

Characteristics of Hydraulic Jump on Corrugated Beds-A Review



Engineering

KEYWORDS : Hydraulic jump ;Corrugated bed; Energy dissipation; Sequent Depth Ratio.

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ABSTRACT

The paper presents a broad review of the available literature on the characteristics of hydraulic jump on different types of roughened or corrugated beds. The main objective of this study is to examine the potential use of roughened or corrugated beds for reducing the hydraulic jump length, roller length, sequent depth, to study the effectiveness of corrugated bed for energy dissipation below hydraulic structures and to study the bed shear stress. Hydraulic jumps are frequently used for excessive kinetic energy dissipation under hydraulic structures and the jumps are often generated with the assistant of baffle blocks and kept inside the stilling basin. Corrugated or roughened beds showed considerable energy dissipation at the downstream. The jump length and sequent depth also significantly reduced with respect to the smooth bed. Consequently, the use of corrugated and roughened beds reduced the scouring length and scouring depth as well as the stilling basin installation cost. The implementation of corrugated or roughened beds, and highlights their findings in different installation systems by many researchers are discussed in this paper. Comparison between different roughened shapes with different dimensions and spacing is also discussed. Finally, it is found that the applications of corrugated or roughened beds are always showed better performance than that of the smooth bed. In addition, some research needs for the future is identified by this study.

1. INTRODUCTION

Hydraulic jump occurs when a high velocity supercritical flow drops to that of a subcritical flow, the rapid following flow is abruptly slowed and increases its height, converting some of the kinetic energy into potential energy. The condition of occurrence of a hydraulic jump is to change flow suddenly from supercritical flow (low depth with high velocity) to subcritical flow (high depth with a low velocity), Chow. It occurs in a canal below a regulating sluice, at the toe of a spillway or at the place where a steep channel slope suddenly turns flat. However, some of the recent work defines this change as a transitory process where the supercritical state transforms into the subcritical in a finite distance or a "transition zone."

The study in this paper represents the results of various studies in which the hydraulic jump characteristics were measured in different channel bed conditions, and suggests future research directions. Numerous studies have been conducted to investigate the hydraulic jump characteristics considering the different bed conditions some equations have been developed to establish the relationship between different parameters of hydraulic jump. The available literature on the characteristics of hydraulic jump on different types of roughened or corrugated beds is as follows.

2. LITERATURE REVIEW

N.G.P.B.Neluwala, K.T.S. Karunanayake, K.B.G.M. Sandarwan and K.P.P. Pathirana

This research attempts to investigate the characteristics of hydraulic jumps formed on rough, horizontal channel beds under different flow conditions using laboratory investigations. A series of experiments were carried out in a rectangular flume which consists of artificially roughened beds formed by placing rectangular wooden strips in specific intervals. 140 experimental runs were conducted for rough channel beds covering the flow rates from 8 to 25 l/s. The hydraulic parameters such as, initial water depth, sequent water depth, and flow rate were measured for different bed roughnesses.

The analysis of experimental data showed that the rough bed reduces the distance to the jump from the gate and the sequent depth ratio than those on smooth beds while creating a high energy loss. With the availability of a large number of experimental data on hydraulic jumps over rough channel beds, mathematical formulations were developed to express the hydraulic jump characteristics relating roughness parameters such as; rough-

ness density and roughness height. A new parameter called 'roughness density' ($d = \text{width of roughness element} / \text{Spacing}$) was included into the analysis to represent the roughness spacing. Maximum effect of roughness elements occurred at a roughness density of 0.23. At this stage the sequent depth ratio reduced up to 34%

Mainly focussed on the parameter roughness density in this paper and concluded that for artificially roughened beds jump characteristics are function of Froude number, roughness height and roughness density.

Hossam Mohamed Ali Ahmed^a, Mohamed El Gendy^b, Ahmed Mohamed Hassan Mirdan^c, Abdel Azim Mohamed Ali^d, Fahmy Salah Fahmy Abdel Haleem^e

This paper presents a comprehensive review of the available literature on the hydraulic jump properties on corrugated beds. In the present study the effect of spaced triangular strip corrugated bed on submerged jump characteristics has been experimentally investigated. Thirty experimental runs were carried out considering wide range of Froude numbers ranging from 1.68 to 9.29. Experiments were conducted for both smooth and rough bed. The triangular corrugated sheet of 40-mm height and 40-mm width and with side angles of 45° is kept constant. Spacing considered between roughness elements were 4,8,12,16 and 20 cm. The results confirm that sequent depth and jump length were reduced by average values 15.14% and 21.03%, respectively, whereas, jump efficiency was increased by 50.31% at optimum spaced roughness compared to a classical jump respectively. The optimum spacing between corrugated bed sheets $S = 3t = 12$ cm. Dimensionless relationships were deduced to predict the jump characteristics. Results of the present study were agreed satisfactorily with the previous studies.

According to experimental analysis optimum spacing corrugated sheet gave better results than continuous corrugated sheet.

A. Abbaspour^{*}, A. Hosseinzadeh Dalir, D. Farsadzadeh, A.A. Sadraddini

In this paper hydraulic jump characteristics were studied experimentally over six sinusoidal corrugated beds with varying wave steepness, which had corrugation and Froude numbers in the range of 0.286-0.625 and 3.8-8.6, respectively. The effects of wave height and length of corrugation on the basic jump char-

acteristics, including free surface location, velocity, shear stress distribution and energy dissipation, were studied for a range of Froude numbers. The dimensionless hydraulic parameters were found to be a function of the Froude number. The results showed that the tail water depth and the length of the jump on corrugated beds are smaller than those of the corresponding jump on a smooth bed. The results showed that for a given supercritical depth, δ , and Froude number, F_r , the tail water depth of a jump on a corrugated bed is about 20% smaller than that on smooth beds in the range of Froude number 3.6–8.6 and wave steepness values 0.286–0.625. The analysis of velocity profiles at different sections in the jump showed that the velocity profiles were similar to those of a simple plane wall jet. The normalized boundary layer thickness d/b was equal to 0.57 for jumps on a corrugated bed, compared to 0.16 for the simple wall jet. The analysis and comparison of the bed shear force and shear stress coefficient showed that shear stress on a corrugated bed is about 10 times that of a smooth bed.

The results of this study are in good agreement with previous results and showed that corrugated beds can be used to dissipate the excess hydraulic jump energy in stilling basins. In this study, the values of the energy loss parameter for jumps on a corrugated bed were 5–19%, and for Froude Numbers more than 7, energy loss parameter was about 10%.

Farhad Izadjoo and Mahmood Shafai-Bejestan

In the present study the effect of trapezoidal shape corrugated bed on flow characteristics of hydraulic jump has been experimentally investigated. Flumes of 25 and 50 cm in width were used and total of 42 tests conducted. For wide range of Froude numbers ranging from 4–12 experiments were performed. Six values of 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 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%. And concluded that corrugating the stilling bed can decrease the cost of stilling basin.

In this study the length of the roller jump was found to depend largely on corrugate spacing than to their height. Although 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.

Ibrahim H. Elsebaie¹ and Shazy Shabayek²

In this paper the study of effect of different shapes of corrugated beds on the characteristics of hydraulic jumps was performed. Five shapes of corrugations (sinusoidal, triangular, trapezoidal with two side slopes and rectangular) of the same amplitude 18 mm and wavelength 65 mm were tested. Two values of relative roughness t/y_1 of 0.36 and 0.72 were studied. Experiments were performed for a range of the Froude number from 3 to 7.5. It was found that, for all shapes of corrugated beds, the tailwater depth required to form a jump was appreciably smaller than that for the corresponding jumps on smooth beds. The length of the jump on the different corrugated beds was less than half of that on smooth beds. The integrated bed shear stress on the corrugated beds was more than 15 times that on smooth beds. For the same amplitude and wavelength, it was found that the effect of the shape of corrugations is relatively small. The results of this study confirm the effectiveness of corrugated beds for energy dissipation below hydraulic structures.

As per study it seems that the dynamics of the boundary shear stress on corrugated beds and the factors affecting it are not completely understood and need further investigation so that

these differences would be properly explained.

Fahmy S. Abdelhaleem¹, Amin A. M.², and Helal Y. Esam³

In this research, an experimental study is conducted. The objective of this paper is to study the effect of corrugated beds of considered shapes (semi-circular, trapezoidal and triangular) on the characteristics of hydraulic jump and on the downstream deformed scour hole. Considering wide range of Froude numbers ranging from 2.0 to 6.5 Forty eight experimental runs were carried out. Five values of the relative roughness of corrugated shapes were investigated. A case of smooth bed is included to estimate the influence of corrugated beds on hydraulic jump parameters and the scour hole dimensions. The results obtained from experiment were analyzed and graphically presented and also, simple formulae are developed to estimate the hydraulic jump parameters and the scour hole dimensions. From experiments The required tail water depths for jumps over different semi-circular, trapezoidal and triangular corrugated beds is respectively, 86%, 85.5% and 82.6% of the same variable for jump over smooth bed. The semi-circular, trapezoidal and triangular corrugated beds reduce the length of jump by 10%, 11% and 14%, respectively. The relative energy loss for smooth bed ranges from 10% to 62%, while, for semi-circular, trapezoidal and triangular corrugated beds ranges from 14% to 64%, 15% to 65% and 16% to 66%, respectively.

The results of this study confirm the effectiveness of corrugated beds for energy dissipation downstream hydraulic structures and corrugating the stilling bed can decrease the cost of stilling basins.

Among the three investigated shapes, triangular shape is the best corrugated shape This gave better results.

G. Ezizah, N. Yousif and S. Mostafa.

In this paper experimental study was carried out for testing a new shape of roughness elements U shape and finding out the best intensity and length for that shape. From the experiments it was found that the best Roughness length = 18 and the best intensity $I \approx 12.5\%$ which gives minimum jump length, minimum relative depth. U shape roughness is better than the cubic shape from hydraulic point of view. U shape reduces the relative jump length by 28–47%, reduces the relative sequent depth of jump up-to 14–20%, compared with the smooth bed. From sensitivity analysis it was noticed that the change in the length of jump is more sensitive to the change in intensity rather than the change in roughness length by increasing the values of I or / above their optimal values. But the change in the length of jump is more sensitive to the change in roughness length rather than the change in intensity by decreasing the values of I or / under their optimal values.

In this study mainly concentrated on two main parameters, Intensity of roughness and relative roughness length. And focused on sensitivity analysis also.

M. Shafai Bejestan and K. Neisi

In this study a new roughened bed hydraulic jump stilling basin is introduced. In this experiment the basin floor covers with cubic rough element. Study was performed in order to investigate the effects of jump on the characteristics of stilling basins. On the bed of the flume downstream of ogee spillway rough elements are glued in such a way that the incoming water jet is just above the element surface. Under different Froude numbers ranging from 4.5 to 12 each rough element shape was tested. During each test the water surface profile, the roller jump length and the jump length were measured and the longitude and vertical flow velocity were also measured in some tests. The experimental results indicate that the presence of a rough element can increase the shear force and reduce the jump length and

sequent depth of flow. the reduction of the required tail water depth is about 26% and the hydraulic jump length is reduced about 41%. Comparison of the results with the previous studies shows that using the new roughened (lozenge roughness) bed the length of the basin can be decrease as low as 40% of the regular basins. At last it is also suggested that more tests on large scale model should be conducted before any field application.

The dimensions of the new basin (lozenge roughness) found to be smaller than the existing basins.

S. A. Ead, M.ASCE¹, and N. Rajaratnam, F.ASCE²

In this paper laboratory study of hydraulic jumps on corrugated beds is performed and results are presented. By considering a range of Froude numbers from 4 to 10 experiments were performed. Three values of the relative roughness /of 0.50, 0.43, and 0.25 were studied. It was found that the tailwater depth required to form a jump was appreciably smaller than that for the corresponding jumps on smooth beds and the length of the jumps was about half of those on smooth beds. The integrated bed shear stress on the corrugated bed was about 10 times that on smooth beds. The axial velocity profiles at different sections in the jump were found to be similar, with some differences from the profile of the simple plane wall jet. The maximum velocity at any section in terms of the velocity of the supercritical stream was correlated with the longitudinal distance *x* in terms of *L*, which is the distance where =0.5, and this relation was the same as that for jumps on smooth beds with the difference that /was much smaller for jumps on corrugated beds. The normalized boundary layer thickness *d/b*, where *b* is the length scale of the velocity profile, was equal to 0.45 for jumps on corrugated beds compared to 0.16 for the simple wall jet. The results of this study show the attractiveness of corrugated beds for energy dissipation below hydraulic structures.

In this paper mainly focussed on the relative roughness and properties are studied. Before using this idea in practice it is useful to perform experiments to evaluate the effect of / over a larger range and the effect of the wavelength of the corrugations.

Mohammad Javad Nasr Esfahani¹ and Mahmood Shafai Bejestan²

The aim of the present paper is to study the effect of roughened bed on flow characteristics of hydraulic jump at abrupt drop. This study was conducted to evaluate the performance of two types of roughness height on the characteristics of a hydraulic jump on an abrupt drop..Total of 75 tests conducted in a wide flume of 80 cm in width and 15 meter long. Experimental tests were performed for wide range of Froude numbers ranging from 3.03 to 11.68. The experimental results show that roughening bed of stilling basin can reduce the jump length as much as about 40%. The results reported in this paper may be helpful in the design of a stilling basin with a negative step and rough beds.

In this study the intensity of roughness concentration I was kept constant. For abrupt jump of roughened bed basin no study can be found in the literature since this study was conducted. The present study is concerned with the installation of cubic roughness placed regularly on the bed, at an abrupt drop. On abrupt drop also better results are obtained.

3. HYDRAULIC JUMP PROPERTIES/ CHARACTERISTICS

In general, hydraulic jump characteristics on a corrugated bed are dependent on fluid properties, bed dimensions and hydraulic state of flow.

3.1 Sequent Depth Ratio

Tail water depth () and Hydraulic jump length (L_j) over corrugated and roughened beds mainly depend on the upstream flow

characteristics, such as flow velocity (), flow depth (), fluid density (ρ), fluid viscosity (μ), acceleration of gravity (g), bed corrugation and roughened amplitude (t), wavelength of corrugations, s. Thus, the jump length or sequent depth of the jump can be written as a function of:

$$y_2 \text{ or } L_j = f(V_1, y_1, g, \mu, \rho, t, s) \text{-----(1)}$$

If y₁, g and ρ are considered as three repeated variables, and by applying the Pi theorem, Equation (1) can be written in the following form as Equation (2):

$$y_2/y_1 \text{ or } L_j/y_2 = f(F_1 = V_1/\sqrt{gy_1}, R_o = V_1y_1/\mu, t/y_1, s/y_1) \text{-----(2)}$$

where and are the Froude number and Reynolds number, respectively, at the upstream of the hydraulic jump. For a large Reynolds number, if the viscous force is neglected (Rajaratnam, 1976; Hager and Bremen, 1989), then the final expressions of sequent depth or length of the jump can be written as Equation (3):

$$y_2/y_1 \text{ or } L_j/y_2 = f(F_1, t/y_1, s/y_1) \text{-----(3)}$$

The difference between sequent depth and sequent depth of classical jump () have been investigated by some researchers using the following Equation (4):

$$D = \frac{y_2^2 - y_1^2}{y_2^2} \text{-----(4)}$$

where D is the dimensionless index.

For a typical jump formed on a smooth bed in a rectangular channel, the conservation of momentum between upstream and downstream sections of the jump and satisfaction of flow continuity leads to the reputed Belanger equation (Chow, 1959; Rajaratnam, 1967):

$$\frac{y_2}{y_1} = \frac{1}{2}(\sqrt{1 + 8F_1^2} - 1)$$

y₂^{*} is the subcritical depth
 y₁ is the supercritical depth
 F₁ is the Froude number of the supercritical flow

Relation between relative sequent depth y₂/y₁ and Froude number . F₁
 Relation between depth dimensionless index, D and F₁ .

3.2 Jump length ratio

In order to determine the length of the jump, L_j, in the experiments, a non-dimensionalized length L_j/y₂ was used, where y₂ is the calculated value of the sequent depth.

$$L_j/y_2 = f(F_1 = V_1/\sqrt{gy_1}, R_o = V_1y_1/\mu, t/y_1, s/y_1)$$

Relation between and studied and plotted.
 Relative jump length (L_j/y₂) is measured and plotted graph of (L_j/y₂) vs F₁

Peterka (1958), reported the relative length of the jump for a considerable range of upstream Froude numbers as follows:

$$\lambda_j = 220 \tanh \left[\frac{F_1 - 1}{22} \right], 4 < F_1 < 12$$

or, simply:
 L_j = 6y₂
 Where,
 λ_j is the relative length of the jump
 L_j is the length of the jump
 y₂^{*} is the sequent depth of y₁

3.3 Bed shear stress

Corrugated and roughened beds are generally installed on the channel bed for increasing the bed shear stress, which, consequently, reduces the sequent depth and hydraulic jump length. The bed shear stress of a jump on a corrugated bed is obtained by using the integral momentum equation. The following momentum equation is frequently used to calculate the bed shear stress:

$$F_{\tau} = (P_1 - P_2) + (M_1 - M_2)$$

Where P_1, P_2, M_1 and M_2 are the integrated pressure and momentum at the sections prior and after the hydraulic jump occur. The shear force index is calculated using Equation (6) as follows (Rajaratnam, 1965):

$$\varepsilon = \frac{F_{\tau}}{0.5\gamma y_1^2}$$

where γ is unit weight of water. Variation of ε with Fr_1 is plotted.

3.4 Energy dissipation

Although momentum is conserved throughout the hydraulic jump, the energy is not. Large amount of energy is dissipated in a hydraulic jump due to eddy and secondary wave formation. Hydraulic jump has been accepted as the most effective and efficient method of dissipating energy for water flowing over a barrage or spillway.

The amount of dissipated energy per unit weight of a fluid flow in a smooth channel can be expressed as follows

$$E_L = E_1 - E_2 = \left(y_1 + \frac{q^2}{2gy_1^2} \right) - \left(y_2 + \frac{q^2}{2gy_2^2} \right) = \frac{(y_2 - y_1)^3}{4y_1y_2}$$

For similar Froude numbers the energy loss of a jump on a corrugated bed is greater than that on a smooth bed. The energy loss parameter, G , was defined by the following equation (Tokay, 2005):

$$G = \frac{E_L - E_L^*}{E_L^*} \times 100$$

where E_L^* and E_L are the energy loss in a classical jump on smooth and corrugated beds, respectively, with a similar supercritical depth y_1 and Froude number Fr_1

The efficiency of the hydraulic jump (η) can be expressed as $\eta = (E_2/E_1) \%$ where E_1 and E_2 are the energies before and after the jump.

Relative loss energy E_L/E_1 and F_{r1} are studied.

Relation between jump efficiency η and F_{r1} is studied by plotting graph.

4. CONCLUSIONS

According to the review of the hydraulic jump properties considering different channel bed condition the following major conclusions can be represent:

- Corrugated bed increases bed shear stress so it always shows better performance than a smooth bed channel in reducing hydraulic jump length and sequent depth.
- The hydraulic jump length reduction and sequent depth reduction mainly depended on Froude number. For smaller values of Froude numbers the amount of reduction is low while it increases with larger values of Froude numbers.
- The present study confirmed the effectiveness of corrugated beds for energy dissipation downstream the hydraulic structures.
- It reduces the cost of the stilling basin.
- To investigate the effect of the change of intensity and roughness length parameters on the hydraulic jump length, the sensitivity analysis was carried out in few studies but more investigations are required in this regard.
- It is suggested that more tests on large scale model should be conducted before any field application.

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