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Corrugated Bed Hydraulic Jump Stilling Basin

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Abstract: Hydraulic jump stilling basins are used as an energy dissipater structures downstream of gates, spillways and weirs. In the present study the effect of trapezoidal shape corrugated bed on flow characteristics of hydraulic jump has been experimentally investigated. Total of 42 tests conducted in a flumes of 25 and 50 cm in width. Experimental were performed for wide range of Froude numbers ranging from 4 to 12. Six values of the relative roughness of corrugated shapes were studied. In all tests water surface profile and in 10 tests the vertical and the axial velocity profile were measured. From the analysis of data, the relative conjugate depths and the length of hydraulic jump were plotted against the Froude number. Comparison of these parameters with the same parameters in smooth bed hydraulic jump shows that the conjugate depth decreases 20% and the hydraulic jump length decreases 50%. These results show that corrugating the stilling bed can decrease the cost of stilling basin.

Key words: Hydraulic jump, stilling basin, energy dissipaters, open channel, corrugate, roughness

INTRODUCTION

Hydraulic jump is generally used for the dissipation of excess kinetic energy downstream of hydraulic structures such as drops, spillways, chutes and gates. The structures which are constructed at great costs downstream of the these studies are called energy dissipation structures. The Hydraulic jump which occur in wide rectangular horizontal channels with smooth bed is defined as being a classical jump and has been widely studied by Peterka (1958), Rajaratnam (1967), McCorquodale (1986) and Hager (1992). If Y_1 and U_1 are defined as being the average depth and velocity of the flow upstream of the jump with a Froude number of

$$F_{v1} = \frac{U_1}{\sqrt{gy1}}$$

in which g is the acceleration of gravity. Using the Blanger equation, the conjugate depth (Y_2*) will be obtained as follows:

$$\frac{Y_2^*}{Y_1} = \frac{1}{2}\left[\sqrt{1+8F_{r1}^2 - 1}\right] \qquad (1)$$

As stated before, hydraulic jumps over smooth bed have been studied in the past, however previous studies on hydraulic jumps over rough bed were not comprehensive. Rajaratnam (1968) carried out the first systematic studies on hydraulic jumps over rough bed. He introduced a parameter called the relative roughness

$$K = \frac{k_e}{Y_1}$$

in which k_e is the equivalent roughness element and Y_1 is the initial depth of the incoming jet above the rough surface. Rajaratnam had shown that the length of the roller (Lr) and the length of the jump (Lj) upon rough bed (in comparison to the same parameters in jumps upon smooth bed) would decrease significantly. Figure 1 shows the definition of jump characteristics over rough bed.

Leutheusser and Schiller (1975) also conducted studies upon the incoming jet over rough surfaces. They found that the existence of a developed supercritical flow downstream of the gates or spillways upon rough bed requires less length in comparison to smooth bed. It was also found that if the bed is rough, the boundary layers would develop faster. Hughes and Flack (1984) also carried out experimental research on hydraulic jumps upon rough bed. They found that boundary layer roughness will definitely decrease the sub-critical depth and length of the jump and the extent of this decrease is related to the Froude number and relative roughness of the bed. Mohamed Ali (1991) performed a series of experiments upon rough bed using cubed elements and showed that the relative length of the jumps over rough bed in comparison to classical jumps varies from 27.4 to 67.4%. Ead *et al.* (2000) performed tests on the changing of the velocity field in turbulent flows within a 62 cm corrugated pipe with 3 various slopes under different flow

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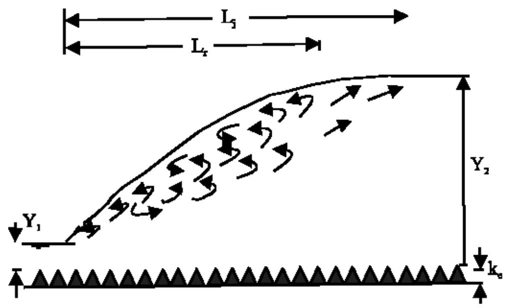

Fig. 1: Hydraulic jump over rough bed

characteristics. They found that the velocities in the boundary layer of the corrugated pipe are relatively low. Ead and Rajaratnam (2002) performed an experimental study upon hydraulic jumps over round shape corrugated bed. Froude numbers ranging from 4 to 10 were taken into account and the value of the relative roughness t/Y_1 in which t is the height of the corrugated was considered as being between 0.25 to 0.5. They observed that the tailwater depth required for the hydraulic jump over corrugated bed is less than that required for jumps over smooth bed. It was also observed that the length of the jump is approximately half of that which occurs over smooth bed.

A historical review of the previous research shows that the roughness of stilling basin bed can effectively decrease the required conjugate depth and length of the jump in which eventually can reduce the costs of energy dissipating stilling basins. It is of note that the verification of such an assumption requires further study as the research carried out to date is quite sparse. Thus the main purpose of this research is to conduct experimental study to investigate the effect of trapezoidal corrugated shape on the characteristics of jump. The experiments were carried out in the Hydraulic laboratory of Shahid Chamran University in Ahwaz and the results are presented in this paper.

MATERIALS AND METHODS

In order to reach the main purpose of this study, two rectangular flumes 25 and 50 cm wide, 40 cm high and lengths of 12 and 9 m were used. The required Froude numbers was obtained by increasing the initial 2 m length of the flume by 140 cm and the supercritical flow and initial depth of the jump was developed using a slide gate.

To create the required roughness of the bed, wooden baffles with a trapezoidal cross section were attached upon Plexiglas's sheets and in order to diminish the effects of cavitations, the upper surface of the corrugated were set at the same level of the upstream bed as it has been shown in Fig. 2. The liner baffle blocks upon the bed acted as a depression and created a vortex effect which in themselves would increase the bed's Reynolds shear stress. In Table 1 the characteristics of the trapezoidal corrugated dimensions have been presented.

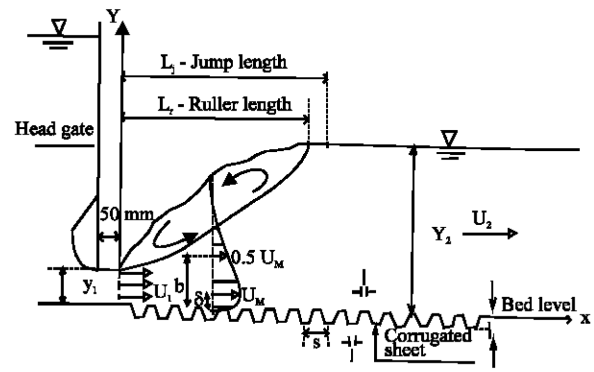

Fig. 2: Definition of a free jump over a corrugated bed

Table 1: Geometric dimensions of corrugated used in the study

Type of bed	l (mm)	s (mm)	t (mm)
1	10	34	13
2	10	68	13
3	10	68	26
4	10	125	26

In which l is the corrugate wave length, s is the corrugate spacing and t is corrugate height

Water was supplied by 120 hp pump from an underground storage tank in the laboratory and transported to the 6 m main tower which, the flow would then enter the flume after passing through a regulating valve. Throughout this study the flow rate was measured using a 53° v-notch weir installed at the downstream of the flume. The experiments were carried out using 3 different Y_1 with values of 15, 25 and 35 mm. The tail water depth in the flume was controlled by a tailgate at the end of the flume. Using this gate the experiments were conducted in such a manner that the jumps started at the toe of the corrugated bed, which is approximately 50 mm distant from the gate itself as it is shown in Fig. 2. Throughout the experiments, water surface flow profile was measured with an accuracy of 0.1 mm point gage and the horizontal velocity was measured using a pitot tube.

Velocity measurements were taken within the centerline of the flume where the super critical inflow develops and other measurements were taken at several cross-sections along the length of the jump. Total of 42 tests were conducted throughout this study. The tests were carried out using Froude numbers ranging from 4 to 12 and Reynolds's numbers ranging from 22960 to 166640. By selecting depth of 15, 25 and 35 mm for Y_1 and two roughness heights of 13 and 26 mm for t, six different relative roughness values equaling, respectively

0.371, 0.52, 0.743, 0.867, 1.04 and 1.733 were identified and experiments carried out upon them. In all experiments, the surface profile and in each of the subsequent seven experiments the velocity profile at different sections along the jump were measured.

RESULTS AND DISCUSSION

Conjugate depth: For hydraulic jumps over corrugated bed with a supercritical depth (Y_1) and average inflow velocity U_1, the conjugate depth of the jump (Y_2) can be shown to be function of:

$$f_1 (Y_2, Y_1, U_1, g, \rho, \upsilon, t, s) = 0 \tag{2}$$

In which g is the acceleration of gravity ρ, υ are the mass density and viscosity of water, respectively and other variables have been defined previously. Using Buckingham's theory, the following dimensionless relationship is thus obtained:

$$\frac{Y_2}{Y_1} = f_2(F_{r1} = \frac{U_1}{\sqrt{gy_1}}, R_1 = \frac{U_1 Y_1}{\nu}, \frac{t}{Y_1}, \frac{s}{Y_1}) \tag{3}$$

In this equation F_{r1} and R_1 are, respectively the Froude and Reynolds' values at the beginning of the Jump. The value of the Reynolds's number in these experiments was quite high. This means that viscosity has no effect and thus Reynolds number can be eliminated from analysis. As a result Eq. 3 would change into Eq. 4:

$$\frac{Y_2}{Y_1} = f_3(F_{r1}, \frac{t}{y_1}, \frac{s}{y_1}) \tag{4}$$

using the obtained results, the relation between dimensionless parameters of Eq. 4 was plotted which is shown in Fig. 3.

Figure 3 shows that the values of $\frac{t}{Y_1}$ and $\frac{s}{y_1}$ do not have a great effect on $\frac{Y_2}{Y_1}$. In addition it becomes apparent that the proportion of $\frac{Y_2}{Y_1}$ and F_{r1} provides us with the following equation:

$$\frac{Y_2}{Y_1} = 1.047F_{r1} + 0.5902 \tag{5}$$

The logic behind such a phenomena is that since the height of the baffles and the upstream bed are on the same level, the baffles act as slumps and the values of $\frac{t}{Y_1}$ and $\frac{s}{y_1}$ will be ineffective in the $\frac{Y_2}{Y_1}$ relationship.

The required tailwater depth for the development of jumps over corrugated bed (Y_2) is less than Y_2^* required

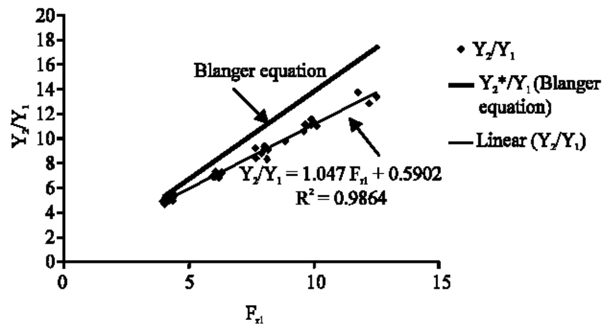

Fig. 3: Relationship between $\frac{Y_2}{Y_1}$ and F_{r1} in classic jumps and Jumps over corrugated bed

for classic jumps. In order to show the amount of difference between Y_2 and Y_2^* a dimensionless index (D) which is defined as follow:

$$D = \frac{Y_2^* - Y_2}{Y_2^*} \tag{6}$$

was computed for all experimental tests and was plotted against Froude number. The results indicated that D is almost constant and has an average amount equal to 0.2. This means that the required tailwater depth for jump over trapezoidal corrugated bed is 80% of the same variable for jump over smooth bed. Comparing of the value of D obtained in this study with the same value for type II and III USBR stilling basins which are, respectively 0.17 and 0.21 (Peterka, 1958) and the results obtained by Ead and Rajaratnam (2002) in which the average D was equal to 0.25 it is seen that trapezoidal shape of corrugation has greatly decrease the required tailwater depth.

Length of the jump: Figure 5 shows the relationship between the Froude number and the dimensionless length of the Jump. According to Fig. 5, the ratio of $^{Lj}/_{Y2}*$ is almost independent of Froude number and is equal to 3. In this Fig. 4, the same relation for classical jump has been shown. As it is obvious from this Fig. 4, the length of the classical jump is twice of the length of jumps over corrugated bed.

The effect of the baffle height (t) upon the length of the roller jump (Lr) has been shown in, Fig. 5a-c. These Fig. 5a-c show that the height of the baffles will have no effect whatsoever in the length of the hydraulic jump. Ead and Rajaratnam (2002) also found the same results for jump over round shape corrugate.

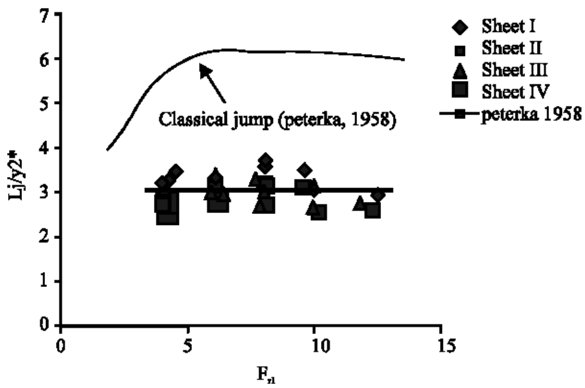

Fig. 4: Length of jumps over corrugated bed and classic jumps

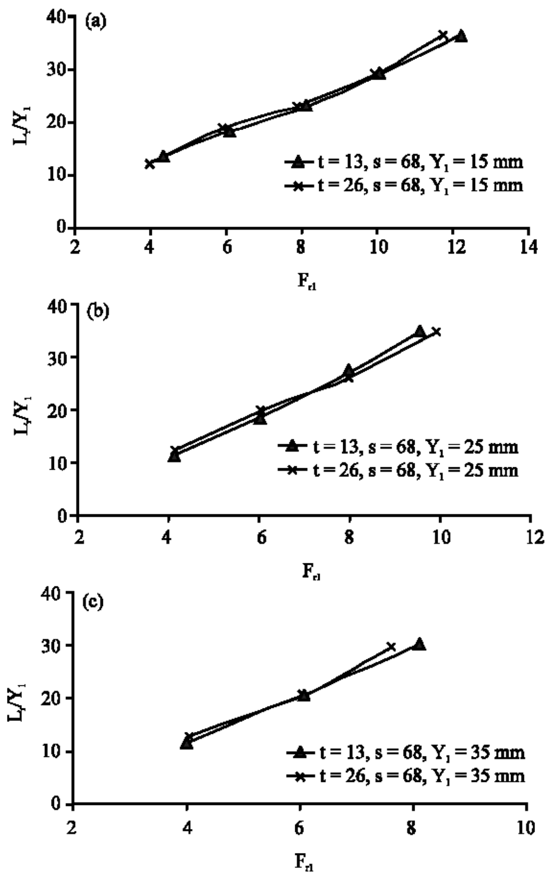

Fig. 5: The effect of the corrugate height (t) upon the length of the roller (Lr)

The length of roller jump was found to depend largely to corrugate spacing as shown in Fig. 6a-c than their height.

Velocity field: In Fig. 7, the velocity profiles along the hydraulic jump related to two of the experimental tests are plotted. These profiles adequately show the changes in

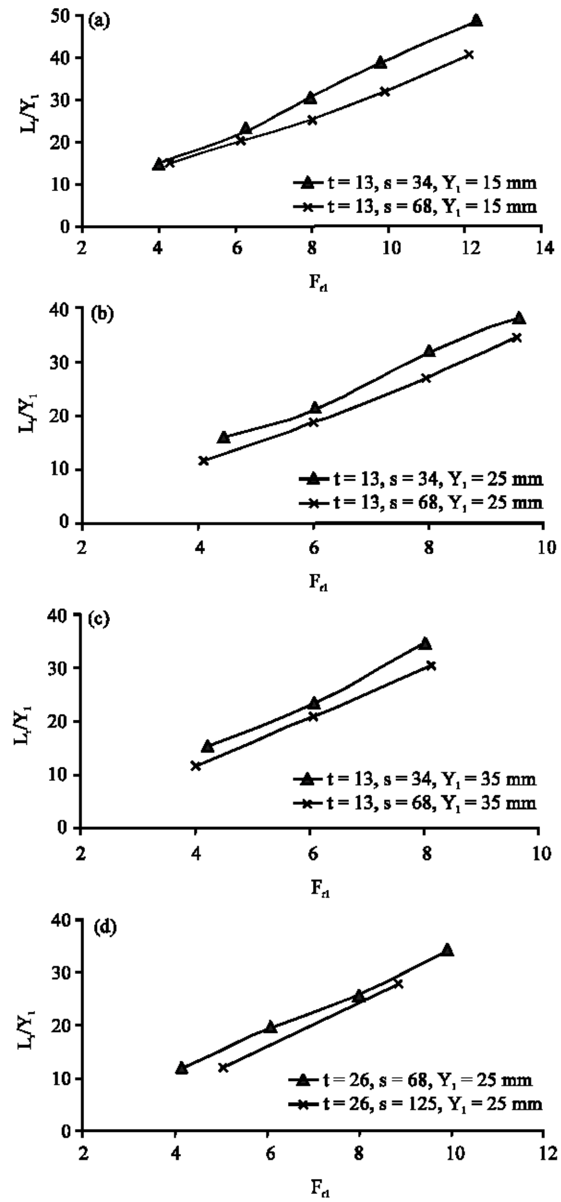

Fig. 6: Effect of the corrugate spacing (s) upon the length of the roller (Lr)

velocity. In these figures the decrease of the velocity as the distance increases from the toe of the jump can be easily seen.

Bed shear stress: The increase of the bed shear stress, is one of the main cause for reduction of the tailwater depth and the length of the hydraulic jump over corrugated bed. In order to study this phenomenon, in this section, the bed shear stress is calculated. To do so using the momentum equation and taken F_t as being the total bed shear forces, it is possible to write:

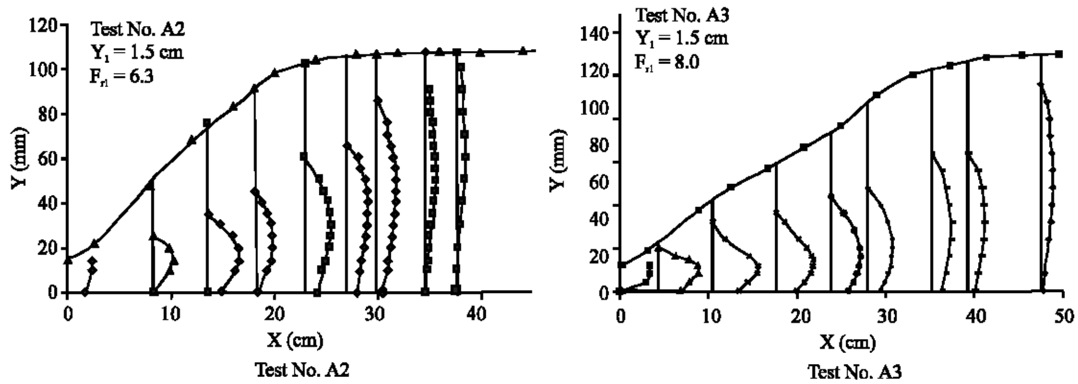

Fig. 7: Velocity profiles along the hydraulic jump

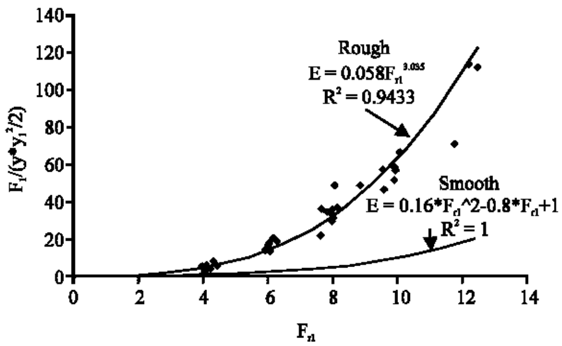

Fig. 8: Comparison of the shear stress indices for jumps over smooth and corrugated bed

$$F_t = (P_1-P_2)+(M_1-M_2) \qquad (7)$$

In this equation P_1, P_2, M_1 and M_2 are, respectively pressure and Momentum prior and after the jump. The index of the shear force also can be defined as:

$$\varepsilon = \frac{F_t}{\gamma Y_1^2/2} \qquad (8)$$

The value of index was determined for all the experiments and was plotted against F_{r1}. Figure 8 shows that the amount of ε in hydraulic jumps over corrugated bed is almost 10 times that of the bed shear stress in jump over smooth bed.

CONCLUSIONS

The present study was carried out with the purpose of identifying the effects of trapezoidal shape corrugated bed upon the characteristics of hydraulic jumps. Total of 42 tests were conducted and the results analyzed. From these results, the following conclusions can be found:

- The conjugate depth of the jump in comparison is reduced by about 20%. Which is in agreement with the finding of Ead and Rajaratnam (2002).
- The ratio of the length of the jump to the conjugate depth was found to be independent of Froude number and is equal to 3. This means that length of the jump is reduced by 50% decrease in comparison to jump over smooth bed.
- The length of the roller jump was found to depend largely to the corrugate spacing than to their height.
- The amount of bed shear stress in trapezoidal corrugated bed is approximately 10 times that of bed shear stress in classic jumps
- The amount of shear stress was found to be a function of the Froude number.

Although the results of this study, over trapezoidal shape corrugated and the results of Ead and Rajaratnam (2002), over round shape corrugated, have proven that the dimensions of the stilling basin can be reduced considerably if the bed be corrugated, however further research is needed to conduct in prototype before applying in the field/

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NOTATION

The following symbols are used in this paper:

D = Dimensionless index
F_{r1} = Froude number

F_t = The total bed shear forces
g = The acceleration of gravity
k_e = The equivalent roughness element
K = Relative roughness
Lj is the hydraulic jump
Lr is the length of roller jump
M_1 and M_2 are the momentum force before and after the jump
P_1 and P_2 are the hydrostatic pressure force before and after the jump
R_1 = Reynolds number
s = Distance between two corrugated
t = The height of corrugated bed
U_1 is the flow velocity before the jump
Y_1 and Y_2 are the floe depth before and after the jump in corrugated bed stilling basin
Y_2* = The subsequent sub-critical flow for classic jump
ρ = The mass density of water
υ = The kinetic viscosity of water
ε = The index of the shear force

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