# Experimental Studies on Hydraulic Jumps over Corrugated Beds

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**Abstract:** ***A study of the effect of right-angled triangle and stepped rectangular shapes of corrugated beds on the characteristics of hydraulic jump is conducted. Experiments are performed for a range of the supercritical Froude numbers from 4.7 to 7.4. Two shapes of corrugations (right angled triangle and stepped rectangular) of the amplitude to wave length ratio of 0.6 are considered in the present study. It is found that, for two shapes of corrugated beds, the tail water depth required to form a jump is appreciably smaller than that for the corresponding jumps on smooth beds. The results of this study show the efficacy of corrugated beds for energy dissipation downstream hydraulic structures.***

**Keywords:** Open channel flow, Hydraulic jump, Energy dissipation, corrugated beds

## 1. Introduction

Hydraulic jumps have been widely used for energy dissipation downstream hydraulic structures. In hydraulic jump type energy dissipaters, the jumps are often formed with the assistance of baffle blocks and are kept inside the stilling basin is somewhat less than the sequent depth of the free jump [1]. 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 [1], [3] and [4]. If $y_1$ and $u_1$ are respectively, the depth and mean velocity of the supercritical stream just upstream of the jump, with a supercritical Froude number of $F_{r1} = u_1 / \sqrt{gy}$, where g is the acceleration due to gravity, the subcritical sequent depth $y_2^*$ is given by well-known Belanger equation

$$\frac{y_2^*}{y_1} = \frac{1}{2}\left[\sqrt{1+8F_{r1}^2}-1\right] \qquad (1)$$

A preliminary investigation by [5] indicated that, if the bed of the channel on which the jump formed is rough, the tail water depth $y_2$ required to form a jump could be appreciably smaller than the corresponding sequent depth $y_2^*$. For a relatively roughness of the bed in terms of the supercritical depth $y_1$ equal to 0.4, $y_2$ could be as small as 0.8 $y_2^*$, which is significant when it is realized that the tail water depths required for Peterka's Basins II and III in terms of $y_2^*$ are approximately 0.83 and 0.97, respectively. Reference [6] performed a laboratory study of hydraulic jumps on corrugated beds for a range of supercritical Froude numbers from 4 to 10 and three values of relative roughness from 0.25 to 0.5.

## 2. Experimental Arrangement and Detail of Experimental Tests

Experimental study is conducted in a horizontal rectangular flume, 0.45 m wide, 0.6 m deep and 17.00 m long. The channel is made up of steel structure and the sides are made of transparent Plexiglas sheet. 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 might increase the bed shear stresses. Two corrugated wooden sheets of shapes right-angled triangle corrugations is shown in Fig. 1 (a) and stepped rectangle corrugations is shown in Fig. 1 (b) with corrugations of wave length of 65 mm perpendicular to the flow direction and amplitude of 18 mm, respectively.

**Figure 1** (a) Right-angled triangle corrugations

(b) Stepped rectangular corrugations

The discharge through the flume is constant during each test run of 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. 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. Water enters into flume under a sluice gate with a streamlined lip, thereby producing a uniform supercritical stream with a thickness of $y_1$. A tailgate is used to control the tail water depth in the flume. In all the experiments, so that the jumps are formed some distance away from the gate for both right-angled triangle and stepped rectangular corrugated beds (see Fig. 2 (a) and 2 (b)).

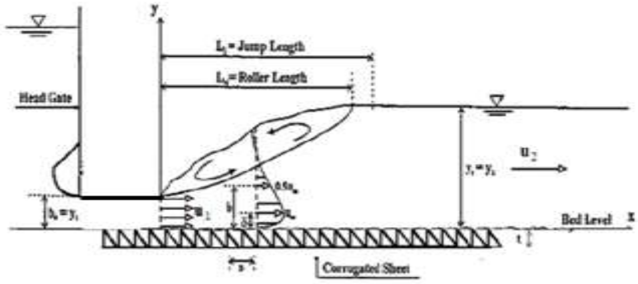

**Figure 2 (a)** Definition sketch for free jump on right-angled triangle corrugated bed

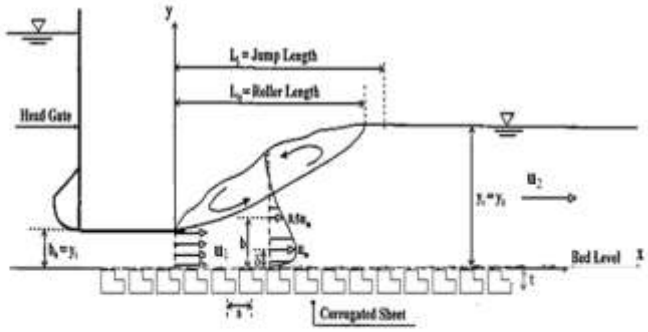

**Figure 2 (b)** Definition sketch for free jump on stepped rectangular corrugated bed

The experiments are conducted and the primary details of these experiments the values are given in Table 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 detail of corrugated beds

| Discharge ($m^3/s$) | Supercritical Froude number | Depth averaged velocity (m/s) | Supercritical depth (m) | Subcritical depth (m) | Subcritical sequent depth |
|---|---|---|---|---|---|
| Right-angled triangle corrugated beds | | | | | |
| 0.034 | 4.7 | 2.51 | 0.03 | 0.078 | 0.199 |
| 0.039 | 5.4 | 2.78 | 0.03 | 0.086 | 0.229 |
| 0.041 | 5.8 | 2.98 | 0.03 | 0.092 | 0.246 |
| 0.044 | 6.2 | 3.23 | 0.03 | 0.11 | 0.263 |
| 0.051 | 7.4 | 3.89 | 0.03 | 0.12 | 0.313 |
| Stepped rectangular corrugated beds | | | | | |
| 0.034 | 4.7 | 2.51 | 0.03 | 0.082 | 0.199 |
| 0.039 | 5.4 | 2.78 | 0.03 | 0.096 | 0.229 |
| 0.041 | 5.8 | 2.98 | 0.03 | 0.1 | 0.246 |
| 0.044 | 6.2 | 3.23 | 0.03 | 0.115 | 0.263 |
| 0.051 | 7.4 | 3.89 | 0.03 | 0.125 | 0.313 |

## 3. Experiment Results and Analysis

### 3.1 Water Surface Profiles

Figs. 3 (a) and (b) show the water surface profiles for the experiments of the jumps on the two corrugated beds, respectively. These water surface profiles are measured in the vertical centre plane of the flume with, a point gauge to an accuracy of ± 0.1 mm. These water surface profiles are used to determine subcritical depth $y_2$ at the end of the jump, which is defined as the section beyond which the water surface is essentially horizontal and length of jump $L_j$. Normalized water surface profiles are shown in Figs. 3 (c-d) where $(Y-y_1)/(y_2-y_1)$ is plotted against $x/L_j$, with $Y$ the depth of flow at any station x. Figs. 3 (c-d) show that the water surface profiles, for each type of corrugated beds, are approximately similar and can represented by one mean curve.

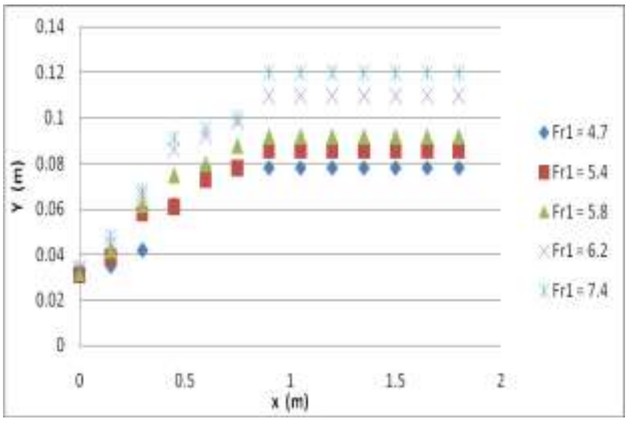

**Fig. 3** (a) Water surface profiles of jumps on right-angled triangle corrugated beds

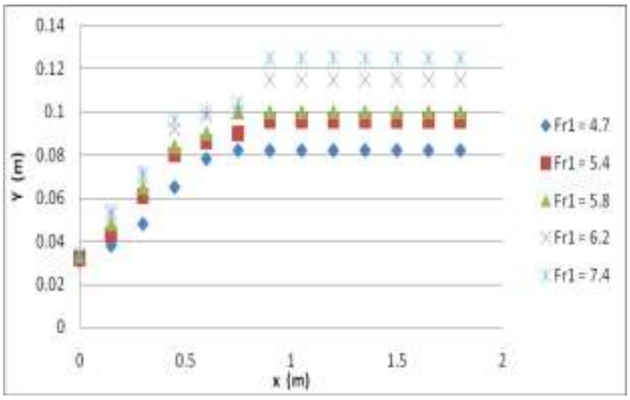

**Figure 3** (b) Water surface profiles of jumps on stepped rectangular corrugated beds

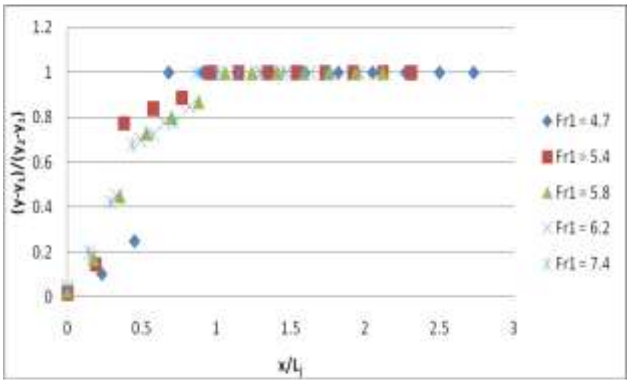

**Figure 3** (c) Normalized water surface profiles of jumps on right-angled triangle corrugated bed

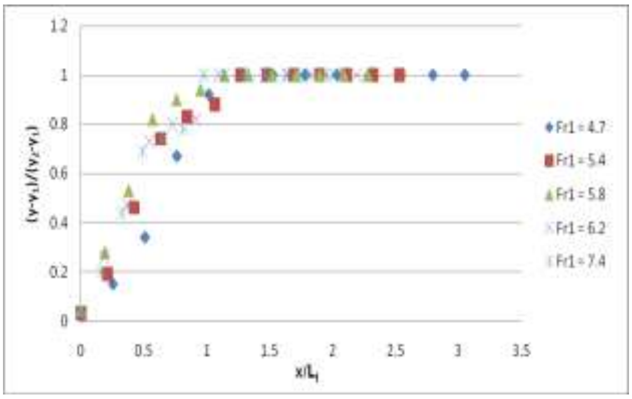

**Figure 3** (d) Normalized water surface profiles of jumps on stepped rectangular corrugated bed

### 3.2 Sequent Depth Ratio

For a hydraulic jump on a corrugated bed of amplitude, with a supercritical stream of depth and mean velocity, sequent depth of jump can be written be a function of

$$f\left(y_1, u_1, g, \rho, \upsilon, t, s\right) = 0 \qquad (2)$$

In which $g$ is the acceleration due to gravity $\rho$, $\upsilon$ are the density and viscosity of water, respectively. The dimensionless relationship expressed in the order

$$\frac{y_2}{y_1} = f\left(F_{r1} = \frac{u_1}{\sqrt{g y_1}}, R_1 = \frac{u_1 y_1}{\upsilon}, \frac{t}{y_1}, \frac{s}{y_1}\right) \qquad (3)$$

For all the experimental work, value of Reynolds number $R_1$ is greater than 25000. So, the effect of viscosity is considered to be neglected and then the values of Reynolds number can be eliminated from the analysis [7]. The experimental results are shown in Fig. 4 with $y_2/y_1$ plotted against supercritical Froude numbers for the two types of corrugated beds. It can be seen from Fig. 4 that the relative roughness and shapes of corrugations do not have significant effect on the depth ratio. To get an appreciation for the reduction in the tail water depth $y_2$ required to form a jump on corrugated bed in comparison with $y_2^*$ of corresponding to classical jump, let us define a dimensionless depth deficit parameter $D = \left(y_2^* - y_2\right)/y_2^*$ [3]. Fig. 4 shows the variation D with $F_{r1}$ for the two shapes of right angled triangle and stepped rectangular corrugated beds used in the experiments and results indicates that, the mean value of depth deficit factor of 0.28 and 0.34 for right-angled triangle and stepped rectangular corrugated beds, respectively.

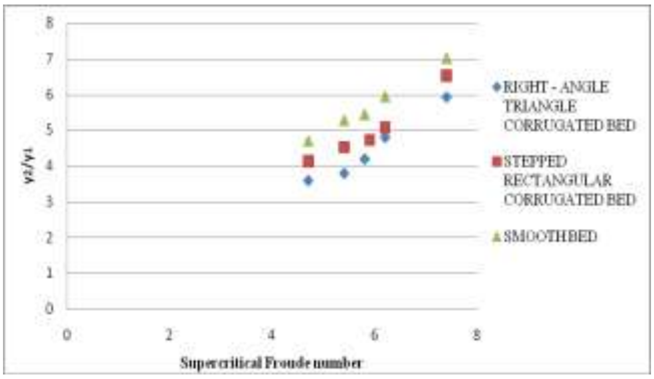

**Figure 4:** Variation of depth ratio $y_2/y_1$ with supercritical Froude numbers for corrugated and smooth beds

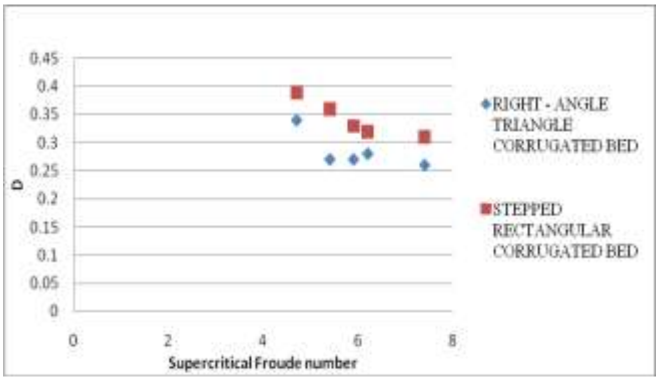

**Figure 5:** Variation of depth deficit factor with supercritical Froude numbers for corrugated beds

### 3.3 Bed Shear Stress

One of the main objectives of installed corrugated bed sheets is to increase bed shear stress, the sequent water depth and to increase length of the hydraulic jump. In the present section, the bed shear stress is expressed using momentum equation and is as follows

$$F_\tau = (p_1 - p_2) + (M_1 - M_2) \qquad (4)$$

Where $p_1$, $p_2$, are integrated pressures and $M_1$, $M_2$ are integrated pressures and momentum fluxes at sections prior and after the hydraulic jump, respectively. The shear force index $\in$ can be written as [3]

$$\in = \frac{F_\tau}{0.5\,\gamma\,y_1^2} \qquad (5)$$

Fig. 6 is plotted in order to show the relation between shear force coefficient $\in$ with supercritical Froude number.

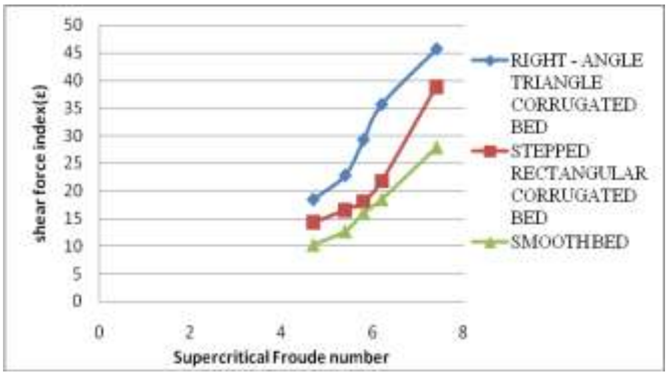

**Figure 6:** Variation of shear force coefficient $\in$ with supercritical Froude numbers for corrugated and smooth beds

## 4. Conclusions

The results of experimental study on hydraulic jump over corrugated beds and downstream local scour have been presented. The characteristics of hydraulic jumps in rectangular channels for two shapes, viz., right-angled triangle and stepped rectangular corrugated beds have been examined. Based on a laboratory study on hydraulic jumps over corrugated beds for a range of supercritical Froude numbers from 4.7 to 7.4, the results are presented in this chapter. The discussion and analysis of the results highlighted the following conclusions: For the Froude number ranges of 3.8 to 8.6, the relative energy loss for sinusoidal corrugated bed ranges from 62% to 82% as presented by [2], while, in the present study for right-angled triangle and stepped rectangular corrugated beds the relative energy loss ranges from 54.8% to 77.3% and 58.6% to 79.3%, respectively. For the supercritical Froude number ranges of 4 to 8 considered in the present study, the ranges of percentage reduction in length of the jump observed for right-angled triangle and stepped rectangular corrugated beds are 11% to 24% and 9% to 18%, respectively, which is much greater than that observed by [6] in case of sinusoidal corrugated beds are ranges from 8% to 16%. Shear stresses over the right-angled triangle and stepped rectangular corrugated beds are almost 16 and 10 times the corresponding shear stresses of smooth beds, respectively. So, right-angled triangle corrugated bed shape is observed to be performing better than the stepped rectangular corrugated bed shape.

### Notations

| | |
|---|---|
| B | Channel width |
| D | Dimensionless depth deficit parameter |
| $F_\tau$ | Integrated bed shear stress per unit width over jump length |
| $F_{r1}$ | Supercritical Froude number |
| g | Acceleration due to gravity |
| Lj | Length of the jump |
| $M_1$ | Momentum flux, per unit width, at section where jump starts |
| $M_2$ | Momentum flux, per unit width, at section where jump ends |
| $p_1$ | Hydrostatic force, per unit width, at section where jump starts |
| $p_2$ | Hydrostatic force, per unit width, at section where jump ends |
| $R_1$ | Reynolds number $R_1 = u_1 y_1 / \upsilon$ |
| S | Wave length of corrugations |
| t | Corrugation height from crest to trough |
| x | Longitudinal distance measured from section where jump starts |
| Y | Depth of flow |
| y | Distance from crest of corrugations |
| $y_1$ | Supercritical initial depth of free jump |
| $y_2$ | Subcritical depth of jump on corrugated bed |
| $y_2^*$ | Subcritical sequent depth of jump on classical jump |
| $\in$ | Shear force coefficient equal to $\in = F_\tau / 0.5\,\gamma\, y_1^2$ |
| $\in_1$ | Shear force coefficient equal to $\in_1 = F_\tau / M_1$ |
| ρ | Mass density of fluid |

## References

[1] A. J. Peterka, “Hydraulic design of stilling basins and energy dissipaters” Engineering Monograph No. 25, U.S. Bureau of Reclamation, Denver, 1958.

[2] Abbaspour A., Farsadizadeh D., Dalir A. H., and Sadraddini A. A. (2009). “Numerical study of hydraulic jumps on corrugated beds using turbulence models.” Turk. J. Eng. Environ. Sci., 33(1), 61–72.

[3] Ead S. A., and Rajaratnam N., (2002). “Hydraulic jumps on corrugated beds”. J. Hydraulic Eng. 128(7), 656-663.

[4] N. Rajaratnam, “Hydraulic Jumps” Adv. Hydrosi., 1967, 4, 197-280.

[5] N. Rajaratnam, “Hydraulic Jumps on corrugated beds” Trans. Eng. Inst. Canada. 1968, 11(A-2), 1-8.

[6] J. A. McCorquodale, “chapter 8: Hydraulic jumps and internal flows”. Encyclopedia of fluid mechanics, N. P. Cheremisinoff, ed., vol. 2, Gulf Publishing, Houston, 1986, 120-173.

[7] W. H., Hager, and R. Bremen, “Classical hydraulic jump, sequent depths”. J. Hydraul. Res., 1989, 27(5), 565-585.