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Experimental Investigations On Hydraulic Jump Over Corrugated Beds

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Abstract: A study of effects of different shapes of corrugated beds on the characteristics of hydraulic jumps was conducted. Experiments were performed for the Froude numbers 4.7, 5.2, 5.8, 6.2, 7.4. Two shapes of corrugations such as rectangle and right angled triangle of same amplitude and wavelength were tested and compared with smooth beds. It was found that, for all shapes of corrugated beds, the tail water depth required to form a jump was smaller than that for the corresponding jumps on smooth beds. Further, the length of the jump on the different corrugated beds was less than half of the smooth beds. The integrated bed shear stress on the corrugated beds was about 12 times that of the smooth beds. It was found that for the same amplitude and wavelength, the effect of the shape of corrugations is relatively small. From the results we can confirm that the effectiveness of corrugated beds can be used for energy dissipations below hydraulic structures.
Key words: corrugated beds, open channel flow, hydraulic jump, energy dissipation

1. INTRODUCTION

For the dissipation of energy below hydraulic structures hydraulic jumps are widely used. In hydraulic jump type energy dissipaters , the jumps are often formed with the assistance of baffle blocks and are kept inside the stilling basin even when tail water depth is somewhat less than the sequent depth of the free jump. A jump formed on a smooth bed with the wide rectangular channel Is often referred to as classic hydraulic jump and has studied extensively. If y1 and u1 are respectively , the depth and mean velocity of the supercritical stream just upstream of the jump, with a froude number of F1= u1/(gy1)0.5 where g is acceleration due to gravity, the subcritical sequent depth y2* is given by well known belanger equation

$$Y_2^*/y_1 = \frac{1}{2}[\sqrt{(1+8F_1^2)} - 1]$$

A preliminary investigations by Rajaratnam indicated that , the channel on which bed is formed is rough, the tail water depth y2 required to form a jump could be smaller than the sequent depth y2*. further studies by many of the scientists supported the reduction of the tail water depth produced in the roughness of the bed. Further rajaratnam found that beds with high roughness have low jumps as compared with the classical jumps.

But the main concern is that roughness elements located in the upstream part of the jumps might subject to the cavitation and possible corrosion , in which case the jump would move downstream to the unprotected streambed, thereby causing erosion and possible damage to the structure. Hence, an exploratory laboratory investigations was performed with the hydraulic jumps occurring on corrugated beds and the results are presented and this idea might be helpful for energy dissipation for a range of hydraulic structures.

2. EXPERIMENTAL STUDY

A. Description Of The Experimental Setup

Appropriate instrumentation for the flow profile measurements are designed and installed during the course of experiments. Experimental study is conducted in a horizontal rectangular flume, 0.45m wide, 0.6m deep and 17.00 m long. The channel is made up of steel structure and the sides are made of transparent plexi glass sheet.

The maximum supercritical Froude number obtained by controlling inlet sluice gate is 7.5 and corresponding to maximum feasible water flow rate.

Corrugated wooden sheets are installed on the bed of flume in such a way that the crests of corrugations are at the same level as the upstream bed on which the supercritical stream is produced by a sluice gate. The corrugations acted as depressions in the bed, to create a system of turbulent eddies which may increase the bed shear stresses. Two corrugated sheets of shapes right angled triangle corrugations as shown in Fig.3.4 and stepped rectangle corrugations as shown in Fig.3.5 with corrugations of wave length of 65 mm perpendicular to the flow direction and amplitude of 18 mm, respectively.

B. Measurements Of Different Experimental Quantities

The discharge through the flume is constant during the experiment with a fixed setting of the pump delivery valve. The setting has been fixed based on occurrence of hydraulic jump formation with different openings of the inlet sluice valve. In the course of experimentation, the quantities that are measured comprise velocity of flow using pitot tube, depths of flow at various locations using point gauge, sluice openings and location of hydraulic jump for subsequent calculations.

A pump is used to supply the head tank feeding the flume and the discharges are measured with the help of pressure data given by tilting flume logger which is connected to flume and located in the supply lines.

Fig.1 Right angle triangle corrugations

Fig.2 Stepped rectangular corrugations

Water enters into flume under a sluice gate with a streamlined lip, thereby producing a uniform supercritical stream with a thickness of y_1.Tailgate is used to control the tail water depth in the flume. In all the experiments, the tailgate is adjusted, the jumps are formed at the starting of corrugated bed, which is about 20 mm from the gate.

A prandtl pitot tube with an external diameter of 3.0 mm as shown in Fig. 3.6, is connected to an inclined manometer as shown in Fig. 3.7. It is used to measure the time-averaged longitudinal velocity u_1. No corrections are made to the velocity observations to account for turbulence and presence of air bubbles. Velocity profiles are measured at several vertical sections within the jumps, in the vertical center plane of the flume, mostly on the crests of corrugations. The experiments are conducted and the primary details of these experiments the values are shown in Table 2.1. The initial depth y_1, measured above the crest level of corrugations on the plane bed, was equal to 30 mm. Values of y_1 and u_1 are selected to achieve wide range of supercritical Froude numbers, from 4.7 to 7.4.

Table.1 Primary details of experiments for right angle triangle and stepped rectangular corrugated beds

Right angle triangle corrugated beds									
Discharge (m^3/s)	Super critical Froude number	Depth averaged velocity (m/s)	Super critical depth (m)	Sub critical depth (m)	Sub critical sequent depth (m)	Length of jump (m)	Depth deficit factor	Relative roughness	Shear force coefficient
0.034	4.7	2.51	0.03	0.108	0.199	0.52	0.34	0.6	10.2
0.039	5.4	2.78	0.03	0.114	0.229	0.62	0.27	0.6	12.7
0.043	5.8	2.98	0.03	0.126	0.246	0.69	0.27	0.6	15.9
0.045	6.2	3.23	0.03	0.144	0.263	0.76	0.28	0.6	18.5

0.05	7.4	3.89	0.03	0.178	0.313	0.82	0.26	0.6	27.9
Stepped rectangular corrugated beds									
0.034	4.7	2.51	0.03	0.124	0.199	0.59	0.39	0.6	14.3
0.039	5.4	2.78	0.03	0.136	0.229	0.71	0.36	0.6	16.6
0.043	5.8	2.98	0.03	0.142	0.246	0.79	0.33	0.6	18.1
0.045	6.2	3.23	0.03	0.152	0.263	0.82	0.32	0.6	21.9
0.05	7.4	3.89	0.03	0.196	0.313	0.92	0.31	0.6	38.9

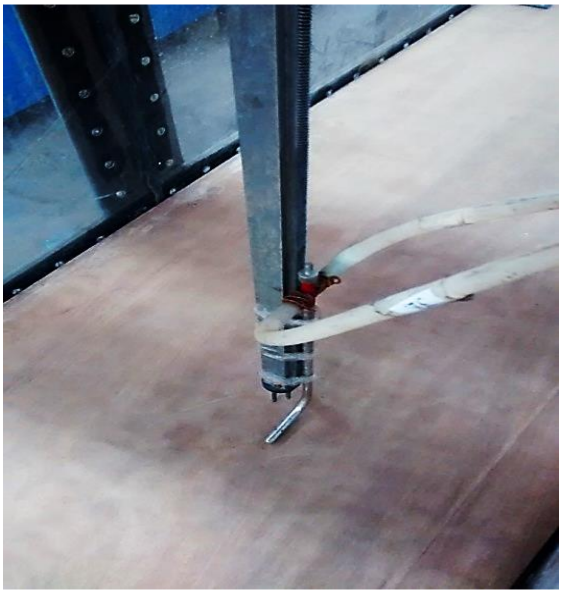

Fig.3 Prandtl pitot tube

Fig.4 Inclined manometer

C. Measurements Of Depths And Location Of Hydraulic Jump

A travelling point gauge assembly with option for moving both across the flume and along the flume have been designed fabricated and installed in the course of present work as shown in Fig. 3.8. The pointer is fitted with measuring scale for indicating the depth of flow. In every set of experiments, head of water in a supply tank, water depth of incoming flow just before jump y_1, water depth just after the jump y_2, starting point of the jump L_x, Length of the jump L_j and depth of water just before the outlet sluice gate, are measured.

Fig.5 Point gauge mounted on the moving trolley

The water depths y_1 and y_2 are measured by point gage. At any particular axial location, the centre line depth measurements are taken. The distance from the inlet sluice gate to point where the water surface is started to suddenly rise up or fluctuate, is defined as starting point of the jump. The length of hydraulic jump is obtained by taking difference between starting point of the jump and end of the jump. The supercritical Froude numbers ranges are kept between 4.7 and 7.4 in experiments that are achievable for the given fixed discharge with different openings of inlet sluice. In the present work, the focus on free jump only for stepped rectangular as shown in Fig. 3.9 and right angle triangle as shown in Fig. 3.

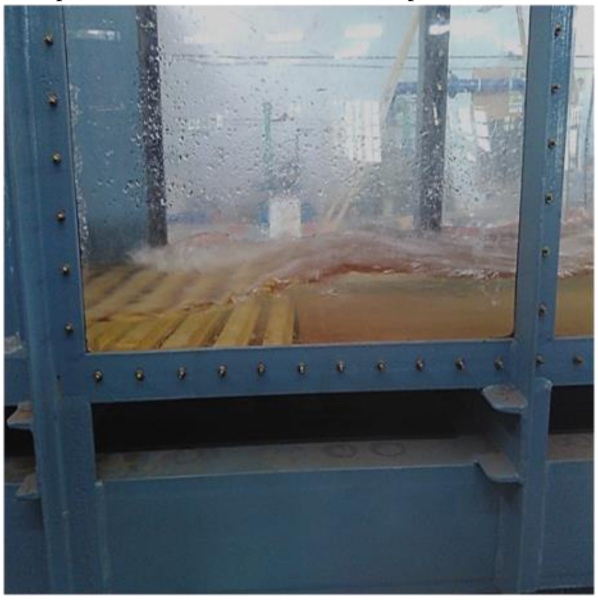

Fig.6 Hydraulic jump on the stepped rectangular corrugated bed

Fig.7 Hydraulic jump on the right angle triangle corrugated bed

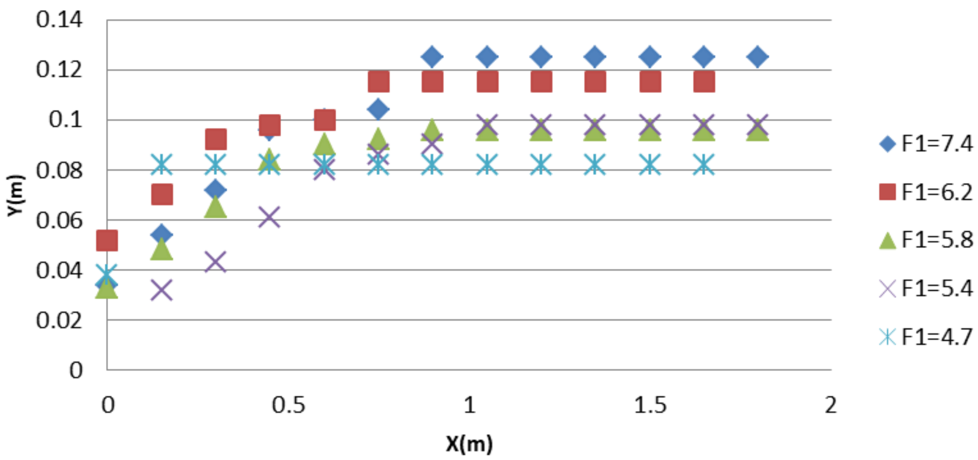

Fig.8 Water surface profile of the right angle triangle corrugated bed.

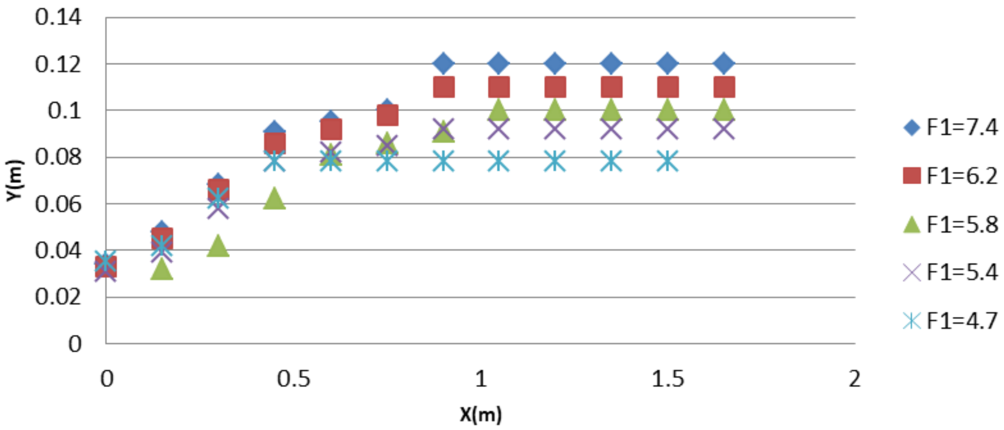

Fig.9 Water surface profile of the stepped rectangular corrugated bed.

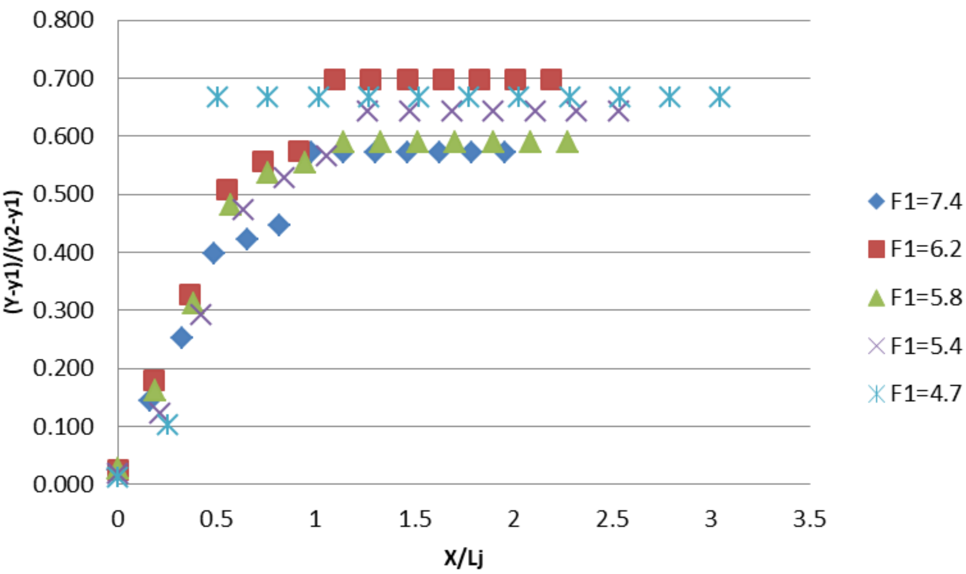

Fig.10 Normalized water surface profile of the stepped rectangular corrugated bed.

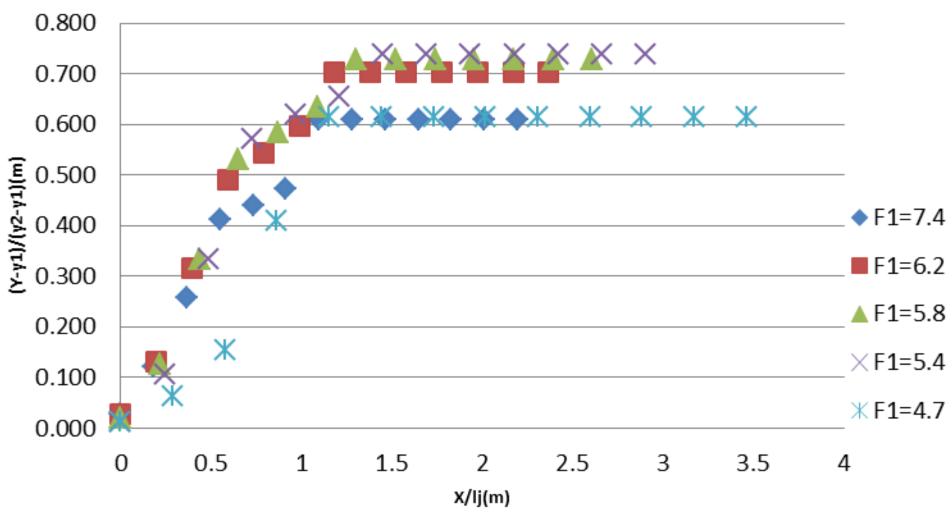

Fig.11 Normalized water surface profile of the right angle triangular corrugated bed.

3. DEPTH DEFICIT FACTOR

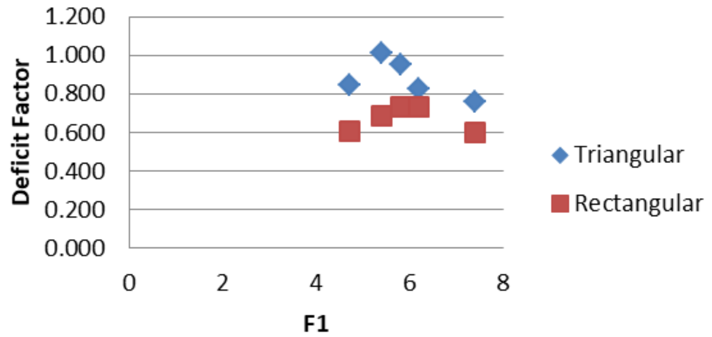

Fig.12 Variation of depth deficit factor D with F_1

4. COEFFICIENT OF LOCAL SKIN FRICTION

The coefficient of local skin friction is defined by where the wall shear stress is the fluid density and is the free stream velocity usually taken outside of the boundary layer or at the inlet.

The skin friction coefficient is defined by

$$F_\tau = \int_{x=0}^{L_j} 0.5 C_f \rho\, u_m^{\,2}\, \Delta x \text{.........}(10)$$

where C_f is coefficient of local skin friction and u_m is maximum velocity at any section. Assuming that C_f is approximately invariant in the x direction, it is evaluated.

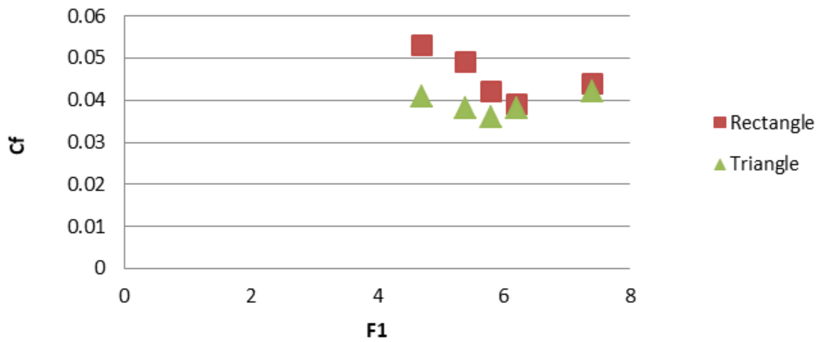

Fig.13 Variation of coefficient of skin friction c_f with F_1

5. MAXIMUM SCOUR LENGTH

Whenever water flows in a channel (natural or artificial), it tries to scour its surface. Silt or gravel or even large boulders are detached from the bed or sides of the channel. These detached particles are swept downstream by the moving water. The maximum scour length L_S is dependent on following independent variables

$$\frac{L_S}{y_1} = f\left(F_{r1}, \frac{y_2}{y_1}, \frac{L_j}{y_1}, \frac{t}{y_1}\right)$$

It is important to predict the relative scour length, based on experimental data and using statistical methods, several models are proposed and their coefficients are estimated. Out of all trials, the best equation predicting the relative scour length can be put in following formation.

$$\frac{L_S}{y_1} = -17.75\, F_{r1} + 8.05\, \frac{y_2}{y_1} + 1.19\, \frac{L_j}{y_2} + 51.79\, \frac{t}{y_1} \text{.........}$$

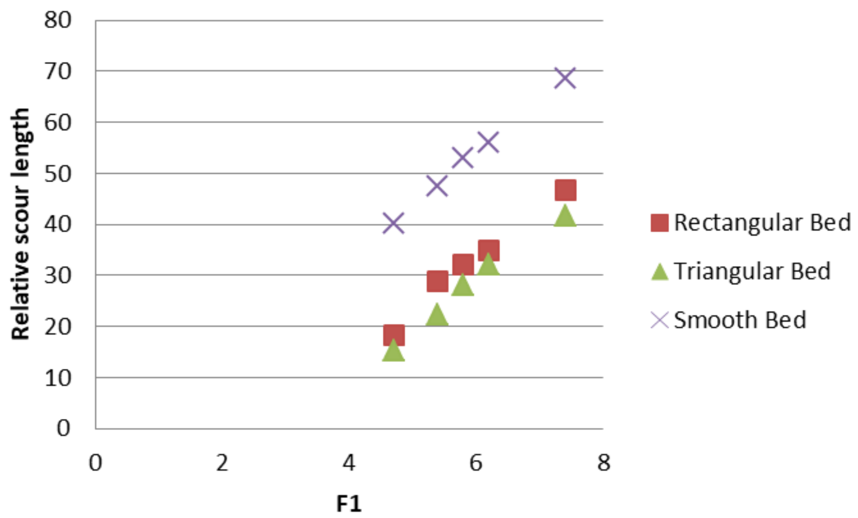

Fig.14 Variation of relative scour length with F_1

6. CONCLUSIONS

On the basis of experimental studies of hydraulic jumps on corrugated beds for the Froude numbers 4.7, 5.4, 5.8, 6.2, 7.4 of two different shapes rectangular and right angle triangular, the following conclusions are drawn. When compared to smooth beds the ratio of tail water depth to super critical depth which is needed to form a jump at any Froude number is noticeably small. When compared to the smooth beds the corrugated beds will have less relative scour length. The relative scour length in stepped rectangular corrugated beds is 41% reduced when compared to smooth beds. The relative scour length in right angle triangular corrugated beds is 49% reduced when compared to the relative scour length in smooth beds.

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NOTATION

The following symbols are used in this paper:

C_f = coefficient of skin friction;
D = dimensionless depth deficit parameter = $(y_2^* - y_2)/ y_2^*$;
F_1 = supercritical Froude number = $U_1/(gy_1)^{0.5}$;
L_j = Length of jump;
x = Longitudinal distance measured from section where jump starts;
Y = depth of flow;
y = distance from crest of corrugations;
y_t = tail water depth;
y_1 = supercritical initial depth of free jump;
y_2 = supercritical depth of jump on corrugated bed;
y_2^* = supercritical sequent depth of classical jump;
ε = shear force coefficient = $(F_1\text{-}1)^2$;

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