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Hydraulic jump basins with wedge-shaped baffles*

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Abstract: This laboratory study deals with the hydraulic jump properties for an artificially roughened bed with wedge-shaped baffle blocks. The experiments were conducted for both smooth and rough beds with a Froude number in the range of $3.06 \le F_1 \le 10.95$ and a relative bed roughness ranging $0.22 \le K_R \le 1.4$. The data from this study were compared with those of rectangular baffle blocks. New experimental formulae were developed for determining the sequent depth ratio and the hydraulic jump length in terms of the inflow Froude number and relative bed roughness. Bélanger's jump equation of a rectangular channel was extended to account for the implications of the bed shear stress coefficient attributable to channel bed roughness. It was found that, in comparison with the smooth bed, the wedge-shaped bed roughness reduced the sequent depth of the hydraulic jump by approximately 16.5% to 30% and the hydraulic jump length by approximately 30% to 53%.

Key words: Energy dissipater, Hydraulic jump, Stilling basins, Wedge-shaped bed roughness
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1 Introduction

A hydraulic jump is the rapid transition from a supercritical to a subcritical open channel flow. A hydraulic jump is defined by its inflow Froude number, $F_1 = V_1/\sqrt{gy_1}$, where V_1 is the inflow velocity, y_1 is the inflow depth, and g is the acceleration of gravity. Hydraulic jumps are divided into two types according to the bed characteristics.

The first type is a classical hydraulic jump with a smooth bed and has been studied extensively (Bradley and Peterka, 1957; Rajaratnam, 1968; Leutheusser and Kartha, 1972; Hager and Bremen, 1989; Chanson, 2006). The relationship between the supercritical initial depth, y_1, of the classical jump and the sequent depth of the jump, y_2^*, for a smooth bed is given by the well-known Bélanger equation:

$$\frac{y_2^*}{y_1} = \frac{1}{2}\left(\sqrt{1+8F_1^2} - 1\right). \tag{1}$$

The second type is a forced hydraulic jump, which uses a rough bed and has been studied by many researchers. Peterka (1958) found that in hydraulic jump energy dissipators, the jumps are often formed with the assistance of baffle blocks and are kept inside the stilling basin even when the tailwater depth is somewhat less than the sequent depth of the free jump. Pillai and Unny (1964), Pillai (1969), and Pillai *et al.* (1989) used different wedge-shaped baffle blocks to shorten the hydraulic jump type stilling basins. Hughes and Flack (1984) performed laboratory investigations to assess the effect of a rough bed on the properties of a hydraulic jump. Different artificially roughened bed materials with relative bed roughness heights in the range of 0.0 to 0.9 were used. The laboratory investigations showed that the bed roughness reduces both the sequent depth and the hydraulic jump length. Mohamed Ali (1991) investigated the hydraulic jump characteristics for a rough channel bed using cubic roughness. Practical equations for the optimum roughness length and a general formula for

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the length of the jumps over a rough bed were produced. It was concluded that the length of the hydraulic jump decreased and that the reduction ranged from 27.4% to approximately 67.4% for upstream Froude numbers ranging from 4 to 10. Ead and Rajaratnam (2002) studied hydraulic jumps over corrugated beds for Froude numbers from 4 to 10. It was noticeable that the bed shear stress coefficient, β, depends primarily on the relative bed roughness height $K_R=H_b/y_1$, where H_b is the roughness height. Additionally, it was observed that the jumps on corrugated beds were half as long as the jumps over smooth beds, and the tailwater depth required to form a jump was appreciably smaller than that for the corresponding jumps on smooth beds. Carollo *et al.* (2007) proposed an expression for the integrated bed shear stress and demonstrated that this equation is practically equivalent to that established by Ead and Rajaratnam (2002). It was observed that the integrated bed shear stress is proportional to the momentum flux, and they derived the following relationship for the sequent depth ratio:

$$\frac{y_2}{y_1}=\frac{1}{2}\left(\sqrt{1+8(1-\beta)F_1^2}-1\right), \tag{2}$$

where y_2 is the sequent depth for a rough bed. The results of Ead and Rajaratnam (2002) and Hughes and Flack (1984) were used for estimating β values and to establish the following empirical relationship between β and K_R:

$$\beta=0.42H_b/y_1. \tag{3}$$

Pagliara *et al.* (2008) studied the parameters that affect the sequent depth and the length of the hydraulic jump over homogenous and non-homogenous rough bed channels downstream of block ramps. A new relationship was proposed to determine the correction coefficient for the general jump equation for both homogenous and non-homogenous rough beds. Barahmand and Shamsai (2010) studied the hydraulic jump on a non-prismatic rough bed, i.e., packed gravel particles, with experiments in a rectangular laboratory flume. A simple relationship was obtained for estimating the sequent depth ratio as a function of the relative roughness and the upstream densimetric Froude number:

$$F_{D1}=\frac{V_1}{\left(g\frac{\rho_1-\rho_a}{\rho_1}y_1\right)^{0.5}},$$

where ρ_1 is the layer averaged density of gravity current and ρ_a is the ambient fluid density. It was found that the sequent depth ratio decreases with the increasing relative roughness. Based on depth-averaged Reynolds momentum equations, Afzal *et al.* (2011) investigated hydraulic jumps over a rough bed in a rectangular channel.

The aim of the present study is to determine the hydraulic jump characteristics occurring over wedge-shaped baffle blocks, as bed roughness, and to compare the results with those of Mohamed Ali (1991), who used rectangular baffle blocks.

2 Experimental

The experimental investigations were conducted in the Hydraulic Laboratory of the Faculty of Engineering Zhejiang University, Hangzhou, China. A hydraulic jump was created downstream of a sluice gate, and its characteristics were measured in a horizontal rectangular flume which was 0.35-m wide, 0.50-m deep, and 7.8-m long (Fig. 1). The two side walls were constructed of plexiglas for observation purposes. The wedge-shaped bed roughness (Fig. 3), with a vertex angle of 150° and cut back at 90°, was fixed on the solid apron in a uniform staggered pattern, so that the blocks were perpendicular to the incoming flow. In Fig. 2, S is the longitudinal distance between the blocks and L is the distance between the blocks in the transverse direction. Two sets of experiments were performed with a total of 90 runs. The first set with a total of 30 runs was performed with a smooth bed, to simulate a classical hydraulic jump and to provide a control for the results of the experimental setup with the available data from the literature. The second set with a total of 60 runs was performed using wedge-shape baffle blocks to represent bed roughness, with the height H_b=0.5−2.0 cm. The range of the relative bed roughness height K_R was 0.22 to 1.40. The water surface profiles were measured at intervals of 1 cm in the longitudinal direction (X) by a point gauge with an accuracy of ±0.1 mm. Because the water surface height of the hydraulic jump varied with time,

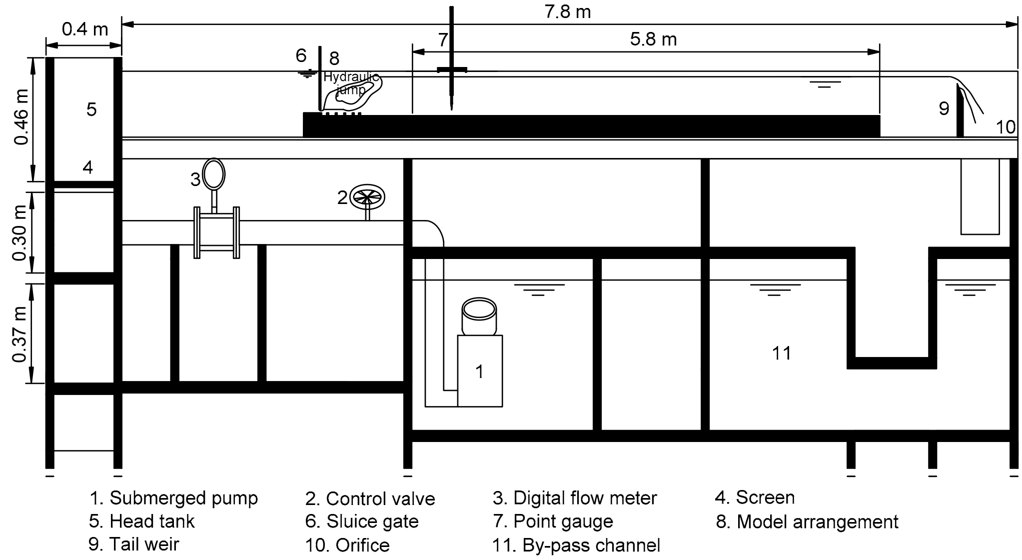

Fig. 1 Testing flume

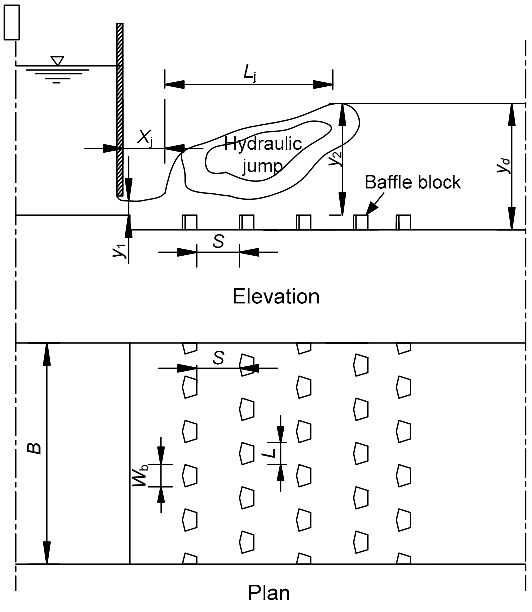

Fig. 2 Model arrangements

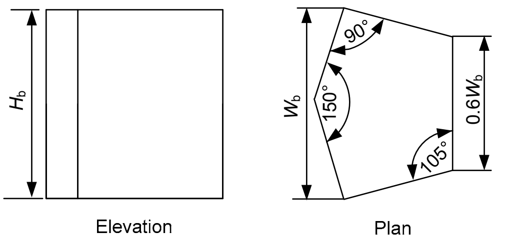

Fig. 3 Dimensions of the wedge-shaped bed roughness

the mean surface height at each position was determined by averaging at least 10 data points. Each point was recorded by the point gauge over a period of 60 s. The supercritical depth, y_1=1.4–2.3 cm, was measured at the toe of the hydraulic jump at a distance, X_j, from the gate. The sequent depth was measured from the profile survey at the location where the water surface became essentially level. The jump length, L_j, was obtained as the horizontal distance between two sections, y_1 and y_2. The hydraulic jump parameters were assessed using snapshots photos taken from the recorded videos. To minimize measurement errors, a square grid (4-cm side) was drawn on the glass walls of the channel. The water discharge at the inlet, which was controlled by an inlet valve located at the supply lines, was measured by an electromagnetic flow meter with an accuracy of ±0.001 m^3/h. The discharge values were chosen to achieve a wide range of inflow Froude numbers (3.06–10.95). The downstream water depth was adjusted by a tail weir, which was adjusted so that the jumps were formed at the start of the roughness bed.

A vertical sluice gate (0.6-m deep) was used to create the hydraulic jump. For all runs, sufficient time was allowed to establish the flow and the jump in the basin before any data were collected. Measurements were taken at various locations laterally across the channel and immediately upstream of the leading edge of the surface roller.

3 Results and discussion

3.1 Sequent depth

Fig. 4 shows the relationships between the sequent depth ratio y_2/y_1, y_2^*/y_1 and F_1 for smooth and rough beds for the experimental results of the present study and other related studies. The data for the smooth bed in the present study agree well with Eq. (1) from the study by Bélanger. The determination of the subcritical sequent depth of the hydraulic jump was subject to considerable experimental scatter and was rather insensitive to changes in the longitudinal position (Leutheusser and Kartha, 1972). An inspection of Fig. 4 reveals that most of the present data and other research data for a rough bed exhibit the same general tendency of falling below the results from the Bélanger equation. An analysis of the data shows that the sequent depth ratios, using wedge-shaped baffle blocks, were reduced by approximately 8.5%–16.7% compared with the sequent depth ratios originating from the baffle blocks with a rectangular shape (Mohamed Ali, 1991). The main reason for the small downstream depth is the existence of increased bed shear stress due to the wedge-shaped bed roughness. Fig. 4 also demonstrates that the value of the sequent depth ratio decreases with an increase of the relative bed roughness height (Rajaratnam, 1968).

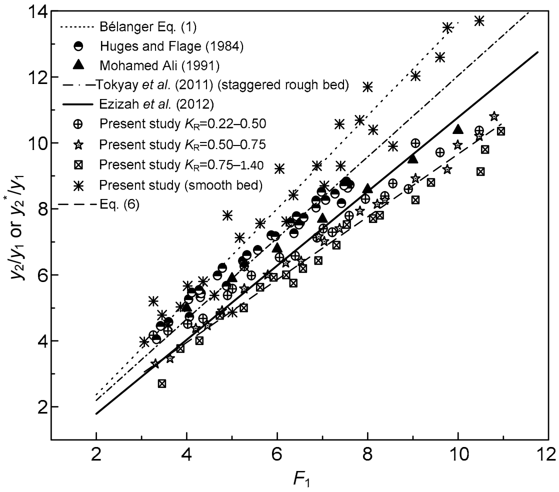

Fig. 4 Sequent depth ratio as a function of the inflow Froude number

3.2 Bed shear stress coefficient

The relationship between the bed shear stress coefficient, β, and the relative bed roughness height, K_R, for the present study, Ead and Rajaratnam (2002), Carollo *et al.* (2007), and Pagliara *et al.* (2008) is presented in Fig. 5. Using the experimental results, the bed shear stress coefficient was calculated from Eq. (2) as follows:

$$\beta = 1 - \frac{(2y_2/y_1+1)^2-1}{8F_1^2}. \tag{4}$$

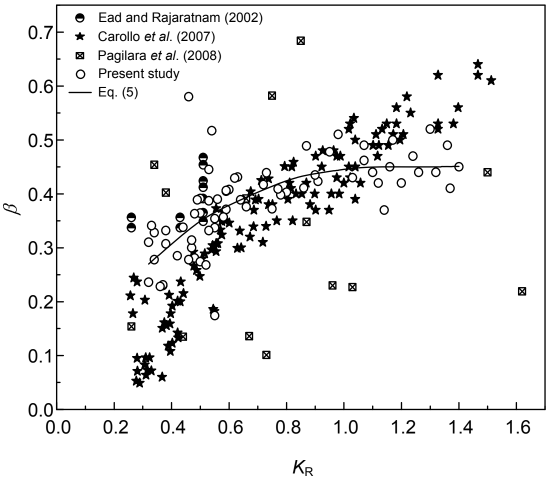

Fig. 5 Bed shear stress coefficient vs. relative bed roughness height

The experimental results shown in Fig. 5 have an appreciable scatter, but these predictions nearly represent the mean of the data. The bed shear stress coefficient increases as the relative bed roughness height increases until K_R=1.1; subsequently, the bed sheer stress coefficient levels off. High scattering data can be observed for data of Pagliara *et al.* (2008), which could be attributed to the use of non-homogeneous rough beds.

A linear regression analysis was used to find an empirical equation for β in terms of K_R as follows:

$$\beta = 0.92K_R^{0.87\exp(-0.72K_R)},\quad 3.06 \le F_1 \le 10.95. \tag{5}$$

The regression coefficient is R^2=0.5 with a standard error of estimate (SEE)=0.05.

By substituting Eq. (5) into Eq. (2), the following equation is obtained:

$$\frac{y_2^2}{y_1} = \frac{1}{2}\left[-1+\sqrt{1+8(1-0.92K_R^{0.87\exp(-0.72K_R)})F_1^2}\right]. \tag{6}$$

When the relative boundary roughness height equals zero (i.e., smooth bed), the bed shear stress coefficient equals zero. Consequently, Eq. (6) becomes the same as the Bélanger equation (Eq. (1)). The calculated sequent depth ratios using Eq. (6) correspond satisfactorily to the experimental data. Eq. (6) has a mean error of 11.3%, R^2=0.91 and SEE=1.2.

Using Eq. (4) to calculate the values of the bed shear stress coefficient for the present study and Mohamed Ali (1991), it can be observed that the values of β for the present study are larger than those for Mohamed Ali (1991), as shown in Table 1. This result indicates that the wedge-shaped bed roughness could introduce more bed shear stress than the cubic baffle blocks, which consequently helps to reduce the hydraulic jump sequent depth.

Table 1 Calculated bed shear stress coefficients for the present study and Mohamed Ali (1991)

F_1	β	
	Mohamed Ali (1991)	Present study
4	0.062	0.231
5	0.188	0.268
6	0.265	0.375
7	0.319	0.421
8	0.357	0.463
9	0.386	0.489
10	0.409	0.550

3.3 Depth deficient factor

Ead and Rajaratnam (2002) used a percentage sequent depth reduction parameter relative to a smooth bed to evaluate the reduction in the sequent depth that is required to form a jump over a corrugated bed. The results of their experiments indicate a constant value of approximately 0.25. The relationship between the percentage sequent depth reduction parameter, $P=(y_2^*-y_2)/y_2^*$, and the hydraulic jump inflow Froude number is presented in Fig. 6. The present study shows that the percentage sequent depth reduction parameter is not constant and that its value ranges from 0.165 to 0.300. This result agrees with the result of Carollo *et al.* (2007), which indicates that the reduction of the sequent depth ratio increases with the inflow Froude number. For Huges and Flage (1984), the percentage sequent depth reduction ranges from 0.02 to 0.11. Alternatively, the following empirical equation can be used, which fits the relationship shown in Fig. 6:

$$P=0.02+0.04\ln F_1+0.17/F_1^5+\ln(K_\mathrm{R})^{0.1},\quad 3.06\le F_1\le 10.95. \tag{7}$$

This empirical relationship is characterized by R^2=0.98 and SEE=1.87.

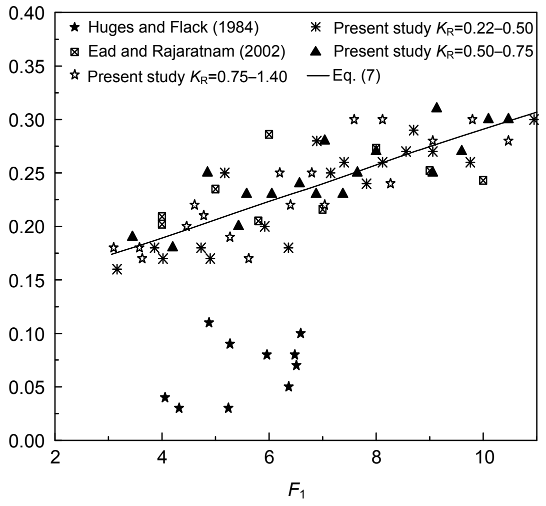

Fig. 6 Relationship between the percentage sequent depth reduction parameter and the hydraulic jump inflow Froude number

3.4 Hydraulic jump length

The measured values of the hydraulic jump length ratio were plotted in Fig. 7 against the initial Froude number, with the relative bed roughness as a parameter. The results of Ead and Rajaratnam (2002), the United States Bureau of Reclamation (USBR) basin (I), Mohamed Ali (1991), and Tokyay *et al.* (2011) were compared with the results of the present study. The curve of the USBR basin (I) represents a hydraulic jump over a smooth bed, whereas the data points from Ead and Rajaratnam (2002), Mohamed Ali (1991), and Tokyay *et al.* (2011) represent a hydraulic jump over a rough bed. For the studied range of the initial Froude number and the relative boundary roughness, it can be observed that the experimental points for the present study and those of other researchers were, in general, located below the curve of the USBR basin (I) corresponding to the smooth bed. The data plot shows excessive scatter, attesting to the well-known difficulties encountered in making the type of hydraulic jump measurements considered here. The data show that the value of L_j / y_2^* decreases as the value of the initial Froude number increases. This result contradicts the finding of Mohamed Ali (1991). According to his study, the value of L_j / y_2^* increases as the value of the initial Froude number increases. The reason for this contradiction could be explained by the fact that the rectangular baffle blocks of Mohamed Ali (1991) were protruding into the flow, while for the present study, the crests of wedge-shaped bed roughness were at the level of the upstream bed carrying the supercritical stream. The hydraulic jump length in terms of the subcritical sequent depth of the corresponding classical jump varies approximately from 3.6 to $2.7y_2^*$. The experimental results suggest that the hydraulic jump length ratio decreases with an increase in relative bed roughness (Rajaratnam, 1968). The best fit equation for the data was obtained by the method of least squares and results in the following equation with R^2=0.94 and SEE=0.6:

$$L_j / y_2^* = 15.1 - 0.54\sqrt{F_1}\ln F_1 - 22/\sqrt{F_1} - \ln(K_R)^{0.03},$$
$$3.06 \le F_1 \le 10.95. \tag{8}$$

Eq. (8) can be used for the practical design of similar stilling basins.

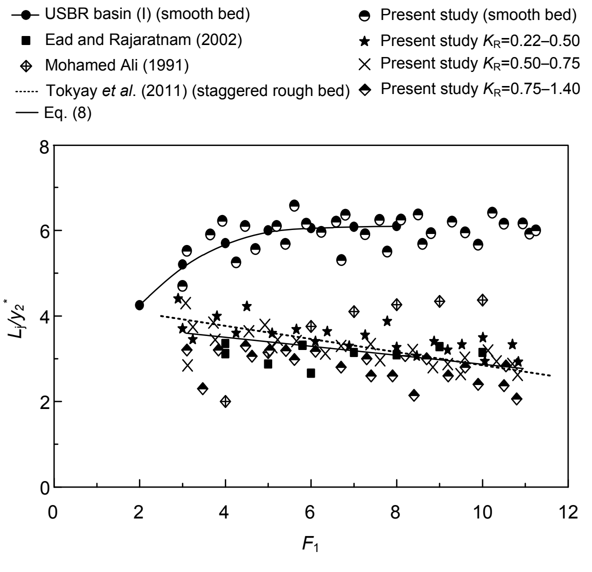

Fig. 7 Non-dimensional jump length as a function of the inflow Froude number

4 Conclusions

Experimental tests were performed to assess the effects of the wedge-shaped bed roughness on the properties of a hydraulic jump. Preliminary tests over a smooth horizontal bed confirmed the results reported in the literature. A comparison between the wedge-shaped bed roughness and the rectangular baffle blocks shows that the former reduces the sequent depth and the hydraulic jump length much more efficiently than the latter. The sequent depth ratio increases as the initial Froude number increases, while this ratio decreases with an increase of the relative bed roughness. A new relationship was proposed to determine the bed shear stress coefficient for a rough bed. The initial Froude number has a more pronounced influence on the jump length than the relative boundary roughness. The hydraulic jump length ratio decreases with an increase of relative bed roughness. New experimental formulas were furnished for determining the sequent depth ratio and the hydraulic jump length in terms of the inflow Froude number and relative bed roughness.

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