length of the jump	2.888	0.3437	0.96

Calculated values of L_j/Y_2 by equations of Hager and Wanoscheck (1987) are also presented in Fig. (5). However the results of present study are nearly similar to those due to them. Values of L_r/Y_2 are also compared with those of Hager and Wanoscheck (1987) in Fig. (6). It is seen in this figure that these data consistently lie below the data obtained in the present study. Also, the results are compared whit those of Achour and Debabeche (2003). It is seen that, their results somewhat overestimates the length of the jump, in which may be due to different experimental conditions.

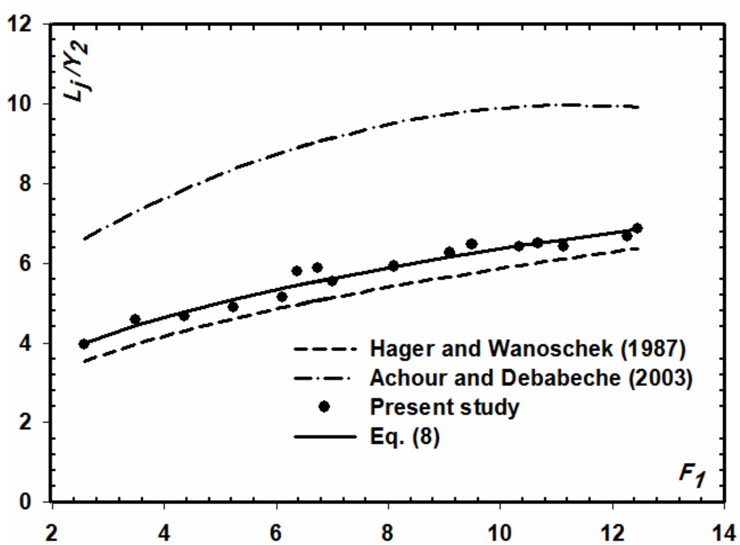

Fig. 5. Variations of relative length of jump with F_1

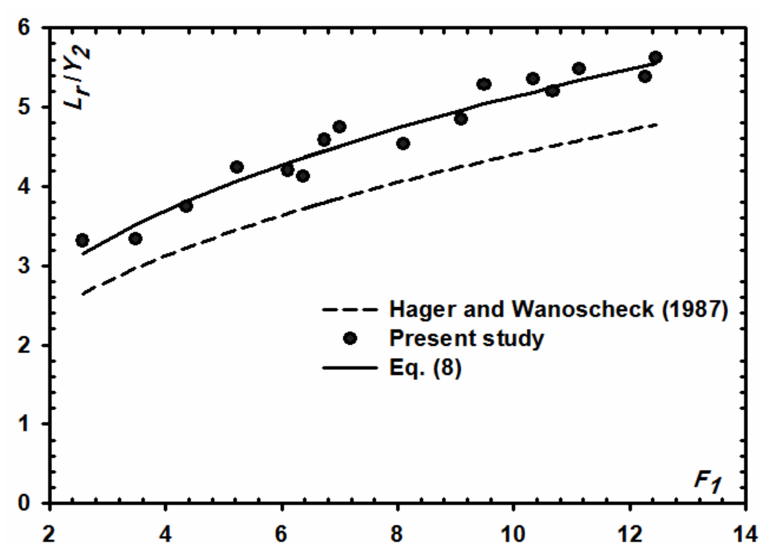

Figure 6. Variations of relative length of surface rollers with F_1

4. Conclusion

Development of a controlled hydraulic jump in a triangular channel with a broad crested end sill is studied. Based on the experimental results, it is found that hydraulic jump can be formed in a triangular channel where the adequate tailwater is not available by placing a broad crested sill which has more stability than a thin crested sill. The results are compared with the results of Hager and Wanoscheck (1987), Achour and Debabeche (2003) and Debabeche and Achour (2007). Variations of sequent depth ratio with respect to both inflow Froude number and relative sill height are plotted. Empirical equation is obtained for the relative sill height based on the experimental data. Also the power form equations are proposed to predict the length of the surface rollers and the jump length.

The results may be used to design a triangular irrigation ditch using a single broad crested sill at the end of classical hydraulic jump wherever the sufficient tailwater is not available.

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