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Investigation of hydraulic jumps on rough beds with adverse slope: A roughness froude number approach

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The Bélanger equation has been found to be inadequate for predicting sequent depth in hydraulic jumps occurring on rough, sloping channel beds. To address this limitation, a roughness Froude number incorporating the effects of bed roughness and channel slope has been introduced in this study. Three sets of experimental runs have been conducted in a channel flume using three bed roughness values (0.0256 m, 0.0387 m, and 0.0438 m) and three adverse slopes (-0.025, -0.030, and -0.035). The resulting datasets have been used to tabulate sequent depth and jump length and to develop two regression-based semi-empirical relationships relating the roughness Froude number to the sequent depth ratio and the relative jump length, respectively, for hydraulic jumps on adverse slopes. The proposed equations have been validated against experimental observations and have shown agreement within deviations of 30% for sequent depth and 33% for jump length.

Keywords: Experimental flume study, Jump Length, Open channel flow, Regression, Sequent depth ratio

1 Introduction

Hydraulic jump is turbulent in nature causing surface waves and dissipation of energy[1]. An intricate flow pattern is involved in the roller length of a hydraulic jump where exchange of air and water takes place[2]. The important variable of a hydraulic jump to be considered in designing stilling basins is the hydraulic jump length. From the perspective of engineering, the stilling basin length should be effective in its purpose and also economical in construction. The stilling basin length should be least in length as well as its cost of construction[3]. Practically hydraulic jump control accessories are typically placed in the basin. However, sills and baffles serve only as protective measures, and the stilling basin is generally designed such that the hydraulic jump occurs on it[4]. The main problem with baffles is the possibility of cavitation in the jumps. However, in certain situations, the hydraulic jumps move downstream of channels along a natural bed, causing erosion and may cause damage to hydraulic structures. However, if jumps occur on corrugated beds, the sequent depth and hydraulic jump length would be significantly reduced[5]. Izadjoo and Shafaei[6] conducted the study of hydraulic jumps on stilling basin with rough beds. A factor called as relative roughness was introduced and showed that the length of the roller and the length of the hydraulic jump on rough bed were substantially decreased. Using a rectangular channel, Afzal *et al.*[7] investigated a hydraulic jump which was turbulent in nature, over a rough bed and found that the roughness of the interior rough bed passively contributed to the imposition of wall shear stress in an outer layer hydraulic jump. They suggested solutions for sequent depth ratio, roller length, and profiles of hydraulic jump depend on the upstream Froude number and drag force which is owing to roughness and kinetic energy factor. Their results may be inferred from traditional jump theory by substituting the upstream Froude number with the effective Froude number. The shear stress over the corrugated beds also increased in comparison to the classical hydraulic jump[5,6,8-10]. Abrishami and Sanei[11] showed that there are no limitations on the occurrence of hydraulic jumps on any adverse slope. In their investigation of the hydraulic jump on adverse slopes, Khadar and Rajagopal[12] inferred that, depending on the initial Froude number, a hydraulic jump can occur on any adverse slope. According to the study done by McCorquodale and Mohamed[13] focusing on the jump over stilling basins with an adverse slope, it was observed that the hydraulic jump would occur at Froude numbers more than 9 and would necessitate constant tail-water modification to keep the jump

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stationary at Froude numbers below 4. Pagliara and Peruginelli[14] experimented with sill-controlled and traditional adverse-slope hydraulic jumps. They demonstrated that a hydraulic that is stabilised on an adverse slope by a sill and suggested a formula for the sequent depth ratio under both sill-controlled and limited circumstances. Beirami and Chamani[15] presented a type of hydraulic jump known as the "B-F jump," in which the jump end is situated on an adverse slope and the jump toe is on a positive slope. They presented a general formula for the calculation of the sequent depth ratio for hydraulic jumps based on the momentum principle. Beirami and Chamani[16] introduced a semi-empirical technique to predict the length of roller of the hydraulic jump on adverse slopes using the energy concept. They demonstrated that the classical jump's energy losses are larger than those on either a positive or negative slope. According to Nishank and Ellora[17] bed roughness increases shear stress, which leads to increased energy dissipation and decreased jump length and subsequent depth. Substantial research has been done on horizontal and adverse slopes to examine the influence of roughness on hydraulic jump characteristics. The present study aims on investigating the effect of roughness Froude number (F_*) on the sequent depth and length of the hydraulic jump on rough channel bed with adverse slope.

2 Materials and Methods

Experimental runs were conducted in re-circulating rectangular channel flume having length 16m, 0.6m in width and depth 0.8m, located in the Hydraulics Laboratory, Department of Civil Engineering, National Institute of Technology Manipur. A vertical sluice gate was utilized to provide upstream control so as to generate supercritical flow conditions and force a hydraulic jump. The flow velocities were recorded using the flow probe (FP 211) having a precision of 0.1 ft/s. The flow depths were recorded using digital point gauges having a precision of ±0.1mm. The formation of the hydraulic jumps was controlled using a tailrace sluice gate at the ending part of the channel flume. Figure 1 shows the formation of hydraulic jump in the laboratory channel flume. Flow data were collected at two points at the vena contracta of the upstream sluice gate before the hydraulic jump and second after the jump. The experiments were conducted on three representative roughness heights of bed, K_s viz. 0.0256m, 0.0387m and 0.438m, and three adverse slopes, S_o of the channel flume viz. 0.025, 0.030 and 0.035. The particle size distribution of the gravel used as bed roughness material is shown in Fig. 2.

The hydraulic jump parameters such as sequent depth (y_2) and length of the jump (L_j) on a rough bed over slope may depend on the density of water (ρ); dynamic viscosity of water (μ); the representative bed roughness height (K_s); the bed slope (θ), acceleration due to gravity (g); supercritical flow depth (y_1); and average velocity (v_1) at the start of the jump. The relationship of the sequent depth and length of the jump might be given as follows Eqs (1-6):

$$y_2 = f(y_1, v_1, g, \mu, \rho, K_s, \theta) \quad \dots (1)$$

$$L_j = f(y_1, v_1, g, \mu, \rho, \theta) \quad \dots (2)$$

Fig. 1 — Hydraulic jump on adverse slope.

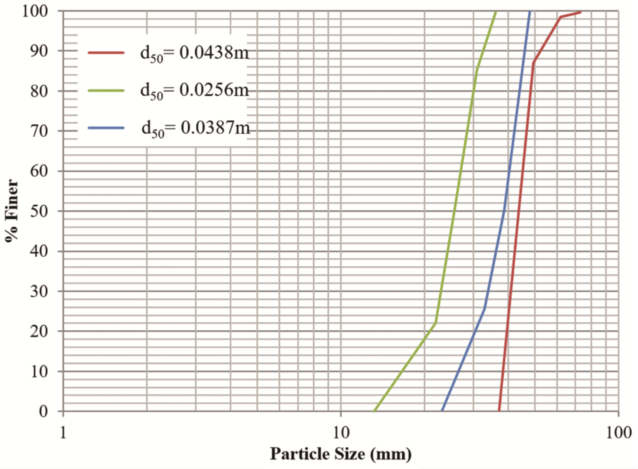

Fig. 2 — Particle size distribution of the used gravel.

Using dimensional analysis, the following dimensionless relations may be obtained as follows:

$$\frac{y_2}{y_1} = f(Re, F_*) \quad \dots (3)$$

$$\frac{L_j}{y_1} = f(Re, F_*) \quad \dots (4)$$

Where, $F_* = \frac{q}{\sqrt{K_s^3 g sin\theta}}$ is the roughness Froude number and *Re* is the Reynolds number.

Viscous effects can be neglected as Reynolds number, Re in the present study were in the range of 53125 –177451 and thus the sequent depth ratio, ($\frac{y_2}{y_1}$) and relative length of the jump, ($\frac{L_j}{y_1}$) can be written as;

$$\frac{y_2}{y_1} = f(F_*) \quad \dots (5)$$

$$\frac{L_j}{y_1} = f(F_*) \quad \dots (6)$$

3 Results and Discussion

3.1 Sequent depth ratio

From Eq (5), it is known that the sequent depth ratio $\frac{y_2}{y_1}$ is dependent on the roughness Froude number. To evaluate the effect of roughness height and slope of the channel, using the Tables (1-3), the values of $\frac{y_2}{y_1}$ are plotted with roughness Froude number, F_* as shown in Fig. 3.

From Fig. 3, it can be observed that the sequent depth ratio increases with the increase in roughness Froude number and decreases with increasing slope. The variation of $\frac{y_2}{y_1}$ with F_* is shown by the following regression-based Eq (7).

$$\frac{y_2}{y_1} = 1.439F_* - 2.06 \quad \dots (7)$$

In order to ascertain the capability of Eq (7), a comparison between the observed $\frac{y_2}{y_1}$ values and the values calculated using Eq (7) is plotted in Fig. 4. According to the Fig. 4, the calculated data were in agreement with the observed data and showed a ± 30% deviation.

3.2 Relative length of jump

In Fig. 5, the observed values of the relative length of the jump, $\frac{L_j}{y_1}$, were plotted with roughness Froude

Table 1 — Observed hydraulic data for So = - 0.025.

Q	q	Ks	y1	y2	Lj	F*	y2/y1	Lj /y1
m3/s	m2/s	m	m	m	m			
0.055	0.092	0.0256	0.04	0.276	2.48	7.20	6.90	61.9
0.061	0.101	0.0256	0.045	0.329	2.86	7.91	7.30	63.5
0.060	0.099	0.0256	0.051	0.345	3.46	7.77	6.76	67.8
0.057	0.096	0.0256	0.057	0.388	3.61	7.50	6.80	63.3
0.032	0.054	0.0256	0.062	0.298	3.29	4.20	4.80	53.1
0.066	0.110	0.0256	0.073	0.533	5.09	8.59	7.30	69.7
0.067	0.111	0.0256	0.077	0.585	5.44	8.70	7.60	70.7
0.047	0.078	0.0256	0.08	0.504	4.38	6.10	6.30	54.8
0.038	0.064	0.0256	0.082	0.443	3.82	5.00	5.40	46.6
0.077	0.129	0.0387	0.044	0.257	2.21	5.43	5.85	50.2
0.117	0.195	0.0387	0.047	0.353	3.11	8.20	7.50	66.1
0.079	0.132	0.0387	0.051	0.298	2.71	5.58	5.85	53.1
0.083	0.138	0.0387	0.055	0.325	2.61	5.80	5.92	47.5
0.098	0.164	0.0387	0.063	0.416	3.43	6.90	6.60	54.4
0.091	0.152	0.0387	0.066	0.409	4.10	6.40	6.20	62.1
0.088	0.146	0.0387	0.073	0.431	4.26	6.16	5.90	58.4
0.063	0.104	0.0387	0.081	0.397	3.59	4.40	4.90	44.3
0.095	0.159	0.0387	0.085	0.553	4.71	6.70	6.50	55.4
0.065	0.109	0.0387	0.087	0.426	3.98	4.60	4.90	45.8
0.079	0.131	0.0438	0.042	0.214	1.83	4.60	5.10	43.5
0.093	0.155	0.0438	0.044	0.238	2.33	5.42	5.40	52.9
0.087	0.146	0.0438	0.052	0.291	2.61	5.10	5.60	50.2
0.082	0.137	0.0438	0.055	0.292	2.76	4.80	5.30	50.1
0.070	0.117	0.0438	0.064	0.301	2.80	4.10	4.70	43.7

Table 2 — Observed hydraulic data for So = - 0.030.

Q m3/s	q m2/s	Ks m	y1 m	y2 m	Lj m	F*	y2/y1	Lj /y1
0.060	0.100	0.0256	0.041	0.267	2.47	7.80	6.5	60.3
0.067	0.112	0.0256	0.043	0.305	2.90	8.80	7.1	67.5
0.066	0.110	0.0256	0.051	0.372	3.21	8.60	7.3	62.9
0.065	0.109	0.0256	0.053	0.393	2.99	8.50	7.4	56.5
0.063	0.105	0.0256	0.058	0.400	3.58	8.20	6.9	61.8
0.065	0.109	0.0256	0.062	0.460	3.50	8.50	7.4	56.5
0.061	0.101	0.0256	0.065	0.436	3.60	7.90	6.7	55.4
0.057	0.094	0.0256	0.068	0.442	3.66	7.40	6.5	53.8
0.064	0.107	0.0256	0.07	0.483	4.23	8.40	6.9	60.4
0.084	0.140	0.0387	0.043	0.249	1.83	5.90	5.8	42.6
0.090	0.149	0.0387	0.045	0.273	2.11	6.30	6.1	46.9
0.061	0.102	0.0387	0.053	0.223	2.07	4.30	4.2	39.1
0.107	0.178	0.0387	0.055	0.352	3.06	7.50	6.4	55.6
0.100	0.166	0.0387	0.059	0.366	3.02	7.00	6.2	51.2
0.091	0.152	0.0387	0.061	0.360	3.02	6.40	5.9	49.6
0.075	0.126	0.0387	0.065	0.355	2.85	5.30	5.5	43.9
0.073	0.121	0.0387	0.069	0.359	2.89	5.10	5.2	41.9
0.079	0.132	0.0387	0.071	0.399	3.24	5.55	5.6	45.7
0.083	0.138	0.0387	0.074	0.407	3.63	5.80	5.5	49.1
0.072	0.120	0.0438	0.04	0.180	1.40	4.20	4.5	35.0
0.077	0.129	0.0438	0.044	0.207	1.81	4.50	4.7	41.2
0.081	0.134	0.0438	0.049	0.235	1.92	4.70	4.8	39.1
0.120	0.200	0.0438	0.056	0.342	3.13	7.00	6.1	55.9
0.085	0.142	0.0438	0.065	0.331	2.95	4.96	5.1	45.4
0.091	0.151	0.0438	0.068	0.371	2.79	5.30	5.5	41.0
0.087	0.145	0.0438	0.076	0.405	2.97	5.08	5.3	39.1
0.069	0.114	0.0438	0.079	0.348	2.98	4.00	4.4	37.7

Table 3 — Observed hydraulic data for So = - 0.035.

Q m3/s	q m2/s	Ks m	y1 m	y2 m	Lj m	F*	y2/y1	Lj /y1
0.063	0.105	0.0256	0.042	0.273	2.39	8.6	6.5	56.8
0.054	0.090	0.0256	0.043	0.254	2.04	7.4	5.9	47.4
0.052	0.087	0.0256	0.048	0.264	2.09	7.1	5.5	43.5
0.059	0.099	0.0256	0.051	0.326	2.70	8.1	6.4	52.9
0.051	0.084	0.0256	0.055	0.307	2.39	6.9	5.6	43.4
0.065	0.108	0.0256	0.058	0.394	3.80	8.8	6.8	65.6
0.056	0.094	0.0256	0.061	0.378	3.33	7.7	6.2	54.6
0.034	0.057	0.0256	0.064	0.279	2.00	4.7	4.4	31.2
0.046	0.077	0.0256	0.069	0.380	2.93	6.3	5.5	42.5
0.070	0.116	0.0387	0.071	0.334	2.42	5.1	4.7	34.1
0.061	0.102	0.0387	0.043	0.189	1.45	4.5	4.4	33.8
0.059	0.098	0.0387	0.052	0.216	1.47	4.3	4.1	28.3
0.072	0.120	0.0387	0.055	0.258	1.93	5.3	4.7	35.0
0.078	0.129	0.0387	0.058	0.302	1.97	5.7	5.2	33.9
0.091	0.152	0.0387	0.062	0.353	2.59	6.7	5.7	41.8
0.082	0.136	0.0387	0.065	0.330	2.89	6	5.1	44.4
0.080	0.134	0.0387	0.072	0.362	2.79	5.9	5.0	38.7
0.055	0.091	0.0387	0.073	0.291	2.00	4	4.0	27.4
0.069	0.115	0.0438	0.042	0.172	1.37	4.2	4.1	32.5

Q = Flume discharge, q = Discharge per unit width, Ks = Representative bed roughness height,
y1 = Supercritical flow depth, y2 = Subcritical flow depth, Lj= Length of jump, F* = Roughness Froude number

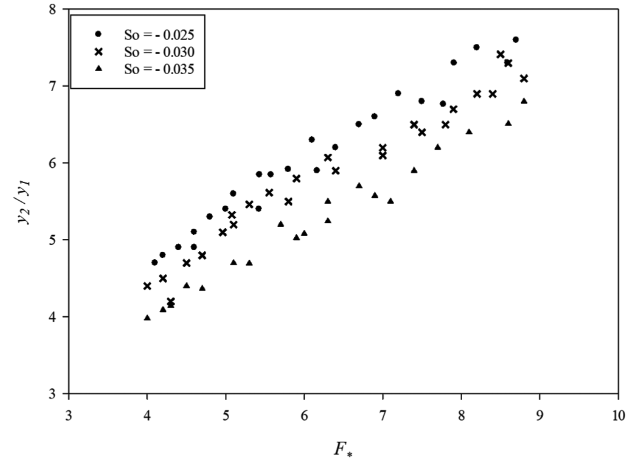

Fig. 3 — Plot of $\frac{y_2}{y_1}$ vs F_*.

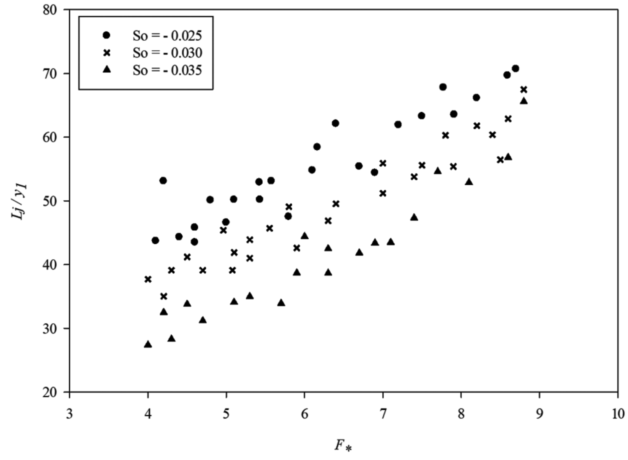

Fig. 5 — $\frac{L_j}{y_1}$versus F_*.

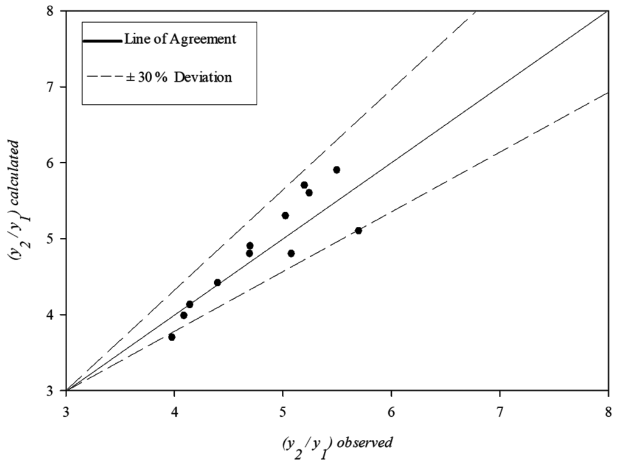

Fig. 4 — Observed values of $\frac{y_2}{y_1}$versus calculated values of $\frac{y_2}{y_1}$ using Eq (7).

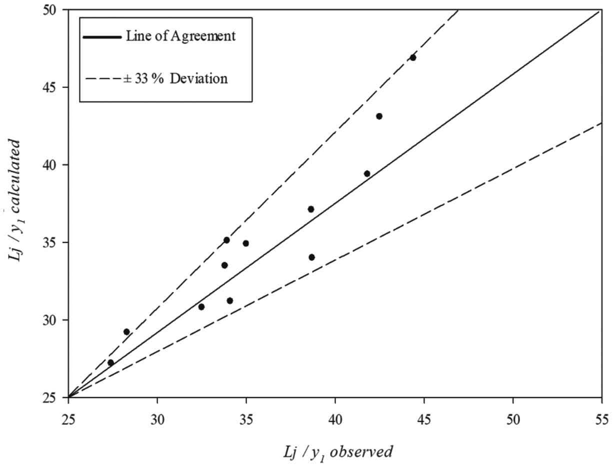

Fig. 6 — Observed value of $\frac{L_j}{y_1}$and calculated value of $\frac{L_j}{y_1}$ using Eq (8).

number, F_* using the data from Tables (1-3). It can be observed that the length of the jump decreases with increasing roughness Froude number and decreases with increasing slope. A regression-based equation was obtained from the observed data,$\frac{L_j}{y_1}$ as shown in Eq (8).

$$\frac{L_j}{y_1} = 0.112F_* + 0.76 \qquad \dots (8)$$

In order to find the capability of Eq (8), a comparison between the observed $\frac{L_j}{y_1}$ values and the values calculated using Eq (8) is plotted in Fig. 6. The calculated values were in good agreement and showed a ± 33% deviation with the observed values (Fig. 6).

4 Conclusion

In this study, the effect of the roughness Froude number on characteristics of the hydraulic jump on the adverse slope has been studied experimentally. From the results, it is observed that roughness Froude number has a linear effect on the sequent depth ratio and relative length of jump on negative slopes. The maximum reduction of sequent depth and relative length of jump was observed on the slope of -0.035. The roughness Froude number which incorporates the height of the bed roughness and slope of the channel bed can utilized in the calculation of sequent depths and length of jump and proposed equations are valid in the range of $3.5 < F_* < 9$ and $0.0256 < K_s < 0.428$.

The authors believe that the suggested Eqs (7 & 8) can be considered in estimating sequent depth ratio and length of jump for rough rectangular channels with adverse slopes. These equations are expected to be useful to hydraulic engineers for designing stilling basins.

Data availability

All relevant data and findings of the study are included in this study and no additional external data was used.

Acknowledgments

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