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Design of Stilling Basins using Artificial Roughness

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Abstract**—**The stilling basins are commonly used to dissipate the energy and protect the downstream floor from erosion. The aim of the present experimental work is to improve the roughened stilling basin using T-shape roughness instead of the regular cubic one and design this new shape. As a result of the present work the best intensity and the best roughness length are identified. Also, it is found that the T-shape roughness save materials and reduce the jump length compared to the cubic one. Sensitivity analysis was performed and it was noticed that the change in the length of jump is more sensitive to the change in roughness length than the change in intensity.

Keywords**—**hydraulic jump, energy dissipater, roughened bed, stilling basin.

I. INTRODUCTION

SEVERAL experimental investigations have been conducted to study the hydraulic performance of stilling basins Ali [7], Hughes et al.[11], Riad [15].

Theoretical equations for the sequent depth ratio of hydraulic jump over rough beds have been developed by many investigators e.g. (Rajaratnam[14], , Alhamid and Negm[4]).

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.

Abdel latif [1] located staggered roughness cubes downstream the sluice gate, to dissipate the energy in the flow. From this study, it was found that the 10% bed roughness intensity was the optimum from both the hydraulics and economical point of view.

AboulAtta [3] carried out experimental works to study the effect of location and length of roughened beds on flow characteristics, using cubic roughness with intensity = 10%. 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 L_b is the location of roughness with respect to the beginning of the jump).

Abdelsalam [2] studied the effect of the height of cubic roughness on flow characteristics using rough channel bed with 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 [6] used cubic roughness with intensity = 10% in his study. He found the best ratio between roughness length and the height of the blocks is equal to 28.

Also, Alhamid [5] conducted experiments on a rough bed using cube blocks and concluded that 12% roughness intensity provided the optimal length of the basin for the flow conditions and roughness arrangement under consideration. Also, empirical formulae were fitted to the experimental data showed good agreement.

Some researches dealt with other shapes of bed roughness. Bejestan and Neisi [8] studied the effect of lozenge roughness shape on the hydraulic jump. They found that this shape reduced the tail water depth by 24% and the hydraulic jump length by 40% compared with the smooth bed.

Ibrahim [12] studied the effect of the intensity of the half cylinder strip of roughness on characteristics of the hydraulic jump and found that the best roughness intensity was I=100%, which means that roughness shape is not an economic solution.

There have been many experimental studies on the effect of corrugated beds on physical parameters of hydraulic jump. Ead and Rajaratnam [9] 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 [16] supported the results of them.

Izadjoo et al. [13] used trapezoidal shape corrugated bed in their study. They confirmed the results of [9] and added that the jump length is more dependent on the wave length of corrugations than their amplitude.

Elsebaie and Shabayek[10] used five different corrugated beds in their study. They conclude that the shear stress on corrugated beds is independent on the shape of corrugation.

The present experimental research aims at improving the efficiency of the stilling basins using a new shape of roughness elements (T-shape) from both the economical and hydraulic point of views and finding out the best intensity and length for the used shape.

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II. THEORETICAL APPROACH

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

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

In which, Lj= 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.

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:

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

In the present study the value of R_N can be neglected, because the viscous force almost has no effect in open channel study with respect to the gravitational force which expressed by Froude number.

During determination of the intensity (I), L_r and L_b were constants and equal to 120cm and 6cm respectively so (2) can be written as:

$$\frac{Y_2}{Y_1} \quad or \quad \frac{L_j}{Y_1} = \phi_3(I, F_1) \quad (3)$$

On the other hand, during the determination of the roughness length L_r, the intensity I and L_b were constants and equal to 8.8% and 6 cm respectively, so (2) can be written as follows:

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

The relative energy loss, E_L/E_1can be obtained by applying the energy and the continuity equations between sections (1) and (2) of the jump elements shown in Fig. 1. So, the final equation for the relative energy loss can be written as follows of the jump:

$$\frac{E_L}{E_1} = 1 - \frac{F_1^2 + 2(Y_2/Y_1)^3}{(Y_2/Y_1)^2(F_1^2 + 1)} \quad (5)$$

In which, E_L= The energy head lost through the hydraulic jump; E_1= the specific energy at section (1); E_2 = the specific energy at section (2).

III. 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 15.3cm wide, 30cm deep, and 245cm long with transparent walls 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 using a hand driven gear system for opening and closing the gate. The 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 T-shape. Its dimensions are shown in Fig. 2, the initial length of roughness was assumed = 120cm 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 (Abdellatif, [1]).

The flow characteristics under five different intensities (I) were tested to determine the best one, (I = the ratio between the area of roughness and the area of basin=4.2701%, 7.2331%, 11.9825%, 14.4662% and 21.5686). Then eight different lengths of roughness were tested (120, 92.2, 78.5, 64.4, 50.2, 36.6, 23.2, and 9.2 cm) with the best intensity.

Each model was tested with four different gate openings (G = 1.5, 2, 2.5, 3 cm), and each gate opening was tested with six different discharges. 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 become stable the difference in manometer reading that used to calculate the discharge (h), initial depth (y_1), sequent depth (y_2), and jump length (L_j) were measured. Also, the water surface profile of the hydraulic jumps were measured.

Also, the test repeated with a smooth bed, to compare its results with those of the T- shaped rough bed.

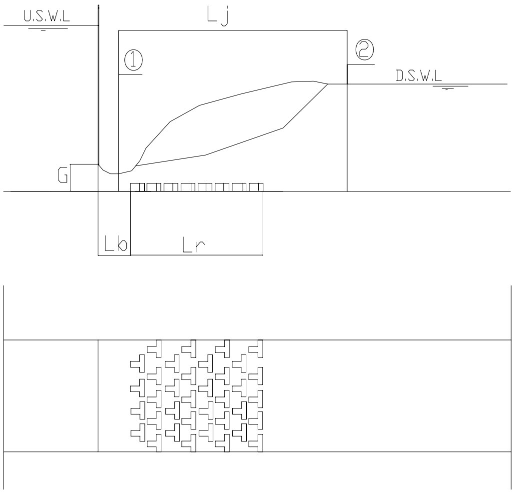
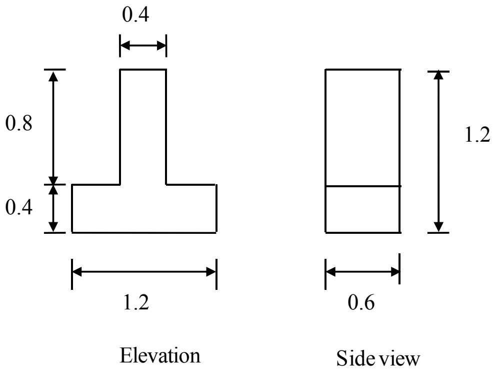


Fig. 1 Sketch for the hydraulic jump over the stilling basin



All dimensions in Cm

Fig. 2 Roughness dimensions

IV. RESULTS AND ANALYSIS

A. The Effect of Roughness Intensity on Flow Characteristics

The relations between flow characteristics (L_j/Y_1, Y_2/Y_1, E_L/E_1) and initial Froude Number for all roughness intensities were tested.

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

$$\frac{L_j}{Y_1} = a + b \ln F_1 \tag{6}$$

$$\frac{Y_2}{Y_1} = a' + b' F_1 \tag{7}$$

$$\frac{E_L}{E_1} = a'' + b'' \ln F_1 \tag{8}$$

In which, L_j/Y_1 = the relative jump length, F_1 = the initial Froude number, Y_2/Y_1 = the relative sequent depth, E_L/E_1 = the relative energy loss.

a, b, a`, b`, a``, b`` = constants depend on roughness intensity.

Relation between constants and the intensity are deduced. Then, by substituting in (6,7,8) we get general equation between flow characteristics and F_1 with different I.

Using this general equation we could plot curves between I and the flow characteristics for different F_1 as shown in Figs. 3,4,5.

From these figures the following results are noticed:

For low initial Froude number (F_1=3,4) the relative jump sequent depth (Y_2/Y_1) changes slightly for changing the roughness intensity but for $F_1 \geq 5$ the rate of change increases as the roughness intensity increases.

Also, L_j/Y_1 decreases with increasing the value of I, reaching a minimum value at I= 7.2-8.8, then starts increasing for larger values of I.

For all Froude number values minimum relative jump length, minimum relative jump sequent depth and maximum relative energy loss are corresponding to I =7.2-8.8%.

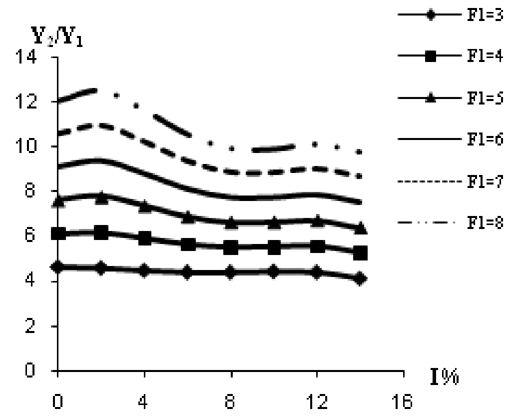


Fig. 3 Relation between Y_2/Y_1 and I for different F_1

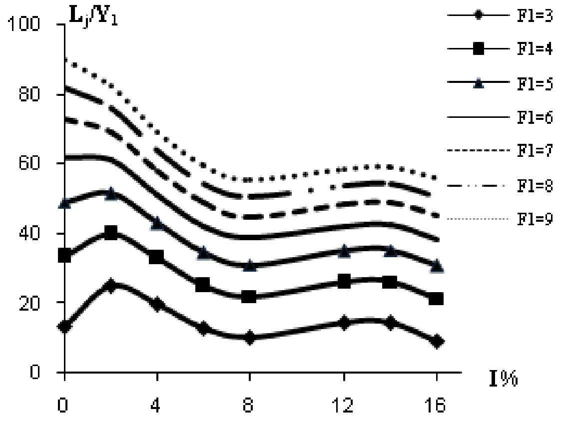


Fig. 4 Relation between L_j/Y_1 and I for different F_1

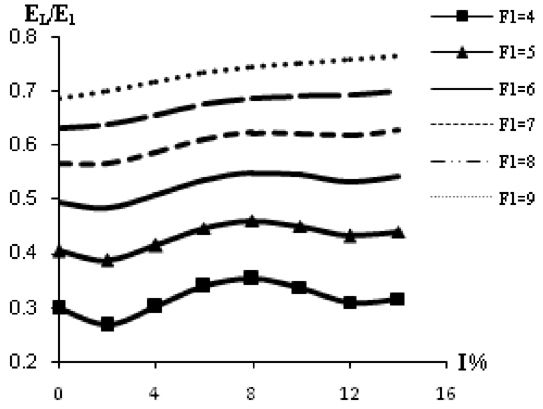


Fig. 5 Relation between E_L/E_1 and I for different F_1

B. The Effect of Roughness Length on Flow Characteristics

The intensity 8.8% was chosen to study the effect of roughness length on jump characteristics. The relation between flow characteristics (L_j/Y_1, Y_2/Y_1, E_L/E_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:

$$\frac{L_j}{Y_1} = c + d \ \ln F_1 \tag{9}$$

$$\frac{Y_2}{Y_1} = c' + d' F_1 \tag{10}$$

$$\frac{E_L}{E_1} = c`` + d`` \ln F_1 \tag{11}$$

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

Relation between constants and the relative roughness length are deduced. Then, by substituting in (9,10,11) we get general equation between flow characteristics and F_1 with different L_r/Y_1. Using this general equation we could plot curves between L_r/Y_1 and the flow characteristics for different F_1 as shown in Figs. 6,7,8.

From these figures the following results are noticed:

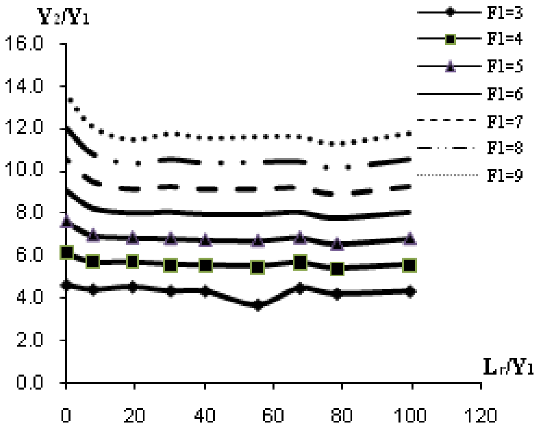


Fig. 6 Relation between $Y_2/Y_1$and $Lr/Y_1$for different F_1

From Fig. 6, it was found that for all Froude numbers the relative jump sequent depth changes slightly by increasing the relative roughness length.

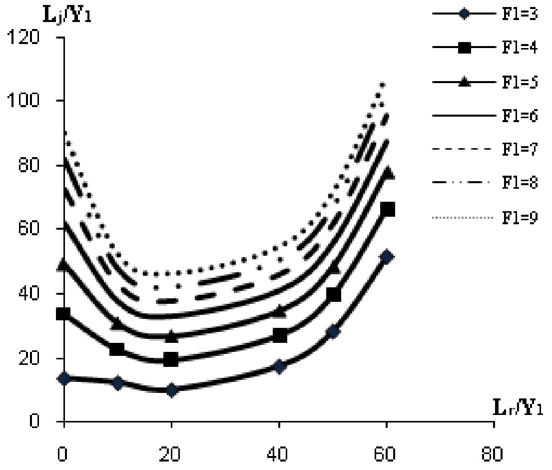


Fig. 7 Relation between L_j/Y_1 and $L_r/Y_1$for different F_1

Fig. 7 shows that, the minimum relative jump length is corresponding to Lr/Y_1=16 to 20 which means the best relative roughness length was equal 16 for economical design.

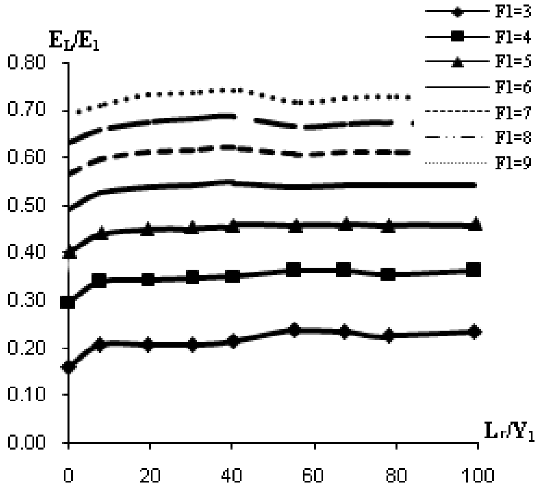


Fig. 8 Relation between $E_L/E_1$and Lr/Y_1 for different F_1

From Fig. 8, it was found that, the relative energy loss increases till the relative roughness length L_r/Y_1=8 then the relative energy loss remains constant for all initial Froude numbers tested. So, the best relative roughness length is equal 16 as it is the same value causing minimum relative jump length.

C. Studying the Efficiency of Stilling Basin Using T-shape Roughness:

In order to study the efficiency of the designed stilling basin, a comparison between the smooth bed and the final designed tested basin was made. The relation between the flow characteristics (Y_2/Y_1, L_j/Y_1 and E_L/E_1) and the initial Froude number was drawn for both previous cases as shown in Figs. 9,10,11.

It was determined that the tail water depth required to form the jump and the length of the jump on beds with T-shape roughness were appreciably smaller than those of the corresponding jumps on a smooth bed. It was also found that the head loss for jumps on beds was higher than those occurring on smooth beds and T- shape roughness was efficient in stabilizing the location of the jump.

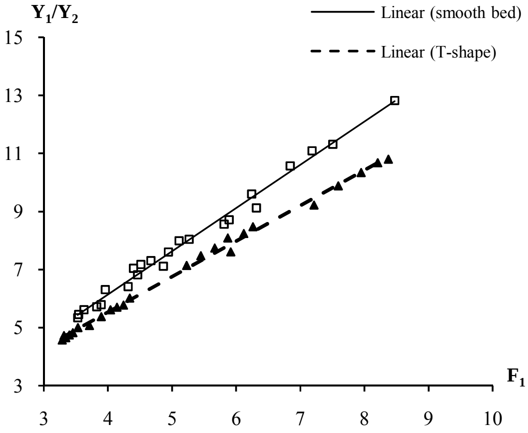


Fig. 9 Comparison between T-shape and smooth bed according to Y_2/Y_1

From Fig. 9 it was found that the T-shape decrease the relative jump sequent depth compared to the smooth bed by 8-15% for Froude number range =3.5- 8.5.

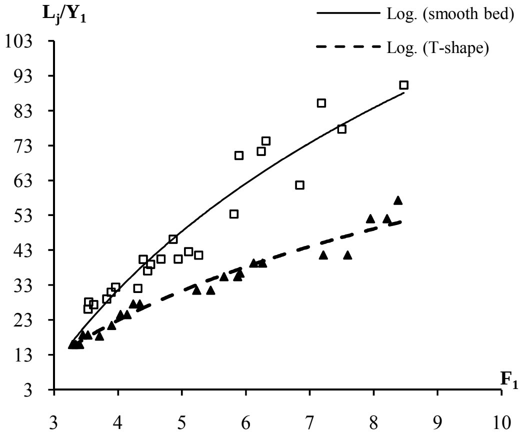


Fig. 10 Comparison between T-shape and smooth bed according to L_j/Y_1

From Fig. 10 it was noticed that the stilling basin effect increases as the initial Froude number increases and the designed stilling basin reduce the relative jump length by 18-28% for F_1 = 3.5-4 respectively and increases till 42% for F_1 = 8.5.

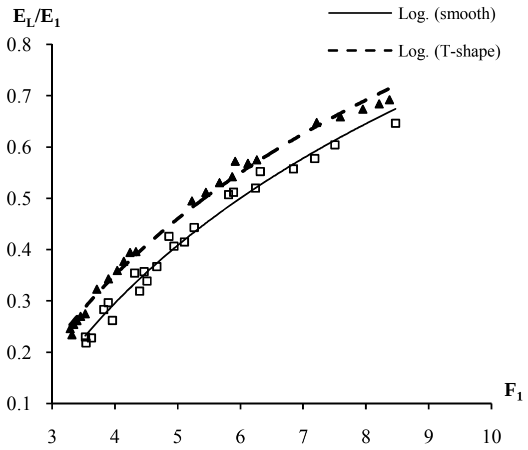


Fig. 11 Comparison between T-shape and smooth bed according to E_L/E_1

Also, the relative energy loss was increased by 8-14% using the T-shape roughness compared to the smooth bed as shown in Fig. 11.

D.Comparison Between T-Shape and Cubic Shape of Roughness

A comparison between the tested shape of roughness (T-shape) and the ordinary shape of roughness (cubic shape) was performed in this section to find out which shape is more efficient and more economic.

1) Efficiency point of view

The data available in literature for cube blocks showed that the reduction in relative jump sequent depth compared with smooth bed is 8-12% . Also, the reduction in jump length is 18-24% for F_1=3.5-4 respectively and increases to 34% at F_1=8.5.

Comparing these data with the results of T- shape roughness, leads to:

The T- shape roughness has minor effect on the relative jump sequent depth compared to the cubic shape, but it compacts the hydraulic jump length.

So, the T-shape roughness is better than the cubic shape from hydraulic point of view.

2) Economical point of view

- *For cubic shape:*

According to previous work the best length of roughness L_r = 15 Y_1 (AboulAtta, [3]), the best intensity I = 10% (Abdellatif, [1]).

- *For T-shape:*

The best Roughness length $L_r = 16\ Y_1$, the best intensity I ≈ 8%.

By calculating the required number of blocks needed by using cubic shape and T- shape, it was found that the T- shape increases the number of roughness elements needed for the basin by about 54%. In spite of this the T-shape saves more materials than the rectangular shape roughness by about 14.4% because the T- shape surface area is less than the cubic one.

E. 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 of study was chosen with I=8%, L_r/Y_1=16 and F_1=6.

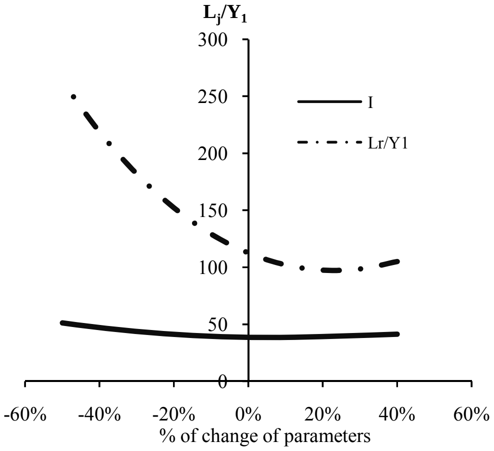


Fig. 12 Sensitivity analysis

From Fig.(12) it was noticed that the change in the length of jump is more sensitive to the change in roughness length than the change in intensity as it has the greatest slope comparing with the intensity.

V. CONCLUSION

To improve the efficiency of the stilling basins, a new roughness shape (T- shape) was tested in the present study. It was found that the best roughness intensity which gives minimum jump length, minimum relative depth, and maximum energy loss is (7.2—8.8%).

Also, it was noticed that increasing the roughness length doesn't make great difference in energy loss. So, the most economical relative roughness length (L_r/Y_1) is equal to 16.

Compared with the smooth bed, the T-shape roughness decreases the relative length of jump by 28-42%, the relative sequent depth of jump up-to 15%, and increases the relative energy loss by 14%. The T- shape roughness compact the length of the jump compared with cubic roughness shape. Also, the T-shape roughness saves more materials than the 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 roughness length than the change in intensity.

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SYMBOLS

E_1 = specific energy at the initial depth
E_2 = specific energy at the sequent depth
E_L = energy loss due to the jump
F_1 = initial Froude number
G = gate opening
g = gravitational acceleration
I = roughness intensity
L_b = location of roughness with respect to the gate
L_j = length of the hydraulic jump
L_r = roughness length

q = discharge per unit width
r = height of the bed roughness
y_1 = initial depth of the jump
y_2 = sequent depth of the jump
ρ = density of water
μ = dynamic viscosity of the water