A Review of Hydraulic Jump Properties in Different Channel Bed Conditions

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Abstract: The main objective of this study is to investigate the potential use of corrugated and roughened beds for reducing the hydraulic jump length and sequent depth. The paper presents a comprehensive review of the available literature on the hydraulic jump properties including different types of corrugated and roughened beds. 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 and 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. This paper discusses the implications of corrugated and roughened beds, and highlights their findings in different installation systems by many researchers. Finally, it is found that the applications of corrugated and roughened beds are always showed better performance than that of the smooth bed. In addition, this study identified some research needs for the future.
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1. Introduction

The hydraulic jump is a common phenomenon in the branch of hydraulics, which is generally observed in open channel flow, such as rivers and spillways. 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 flow's initial kinetic energy into an increase in potential energy. This phenomenon is called the hydraulic jump. The study of hydraulic jump has been going on for around two centuries. The first investigation was carried out by Bidone (1819). Thereafter, the subject continued to receive more attention and a tremendous amount of experimental as well as theoretical work was done by many eminent hydraulicians with regard to free hydraulic jump on horizontal beds. Hydraulic jumps are frequently used for energy dissipation in the case of hydraulic structures. A jump formation in the wide rectangular and horizontal channel with smooth bed conditions is called classical jump, and has been widely investigated (Peterka, 1958; Rajaratnam, 1967; McCorquodale, 1986; Hager, 1992). A wide range of investigation was conducted to evaluate the effectiveness of roughened beds (Rajaratnam, 1968; Hughes and Flack, 1984; Hager, 1992; Alhamid, 1994; Ead et al., 2000) and corrugated beds (Ead and Rajaratnam, 2002; Izadjoo and Shafai-Bajestan, 2005) considering different conditions for reducing the sequent depth and hydraulic jump length. Mohamad Ali (1991) conducted a series of experiments to study the effect of roughened beds using cube blocks and found that the length of hydraulic jump reduced by around 27 to 67% for a Froude number range of 4 to 10. Another study was carried out by Pagliara (2008) for homogeneous and non-homogeneous roughened bed channels, and a jump equation that accounted for bed roughness and non-homogeneity. The generalized solution was proposed by Carollo et al. (2009) for the sequent depth ratio of hydraulic jump over smooth and roughened beds introducing a coefficient of shear force in the momentum equation. This study represents the results of various studies in which the hydraulic jump characteristics were measured in different channel bed conditions, and suggests future research directions.

2. Hydraulic Jump Properties

2.1. Sequent Depth Ratio

Hydraulic jump length (L_j) and tail water depth (y_2) over corrugated and roughened beds (Figure 1) mainly depend on the upstream flow characteristics, such as flow velocity (V_1), flow depth (y_1), fluid density (ρ), fluid viscosity (μ), acceleration of gravity (g), bed corrugation and roughened amplitude (t), and shape of the corrugated bed (ζ). Thus, the jump length or sequent depth of the jump can be written as a function of:

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

If y_1, 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):

$$y_2/y_1 \text{ or } L_j/y_2 = f(F_1 = V_1/\sqrt{gy_1}, R_e = V_1 y_1/\mu, t/y_1, \zeta) \ldots (2)$$

where F_1 and R_e 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):

$$\frac{y_2}{y_1} \text{ or } L_j/y_2 = f(F_1, t/y_1, \zeta) \ldots\ldots\ldots\ldots (3)$$

The magnitude of L_j/y_1 and y_2/y_1 increased with the initial Froude number, while the value of L_j/y_1 and y_2/y_1 decreased for all Froude numbers with the increased value of I at 12.5% (I is the ratio between the area of roughness and the area of basin), and then started to increase for larger values of I (Ezizah et al., 2012). Their study also found that the sequent depth reduced by 14 to 20% with respect to the smooth bed. The variations of sequent depth ratio (y_2/y_1) for the different Froude numbers were studied using a corrugated bed. The investigated results showed that the relative roughness and shape of corrugation had very little significant effect on the sequent depth ratio (Izadjoo and Shafai-Bajestan, 2005; Ead and Elsebaie, 2009). Carolo et al. (2009) conducted a study over the natural roughened bed. Different sizes of cobbles, ranging from 0.46 to 3.2 cm, were used and the Froude number ranges laid from 4 to 12. Their results showed that the roughened bed was more effective for reducing the jump length and sequent depth ratio, in which the reduction depends on both relative roughness (t/y_1) and the Froude number. The difference between sequent depth y_2 and sequent depth of classical jump (y_2^*) have been investigated by some researchers using the following Equation (4):

$$D = \frac{y_2^* - y_2}{y_2^*} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where D is the dimensionless index. Five shapes – sinusoidal, triangular, two trapezoidal and rectangular corrugated beds indicated that the D value was constant at approximately 0.37. The sequent depth ratio (y_2/y_1) was found to be around 88% of the initial Froude number. The results confirm that the shape of corrugation and their relative height (t/y_1) had less significant effect on the hydraulic jump characteristics (Elsebaie and Shabaye, 2010). Abdelhaleem et al. (2012) found that the D values were 0.14, 0.145 and 0.174 for the semi-circular, trapezoidal and triangular corrugated beds, respectively. The results indicated that the tail water depths were, respectively, 86%, 85.5% and 82.6%, of the same variable for the jump over the smooth bed. These results were similar to the findings of Peterka (1958), who carried out an experiment for a stilling basin and obtained D values 0.17 and 0.21 for trapezoidal and triangular corrugated beds, respectively. For the triangular corrugated bed, Ead and Rajaratnam (2002) found the D value 0.25, while Izadjoo and Shafai-Bajestan (2005) obtained a value of 0.20. Thus, it is clear that the triangular corrugated bed was the best shape for reducing the tail water depth.

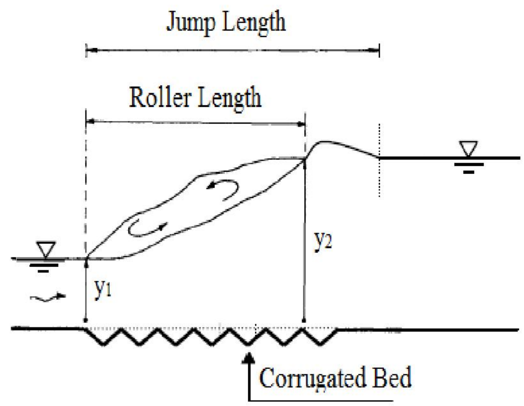

Figure 1: Typical hydraulic jump over corrugated bed

2.2. Jump Length

The corrugated and roughened beds have a significant effect on reducing the hydraulic jump length, as shown in Figure 1. The relationship between the dimensionless length of jump Lj/y_2 and initial Froude number has been established considering different bed conditions. The semi-circular, trapezoidal and triangular corrugated beds reduced the jump length by around 10%, 11% and 14%, respectively (Abdelhaleem et al., 2012). The U-shape corrugated bed reduced the jump length by around 28 to 47% compared to the smooth bed for the range of Froude numbers 3 to 11 (Ezizah et al., 2012). It also showed that the corrugated beds had little effect on the jump length when the Froude number was less than three ($F_1 \leq 3$). Their study result corresponded well with the findings of Elevator ski (1959). In another investigation that was carried out over a roughened bed using T-shape blocks (Aboulatta et al., 2010), the results indicated that a T-shaped roughened bed can reduce the jump length and materials compared to that of the cubic block. A U- shaped roughened bed is more effective in appreciably reducing the jump length and sequent depth compared to the T-shaped roughened bed for Froude number five, even though the difference is small for Froude numbers greater than five (Ezizah et al., 2012). The length of hydraulic jumps over corrugated and roughened beds are always smaller than for the smooth bed.

2.3. 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 following momentum in Equation (5) is frequently used to calculate the bed shear stress:

$$F_\tau = (P_1 - P_2) + (M_1 - M_2) \quad (5)$$

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 (ε) is calculated using Equation (6) as follows (Rajaratnam, 1965):

$$\varepsilon = \frac{F_\tau}{0.5 \gamma y_1^2} \quad (6)$$

where γ is the kinematics viscosity of water. The bed shear stresses over the semi-circular, trapezoidal and triangular corrugated beds were around 8, 9 and 11 times that of the smooth bed (Abdelhaleem et al., 2012; Izadjoo and Shafai-Bajestan, 2005). The hydraulic jump characteristics were also investigated over corrugated beds for variable wave steepness and a Froude number range of 3.8 to 8.6 in which the results showed that the shear stress for the corrugated bed was around 10 times that of the smooth bed (Abbaspour et al., 2009). The corrugated bed also had a significant effect on reducing the ratio of energy ($\Delta E/E_1$) by increasing the bed shear stress. The ranges for relative loss of energy ratio for semi-circular, trapezoidal and triangular corrugated beds were found to be from 14% to 64%, 15% to 65% and 16% to 66%, respectively, while the smooth bed ranges were found to be from 10% to 62% (Abdelhaleem et al., 2012). Similar results were found in the study by Chow (1959). The corrugated beds were effective for energy dissipation downstream hydraulic structures and can reduce the cost of stilling basins (Abdelhaleem et al., 2012; Ezizah et al., 2012; Shafai-Bajestan and Neisi, 2009). It was found that triangular and U-shape corrugated beds were most effective in reducing the jump length and sequent depth.

2.4. Scour Depth and Length

The depth and length of scouring can be significantly reduced by providing the corrugated bed at the downstream bed channel. Maximum scour hole depth (D_s) and scour length (L_s) are dependent on the variables in Equation (7), as follows (Abdelhaleem et al., 2012):

$$Ds / y_1 \text{ or } Ls / y_1 = f\left(F_1, \frac{y2}{y1}, \frac{Lj}{y1}, \frac{t}{y1}\right) \quad (7)$$

The semi-circular, trapezoidal and triangular corrugated beds decreased the ranges of scour depth from 22% to 31%, 25% to 34% and 30% to 36%, respectively, while the scour length decreased the ranges from 17% to 24, 23% to 25% and 24% to 30%, respectively, in comparison with the smooth bed (Abdelhaleem et al., 2012). Based on their experimental data and statistical methods, several models were proposed and their coefficients were calculated. Considering all the trials, the best Equations (8 and 9) for predicting the relative scour depth and length can be written in the following form, respectively:

$$Ds/y_1 = 1.51F_1 + 0.793\frac{y2}{y1} + 0.115\frac{Lj}{y1} + 2.571\frac{t}{y1} - 0.33 \quad (8)$$

$$Ls/y_1 = -17.55F_1 + 8.05\frac{y2}{y1} + 1.19\frac{Lj}{y1} + 51.79\frac{t}{y1} \quad (9)$$

2.5. Roller Length

The roller length (L_r) is the horizontal distance between the toe section of the flow depth y_1 and the roller end, as shown in Figure 1. This length can be estimated by a visualization technique, such as with a float to localize the stagnation point. The experimental studies (Pietrkowski, 1932; Hager, 1992 and Smetana, 1937) suggested that the relation between the roller length and differences between the sequent depths can be written as the following Equation (10):

$$Lr / y_1 = a\left(\frac{y2}{y1} - 1\right) \quad (10)$$

where 'a' is the coefficient, and the suggested values are 6 (Smetana, 1937), 5.5 (Citrini, 1939) and 5.2 according to Mavis and Luksch (Hager et al. 1990). Equation (10) was verified using the roller length data for the smooth and rough beds by many investigations with the coefficient value 'a' depending on bed roughness (Hager et al., 1990; Hughes and Flack, 1984; Ead and Rajaratnam, 2002 and Carollo and Ferro, 2004) based on the roller length data for the rough and smooth beds. Moreover, Carollo and Ferro (2004) also established the applicability of the following relationships as Equations (11) and (12):

$$Lr / y_1 = a_o \left(\frac{y1}{y2}\right)^{1.272} \quad (11)$$

$$Lr / y_1 = b_o (F_1 - 1) \quad (12)$$

where a_o, b_o are the numerical coefficients depending on the bed roughness.

3. Future Research Directions

Numerous studies have been conducted to

investigate the hydraulic jump characteristics considering the different bed conditions. Different types of corrugated and roughened bed channel have been used to identify the efficiency of reduction of the hydraulic jump length and sequent depths. Moreover, some equations have been developed to establish the relationship between different parameters of hydraulic jump. In addition, further studies can be conducted to investigate the better performance of the corrugated bed channel to control the hydraulic jumps. In this context, some research gaps have been identified for future research on the hydraulic jump properties in respect of different bed conditions.

- Factors affecting the dynamics of the boundary shear stress over corrugated beds can be further investigated.
- The effect of larger size boulders used as a roughened bed material can be investigated for hydraulic jump properties.
- Future studies can be carried out to evaluate the hydraulic jump characteristics on sloping bed conditions.
- A new circular shape corrugated bed channel is proposed for further study to investigate the hydraulic jump characteristics.
- Although sensitivity analysis has been carried out in several studies to investigate the effect of the change of intensity and roughness length parameters on the hydraulic jump length, intensive investigations are needed in this regard.
- More extensive investigations are recommended to determine the detailed information concerning the effects of boundary roughness on hydraulic jump.

4. Conclusions

The following prominent conclusions can be depicted from the review of the hydraulic jump properties considering different channel bed conditions:

- A corrugated bed always showed better performance than a smooth bed channel in reducing hydraulic jump length and sequent depth by increasing bed shear stress.
- Generally, corrugated bed produced more eddies, and, consequently, increased the bed shear stress, which reduced the jump length and sequent depth.
- The hydraulic jump length and sequent depth are significantly reduced by bed shear stress, which is dependent on the interaction between the supercritical flow of liquid and the corrugations of the channel bed.
- Among the semi-circular, rectangular, trapezoidal and triangular corrugated beds, the most efficient corrugated bed was the triangular shaped for reducing the sequent depth and jump length. Conversely, it showed the best effectiveness for increasing the bed shear stress.
- The reduction in jump length and sequent depth greatly depended on the Froude number. For small Froude numbers the amount of reduction was low while large value Froude numbers showed a higher reduction.
- Corrugated beds confirmed the effectiveness for energy dissipation at downstream hydraulic structures and reduce the cost of the stilling basin.
- Boundary resistance greatly depended on the Reynolds number and Froude number according to the findings of the smooth bed channel flow characterized by large Froude numbers.

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