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Hydraulic Jumps on New Roughened Beds

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ABSTRACT

Appurtenances are used downstream of hydraulic structures to reduce the length of the stilling basin which should be long enough for the flow pattern to regain its normal behavior and prevent the scour and erosion downstream those structures. 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. A comparison between the U-shape and other roughened shapes showed that the best performance is achieved when using the U-shape roughness. Sensitivity analysis was performed to investigate the effect of change of intensity and roughness length parameters on the hydraulic jump length.

Key words: Energy dissipater, hydraulic jump, roughened bed, stilling basin

INTRODUCTION

The design of the optimal stilling basin requires that the basin satisfies the required efficiency from the hydraulic and economical point of view. Many investigations were conducted in order to study the hydraulic performance of stilling basins (Ali, 1991; Chaurasia, 2003; Goel, 2007; Riad, 2008). Also, many researchers carried out experimental works for increasing the turbulence through the hydraulic jump by using cubic roughness placed on the bed in order to minimize the hydraulic jump length and consequently the stilling basin length.

Mahmoud (1984) and Abdelsalam *et al.* (1986) found that the optimum bed roughness intensity of cubic shape is 10% from both the hydraulics and economical point of view. Aboulatta (1986) used the previous intensity to study the effect of location and length of roughened beds on flow characteristics. It was found that the values of the relative bed roughness length $L_r / Y_1 = 15$ and the relative jump position $L_b / Y_1 = 4.5$ provide best flow characteristics for the jump, (L_r is the roughness length and I_b is the location of roughness with respect to the gate). Abdelsalam (1988) studied the effect of the height of cubic roughness on flow characteristics using roughness intensity = 10%, length = 15 Y_1 and located at distance = 4.5 Y_1. It was found that the best ratio for the best height was $r / Y_1 = 0.4$ to 0.5 for the observed Froude numbers from 4 to 8 where r is the height of bed roughness. Ali (1991) used cubic roughness with intensity = 10% in his study. He found that the best ratio between roughness length and the height of the blocks is equal to 28. Moreover, Alhamid (1994) conducted experiments on a rough bed using cubic blocks. He concluded that 12% roughness intensity provided the optimal length of the basin for the flow conditions and roughness arrangement under consideration.

Negm (2002) collected very large series of experimental data and used it to develop design equations for the optimal rectangular stilling basin with cubic roughness elements. Also, equations for the sequent depth ratio of hydraulic jump over rough beds have been developed by many researchers (Alhamid and Negm, 1996; Carolo *et al.*, 2009).

Some researches dealt with other shapes of bed roughness. Hughes *et al.* (1984) conducted experiments using two strip roughness test beds and three densely packed gravel test beds. Also, Carolo *et al.* (2007) measured the hydraulic jump characteristics on bed roughened by closely packed crushed gravel particles cemented to the bottom. Their observations showed that boundary roughness reduces both the sequent depth and the length of a hydraulic jump and that the observed reductions were related to both Froude number and the degree of roughness.

Bejestan and Neisi (2009) studied the effect of lozenge roughness shape on the hydraulic jump. They found that this shape reduces the tail water depth by 24% and the hydraulic jump length by 40% compared with the smooth bed.

Aboulatta *et al.* (2011) conducted experiments on a rough bed using T-shape blocks. They deduced the best intensity and roughness length. Also, they concluded that T-shape roughness saves materials and reduces the jump length compared to the cubic one.

There have been many experimental studies on the effect of corrugated beds on physical parameters of hydraulic jump. Ead and Rajaratnam (2002) studied the effect of round corrugated bed on hydraulic jump. Their results indicated that the sequent depth decreases 20% and the hydraulic jump length decreases 50%. Also, they found that the bed shear stress on the corrugated bed was about ten times that on smooth bed. Further, Tokyay (2005) supported their results. Izadjoo and Shafai-Bejestan (2007) used trapezoidal shape corrugated bed in their study. They confirmed the results of Ead and Rajaratnam (2002) and added that the jump length is more dependent on the wave length of corrugations than their amplitude. Elsebaie and Shabayek (2010) used five different corrugated beds in their study. They concluded that the shear stress on corrugated beds is independent of the shape of corrugation.

It is impractical to reproduce most of the roughness elements in nature, except small size cubes or blocks. Gravel beds require binding with cementing material to hold the material intact against high velocity flow. Strips are difficult to construct and maintain. Although, corrugations are similarly difficult to construct in concrete and maintain. The concrete of the panel is provided with appropriate reinforcement. This type of construction is difficult with corrugations at the top. An alternative is fixing steel plates with the desired corrugations on the concrete base, but a problem of seepage of flow beneath the plates will emerge which would lead to a dynamic uplift peeling of the plate itself. The only practical way of construction would be with small size cubes or blocks that can be cast along with the base concrete of the panel (Khatsuria, 2009).

The present experimental research aims at improving the efficiency of the stilling basins using a new shape of roughness elements (U-shape) and finding out the best intensity and length for the used shape.

THEORETICAL APPROACH

By using the dimensional analysis the general function representing the considered phenomenon can be written as follows:

$$\phi_1(L_j, Y_1, Y_2, q, L_b, \rho, \mu, L_r, I) = 0 \qquad (1)$$

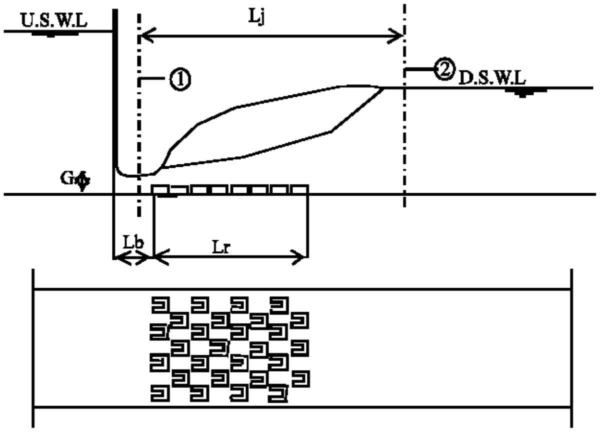

Fig. 1: Sketch of the hydraulic jump over the stilling basin

In which, L_j = length of hydraulic jump; Y_1 = initial water depth; Y_2 = sequent water depth; q = discharge per unit width of the flume; L_b = distance from the gate to the beginning of the roughness; ρ = mass density; μ = dynamic viscosity; g = gravitational acceleration; L_r = length of roughness; I = intensity of roughness as shown in Fig. 1.

Applying Buckingham's π Theorem and taking L_r, ρ and q as the repeating variables (main magnitudes), the above terms may be arranged in the following dimensionless relationship:

$$\phi_2(Y_2 / Y_1, L_j / Y_1, L_b / Y_1, F_1, R_N, L_r / Y_1, I) = 0 \tag{2}$$

In the present study viscous effects may be neglected, because the viscous force almost has no effect in open channel study with respect to the gravitational force expressed by Froude number.

During determination of the intensity (I), the roughness length L_r and L_b were constants and equal to 90 cm and 6 cm respectively so Eq. 2 can be written as:

$$\frac{Y_2}{Y_1} \text{ or } \frac{L_j}{Y_1} = \phi_3(O, F_1) \tag{3}$$

On the other hand, during the determination of the roughness length L_r, the intensity I and L_b were constants and equal to 12.5% and 6 cm respectively, so Eq. 2 can be written as follows:

$$\frac{Y_2}{Y_1} \text{ or } \frac{L_j}{Y_1} = \phi_4\left(\frac{L_r}{Y_1}, F_1\right) \tag{4}$$

EXPERIMENTAL SETUP

The experimental work of the present study was investigated in the hydraulic laboratory of the faculty of Engineering in Ain Shams University. A plexiglass, re-circulating, tilting channel of rectangular cross section was used. The channel is 15.3 cm wide, 30 cm deep and 245 cm long with transparent sides which facilitate the direct observation of the flow. A vertical gate with a sharp beveled lower edge fixed at the inlet section was used to control the upstream flow depth. The

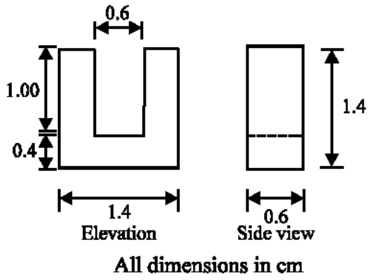

Fig. 2: Roughness dimensions

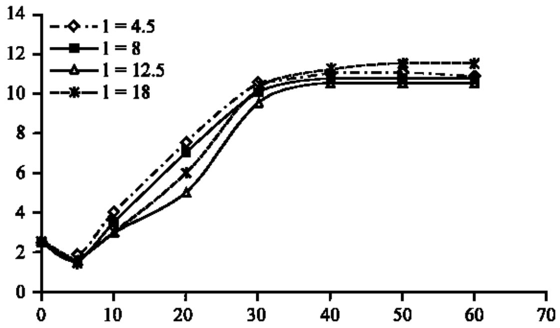

Fig. 3: Water surface profile at Q = 4100 $cm^3 sec^{-1}$, G = 2.5 cm with different intensities

downstream depth was adjusted by means of a tilting gate located at the end of the flume. The water depths were measured by means of point gauges mounted on instrument carriers with 1 mM accuracy. The discharge was measured by a pre-calibrated orifice meter.

The roughness was made of yellow copper and had a U-shape. Its dimensions are shown in Fig. 2, the initial length of roughness was assumed = 90 cm to ensure that it will cover the longest hydraulic jump. And the distance between the beginning of roughness and the sluice gate was taken = twice the maximum gate opening = 6 cm (Mahmoud, 1984).

The flow characteristics under four different intensities (I) were tested to determine the best one, (I = the ratio between the area of roughness and the area of basin = 4.5, 8, 12.5 and 18%). Then eight different lengths of roughness were tested, L_r = (100, 92, 78, 64, 50, 32, 22 and 15 cm) with the best intensity.

Each model was tested with four different gate openings (G = 1.5, 2, 2.5, 3 cm) and different discharges (2000 to 4500 $cm^3 sec^{-1}$). For each run, a specified gate opening is set and a certain flow is allowed to path through the flume. The tail gate is adjusted till the initial depth of the hydraulic jump reaches the vena-contracta section. As the jump becomes stable the difference in manometer readings that used to calculate the discharge, the initial depth (Y_1), the sequent depth (Y_2) and the jump length (L_j) were measured. Also, the water surface profiles of the hydraulic jumps were measured. Figure 3 is a sample of those measurements.

Same experiments were performed with smooth beds, to compare its results with those of the U-shaped rough bed.

RESULTS AND ANALYSIS

The effect of roughness intensity on flow characteristics: The relations between flow characteristics (L_j / Y_1, Y_2 / Y_1) and initial Froude number for all roughness intensities were tested.

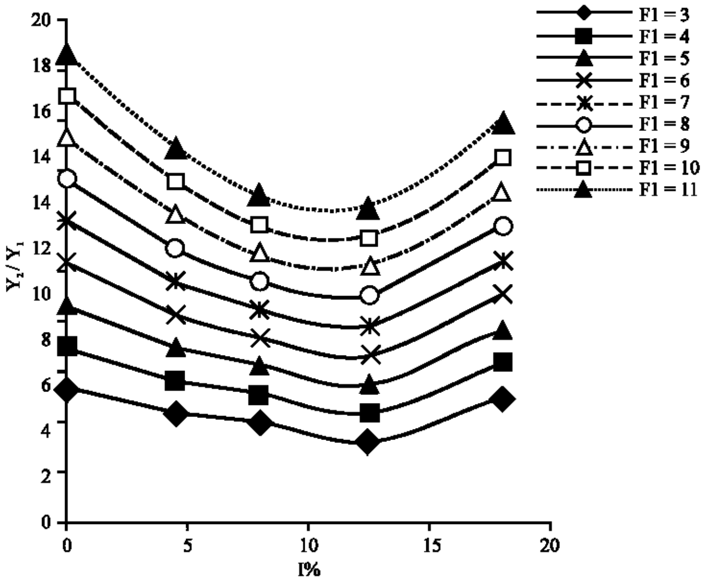

Fig. 4: Relation between Y_2 / Y_1 and I for different F_1

A logarithmic regression analysis of observed data led to the following formulas:

$$\frac{L_j}{Y_1} = a + b \ln F_1 \tag{5}$$

$$\frac{Y_2}{Y_1} = a' + b' F_1 \tag{6}$$

In which, L_j / Y_1 = the relative jump length, F_1 = the initial Froude number, Y_2 / Y_1 = the relative sequent depth, a, b, a\`, b\` = constants depending on roughness intensity.

Relations between constants and the intensity are deduced. Then, by substituting in Eq. 5 and 6 we get general equation between flow characteristics and F_1 with different I.

Using this general equation curves are plotted between I and the flow characteristics for different F_1 as shown in Fig. 4 and 5.

From these Fig. 4 and 5 the following results are noticed:

- The values of Y_2 / Y_1 and L_j / Y_1 increase with increasing the values of initial Froude number for the same I
- For all Froude number values, Y_2 / Y_1 and L_j / Y_1 decrease with increasing the value of I, reaching a minimum value at I = 12.5%, then start increasing for larger values of I. This variation may be attributed to the increase in turbulence level for increased density of roughness due to drag effect of roughness elements reaching an optimum value at I = 12.5%. Then turbulence level starts decreasing as a result of close longitudinal spacing behaving like a smooth bed

The effect of roughness length on flow characteristics: The intensity 12.5% was chosen to study the effect of roughness length on jump characteristics. The relation between flow

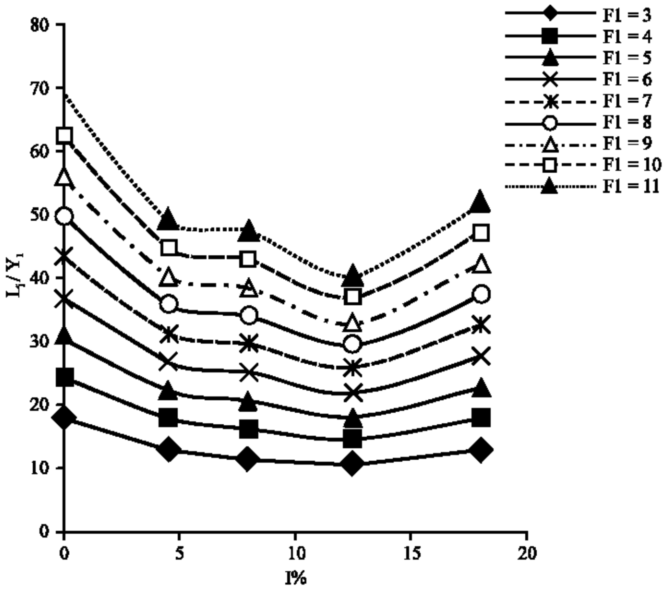

Fig. 5: Relation between L_j / Y_1 and I for different F_1

characteristics (L_j / Y_1, Y_2 / Y_1) and initial Froude number for different tested relative roughness lengths (L_r / Y_1) were tested.

A logarithmic regression analysis of observed data led to the following formulas:

$$\frac{L_j}{Y_1} = c + d \ln F_1 \tag{7}$$

$$\frac{Y_2}{Y_1} = c' + d' F_1 \tag{8}$$

In which, c, d, c\`, d\` = constants depending on roughness Length.

Relations between constants and the relative roughness length are deduced. Then, by substituting in Eq. 7 and 8 we get general equation between flow characteristics and F_1 with different L_r / Y_1. Using this general equation we can plot curves between L_r / Y_1 and the flow characteristics for different F_1 as shown in Fig. 6 and 7.

From these figures, it was found that values of Y_2 / Y_1 and, L_j / Y_1 decrease as L_r / Y_1 increases till L_r / Y_1 = 18. Then these values increase gradually with increasing L_r / Y_1 till L_r / Y_1 = 26-42 and remain constant after that for all initial Froude numbers tested.

So, the best relative roughness length is equal 18 as it is the smallest value of L_r / Y_1 causing minimum relative jump sequent depth and minimum relative jump length.

Studying the efficiency of stilling basin using U-shape roughness: In order to study the efficiency of the designed stilling basin, the relation between the relative energy loss E_L / E_1 (E_L = energy loss due to the jump, E_1 = specific energy at the initial depth) and initial Froude number for optimum designed tested basin (I = 12.5%, L_r / Y_1 = 18) and smooth bed was drawn as

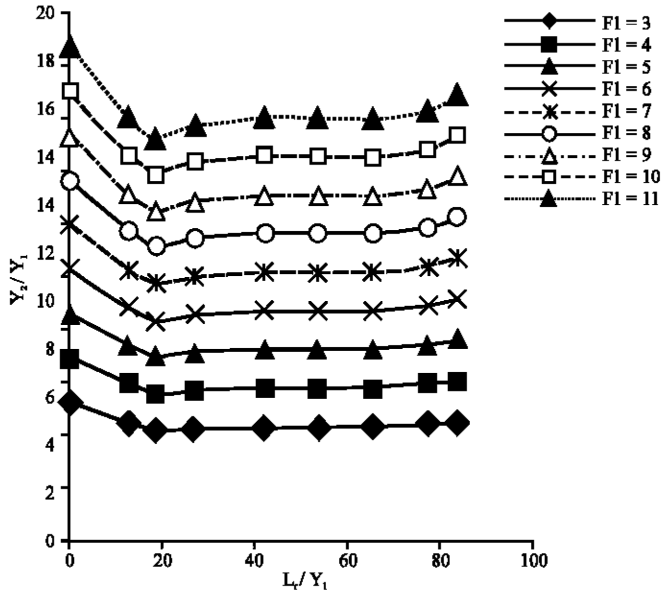

Fig. 6: Relation between Y_2 / Y_1 and L_r / Y_1 for different F_1

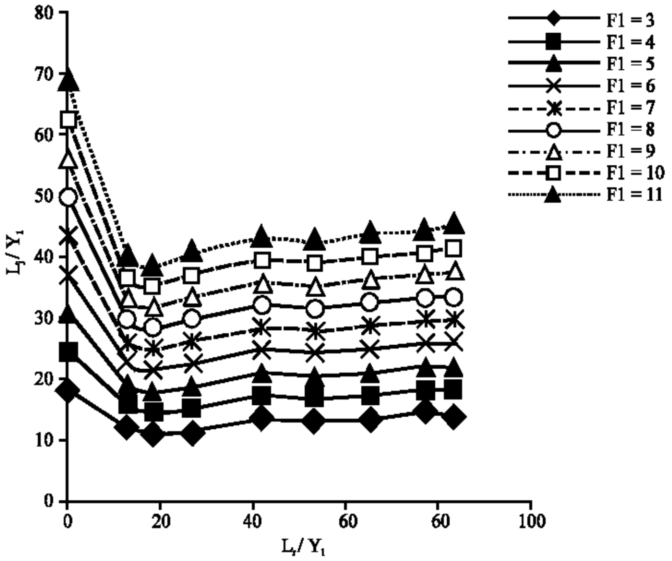

Fig. 7: Relation between L_j / Y_1 and L_r / Y_1 for different F_1

shown in Fig. 8. The figure indicated that the relative energy loss was increased by 11-18% using the U-shape roughness compared to the smooth bed.

Also, a comparison between the optimum designed tested basin with smooth bed, cubic shape roughened bed and T-shape roughened bed was conducted. Relations between the flow characteristics (Y_2 / Y_1, L_j / Y_1) and the initial Froude number were drawn for the previous cases as shown in Fig. 9 and 10.

From Fig. 9 and 10 it was noticed that the stilling basin effect increases as the initial Froude number increases. Also, it was found that the U-shape decreases the relative jump sequent depth by 14- 20% and reduces the relative jump length by 28-47% compared to the smooth bed case for Froude number range = 3-11.

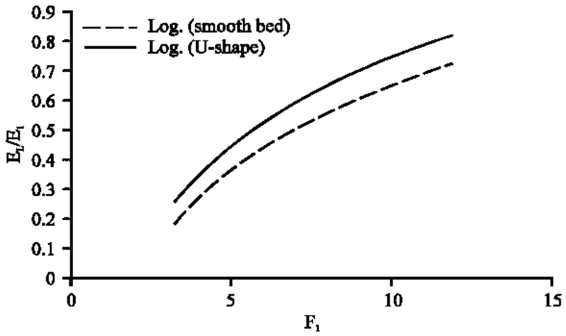

Fig. 8: Comparison between U-shape and smooth bed according to E_L / E_1

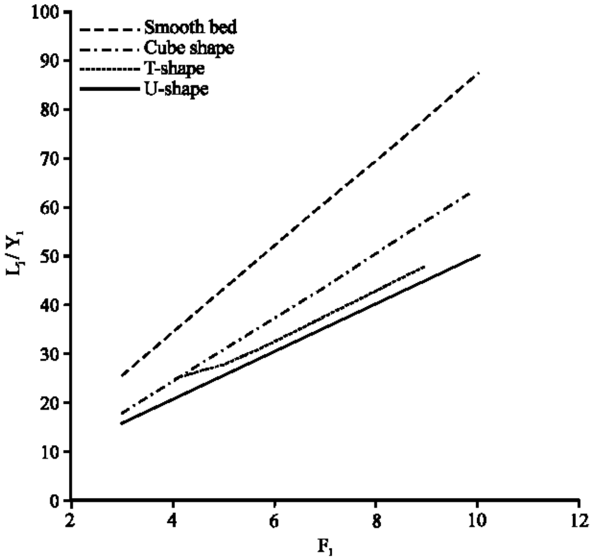

Fig. 9: Comparison between different roughened shapes according to Y_2 / Y_1

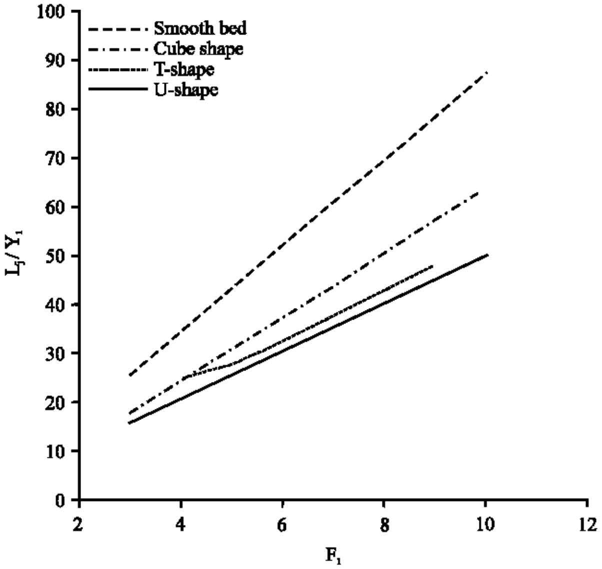

Fig. 10: Comparison between different roughened shapes according to L_j / Y_1

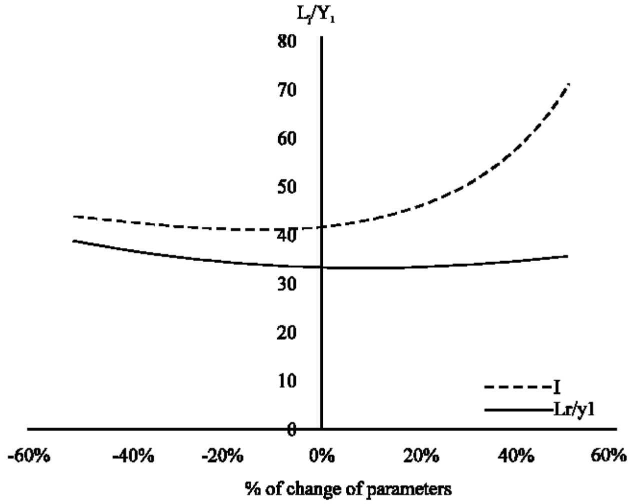

Fig. 11: Sensitivity analysis

Also, the Fig. 9 and 10 show that the tailwater depth required to form the jump and the length of the jump on bed with U-shape roughness were considerably smaller than those of the corresponding jump on a roughened bed with cubic shape elements.

The reason of that reduction could be attributed to the enhanced bed shear stresses produced by the interaction of the supercritical stream with eddies trapped in the cavities of the U-shape. That increases the corresponding excessive localized eddies and turbulence due to rolling of fluid masses and cause a larger energy dissipation with U-shape roughness compared to that of cubic shape.

Also, the figures show that the U-shape roughness decreases the hydraulic jump characteristics by appreciable values compared to T-shape roughness for $F_1 = 5$. But for $F_1>5$ the difference is small.

The sensitivity analysis: In the present work, sensitivity analysis was performed to investigate the effect of change of intensity and roughness length parameters on the hydraulic jump length. So, a case study was chosen with I = 12.5%, $L_r / Y_1 = 18$ and $F_1 = 9$.

From Fig. 11 it was noticed that for I> 2.5% and $L_r / Y_1>18$ the change in the length of jump is more sensitive to the change in intensity rather than the change in roughness length. But for I<12.5% and $L_r / Y_1<18$ the change in the length of jump is more sensitive to the change in roughness length rather than the change in intensity.

CONCLUSIONS

In the present study to improve the efficiency of the stilling basins, a new roughness shape (U-shape) was tested. It was found that the best roughness intensity is 12.5% and the best relative roughness length is 18 as these values give minimum relative jump sequent depth and minimum relative jump length.

Compared with the smooth bed, the U-shape roughness decreases the relative jump sequent depth by 14-20% and reduces the relative jump length by 28-47%. It was found that the U-shape roughness is better than the cubic shape from hydraulic point of view as it decreases the hydraulic jump characteristics with considerable values compared to cubic roughness shape.

Sensitivity analysis was performed to investigate the effect of change of intensity and roughness length parameters on the hydraulic jump length. 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 L_r / Y_1 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 L_r / Y_1 under their optimal values.

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