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Er SV Baria
Senior Research Assistant, Polytechnic in Agricultural Engineering, JAU, Targhadia, Gujarat, India

Dr. ML Gaur
Professor, Anand Agricultural University, Anand, Gujarat, India

NM Damor
Senior Research Assistant, Polytechnic in Agricultural Engineering, JAU, Targhadia, Gujarat, India

Corresponding Author:
Er SV Baria
Senior Research Assistant, Polytechnic in Agricultural Engineering, JAU, Targhadia, Gujarat, India

An experimental investigation on flow characteristics of stepped spillway under varying slope & discharge conditions

Er SV Baria, Dr. ML Gaur and NM Damor

Abstract

The stepped spillway is the most effective hydraulic structure for dissipating energy downstream of the spillway crest. This work evaluates the hydrologic and hydraulic functioning of a prototype hydraulic structure as used in natural channels of small agricultural watersheds, by generating some of the basic information & other relevant parameters for the area under study. The overall values of key flow parameters (h, v, E, n, Fr, Re) have been suitably worked out and analyzed, which altogether gave a broad range under hydraulic structures with varied configurations in regards to discharges and the channel bed slopes. Physical model study plays a vital role in the planning and designing of hydraulic structures. A vast review was done on updated progress on the hydraulic structure and their relevant monitoring and evaluations in hydraulic flume as well as real channel flow conditions the discharges inside the hydraulic flumes were varying in between 0.5 to 5 L/s in the majority of experimental runs. Similarly, the channel bed slopes were kept varying in between 0.5 to 2 percent longitudinal slopes. Efforts are made to derive the real limits of flow conditions all along the channel with in-depth evaluations of flow parameters, flow regimes, and all associated flow conditions. Also, the values of Cd for specific stepped spillway hydraulic structures are attempted here with an effort to further extend its applicability to similar ungauged situations. The Cd values for the stepped Spillway were found the be in the range of 0.004 to 0.107 and alternate predictive equations in this regard too also synthesized in this study.

Keywords: Stepped spillway, froude no., reynolds no., hydraulic flumes, potential head

Introduction

The use of in-stream structures for watershed and stream restoration dates back to the early 1900’s (Thompson 2005; Thornton *et al* 2011) [13, 14]; however, the design, effectiveness, and performance of these types of structures have not been well documented. For natural resource management the “Watershed” is now a day considered as a well-adapted unit for overall agricultural development. This is truer for tropical situations like India and drought-prone regions in particular, as in Gujarat. The concept of watershed management and development has continued for the last three decades with one or other refinements, moreover, the basic constituents while treating any watershed fall into two broad categories *viz.* soft core treatments and hard core treatments. The stepped check dams function, in a variety of ways to reduce the flow velocity, enhance the hydraulic roughness, and thus safely convey the glow, with a variety of flow transactions and transformations (Erdinc 2023) [15]. Two main types of flow exist in stepped spillways. Nappe flow generally occurs on larger steps with small discharges and on relatively mild-sloped spillways (Pegram *et al.* 1999) [9]. Nappe flow is described as having an air pocket at each step (Ohtsu *et al.* 2004) [8]. In contrast, skimming flow generally occurs on steep-sloped spillways with small steps relative to the water depth (Pegram *et al.* 1999) [9]. Skimming flow is described as having a so-called “pseudo bottom” along the step edges with circulating eddies formed at each step (Ohtsu *et al.* 2004) [8]. Several findings have been developed from previous work (Boes and Hager, 2003) [1]. Determine the transition between skimming flow and nappe flow to be dependent on critical depth yc, step height z, and spillway slope.

Rajaratnam (1990) [16] takes into account the non-dimensional parameters dc/ h and h / l. The author has noticed that for several results linked to regime change conditions, the appearance of a skimming regime is observed for a constant value of dc h = 0.8. He proposes the adoption of this value as the beginning of the skimming flow whatever the geometric specifications of the structure are. Several authors have taken this proposition into account in their research work (Christodoulou, 1993) [5]. Kells (1994, 1995) [17] has also studied the influence of two reduced models of spillways with four steps and different shapes (Chanson, 1994) [18]. He has also studied the influence of the downstream and facial infiltration on the measurements. From the author's conclusions, it is shown that the spillway downstream infiltration is more important than that of the facial part. The author's results indicate that there is a noticeable difference between the energy dissipation data of a spillway without downstream infiltration and that with downstream infiltration. The same results indicate that this difference depends on flow rate and may attain a percentage of 30%. Chanson, 2002 [2], 2004 [3], 2006 [4]; Boes and Hager, 2003 [1]; in-Bao *et al*., 2022 [7] examined that as discharges increase, the cells of air described above are alternately filled with a mesh of water and air showing a steady rotation. The flow regime on a stepped spillway depends on the discharge and the step geometry. Amador *et al*., (2002) [19] revealed the findings that the upstream three-quarters of the horizontal face, which are characterized by a hydrostatic behaviour.

Materials and Methods

The research was carried out at the hydraulic laboratory situated in the College of Agricultural Engineering & Technology, AAU, Godhra, and Gujarat, India. The setup involved horizontal rectangular Thick Perspex sheets, each measuring 6 meters in length, securely fastened on either side of the MS Sheet bed. Two gates were installed, one at the upstream end and the other at the downstream, with adjustable features to regulate their positions. Transparent Perspex sheets, 6 mm thick and 6 meters long, were installed on both sides of the Test Section, facilitating direct observation of flow patterns, types, and general flow regimes within the flume. An extensive analysis was conducted on various significant flow parameters (h, v, E, n, Fr, Re) which provided a comprehensive range of data regarding different hydraulic structures with varying configurations in relation to discharge rates and channel bed slopes. The scientific evaluation of the mentioned hydraulic structure involved a visual characterization of hydraulic jumps, Froude number values within the channel, establishment of Stage Discharge relationships, evaluation of the hydraulic performance of scaled-down broad-crested rectangular weirs, determination of Discharge Coefficients and associated predictive equations, as well as an examination of composite influences and variability of Manning's roughness coefficient under diverse flow scenarios concerning both discharge rates and channel bed slope conditions. Notably, Manning's roughness coefficient was meticulously observed under various test conditions, encompassing multiple channel bed slopes (0.5, 1.0, 1.5, and 2 percent) and varying discharge rates (up to 6 measurements for a single structure within the specified ranges). While the study involved a total of approximately 100 test runs with various permutations and combinations, the findings presented herein are confined to about 75 test runs, including multiple replications.

Structural configurations of flume SETUP

The detailed configurations in regards to components/ constituents of tilting hydraulic flumes are provided below in abstract shape followed by a functional conceptual line diagram in, Upstream & Downstream Gates with Fig. **1** handle, Sump Tank: Made from fibre Sheet with MS Angle reinforcement (Size 140 cm (L) x 95 cm (B) x 35 cm (H) with capacity = 500 Liters, Monoblock Pump: 3 HP, Centrifugal, Size 80 x 65 mm, Discharge Head 2 m (range 1.5 to 3 m). The potential capacity of discharge = 10 L/s, RPM 2840, 3 Phase, 230 VAC, Make Kirloskar", Bye-pass arrangement with Gate Valve, "Gun Metal" for controlling the flow, Hook Gauge with Trolley. Range: 0 – 600 mm, Manometer: Acrylic Body Differential Type Range 0–500 mm, Orifice Plate: Made from MS Plate, Dia. 34.5mm, Piping: GI Material – 69 mm size, Starter: AC 3 phase, 7.5 hp.

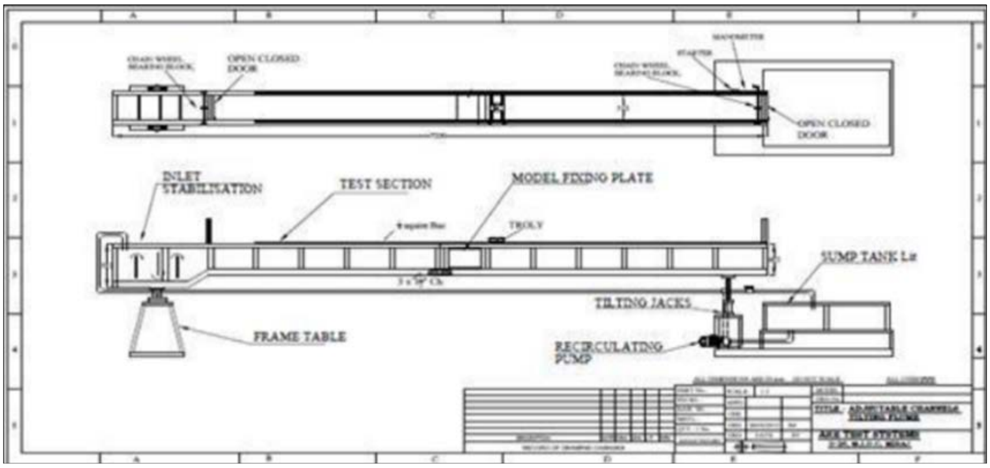


Fig 1: Conceptual line diagram for hydraulic flume studies under present study

The real pictorial view of a tilting hydraulic flume as adopted in the present study is illustrated in Fig. 2. The flume comprising a 500-liter main water tank had a provision to provide the system with adjustable flow rates with the help of a discharge regulator. The ranges of available discharge rates varied from 0.5 lit/sec to 5 lit/sec which were suitably utilized in the present study by incorporating different sloping conditions. The broad categories of channel bed slopes as adopted in present studies remain 0.5%, 1%, 1.5% & 2%. Systematic observations were undertaken inside the flume adopting standard protocols & delivering below given specified entities, Flow depths at varied close interval locations along the longitudinal section of the flume under various sets of discharge rates as well as channel bed slopes. Flume cross-sectional areas, Magnitudes of velocity heads, Water flow velocities, Total energy head, Values of Manning's roughness coefficients, Froude no., Reynolds no. & Type, location & extent of hydraulic jumps as observed during different test conditions under the above-cited combinations.

Fig 2: The real physical view of standard tilting hydraulic flume as adopted in present study

Description of Downscaled Physical Models of Hydraulic Structures

The structures planned and utilized in this study were Stepped Spillway-Wooden. Based upon Experimental Test Conditions in Tilting Hydraulic Flume with Varied Hydraulic configurations in terms of discharges, flow depths, and type of hydraulic structures, a sincere attempt was made to intensively observe the sets of observations inside the hydraulic flume. The average range of discharges, structure dimension as well as slopes as adopted in the study are provided in table 1.

Table 1: Average range of experimental limits adopted in the tilting flume study

Types of Structures	Range of Channel bed slopes (%)	Range of Discharges Rates (Liters/Sec)	Dimensions of the structures
Stepped Spillway – Wooden	0.5 to 2.0 (0.5, 1.0, 1.5,2.0)	0.5 to 5.0 (Random Values – 3 to 4 numbers in each run)	slope tan50 i.e. 1: 3.75; Height 20 cm Base Width 75 cm with 4 equal steps @ 5 cm

This structure was fabricated by utilizing 18 mm plywood, with a piece model comprising steps of desired heights and widths maintaining a predetermined average slope line. The dimensional configuration of this specific hydraulic structure is provided in Table 3.2, while the pictorial view of finally fabricated structure is illustrated in Figure 3. The exact details of the placement of this hydraulic structure inside the tilting hydraulic flume are shown in Figure 4, which is self-explanatory to depict the coverage at upstream as well as downstream ends along with peculiar patterns of flows.

Fig 3: A Pictorial View of Stepped Spillway- Wooden, Showing Physical Configurations as well as flow patterns while placing it In Flume Channel

Fig 4: A Pictorial View of Stepped Spillway – Wooden, Showing Physical Configurations as well as flow patterns while placing it In Flume Channel

Monitoring flow parameters

Monitoring & Recording of Flow Parameters the parameters that were monitored in this research work and the simplistic procedure/methodology adopted for their recording remained as flows, Flow depths, Flow Velocity Heads, Froude Number, Reynold's number, Manning's Roughness Coefficients, Patterns of Hydraulic Jumps.

Hydraulic Jump & Froude Number inside the Existing Channel

The present study dealt with such objectives in mind, where the values of Froude numbers and Reynold's numbers are critically observed and assessed in real flow conditions using a variety of down-scaled hydraulic structures in tilting flumes. The net variations all along the channel bed length are documented reflecting the significant variations in this regard under various options of hydraulic structures which is shown in Fig. 5.

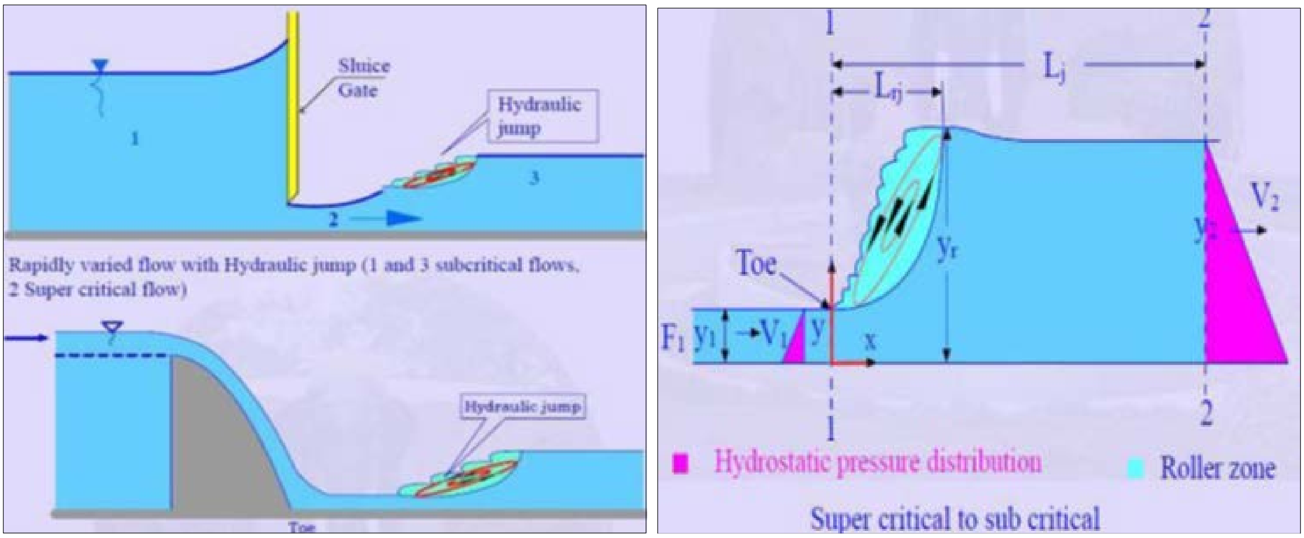


Fig 5: Conceptual Framework of any Hydraulic Jump during Flows in Open Channel

The Froude number in the approach channel (Fr), which is the square root of the ratio of inertial to gravity forces, plays an important role in flume and weir design (Eq.1).

$$F_r = \frac{V}{\sqrt{gh}}\ldots\ldots\ldots\ldots\ldots\ldots \quad (1).$$

In order for a hydraulic jump to occur, the flow must be supercritical. The jump becomes more turbulent and more energy dissipates, as Froude's number increases. A jump can occur only when the Froude's number is greater than 1.0. This number, representing the ratio of inertial and gravity forces, is expressed by the average flow velocity V and the celerity of gravity wave in shallow water.$\sqrt{g.y}$ Using the Froude number one can distinguish Critical flow when Fr = 1, Supercritical flow when Fr> 1, and Subcritical flow when Fr< 1.The pictorial view of the hydraulic jump (Moore, 1943) is shown in Fig. 6.

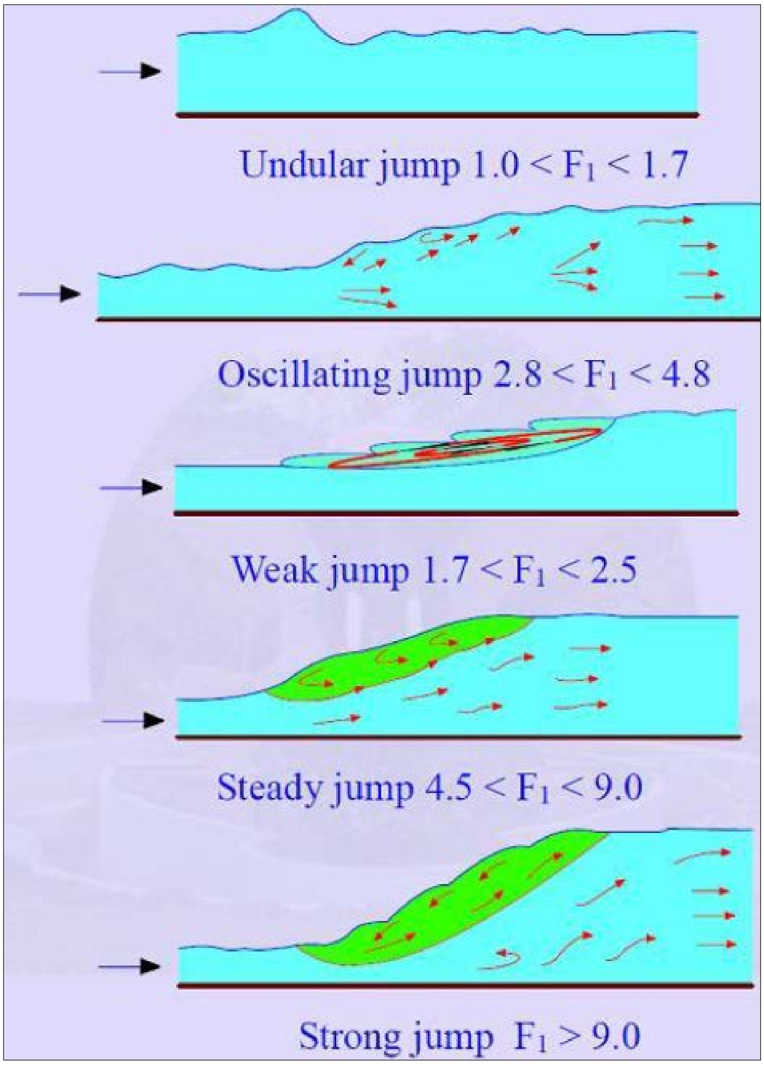


Fig 6: Classifications of Hydraulic Jumps from a Practical Point of View

Composite Influences and Variability of Roughness

For the estimation of such roughness historically we have three basic models, namely Manning's formula, Chazy's formula, and Darcy's Weisbach formula. In the present study only Manning's roughness is taken into account whose standard equation is illustrated as follows in eq.2,

$$V=\frac{1}{n}R^{2/3}S^{1/2}\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (2).$$

Where v is the mean flow velocity, n is Manning's roughness coefficient, R is hydraulic radius, and S is the energy grade slope which is sometimes assumed to be equivalent to channel bed slopes specifically under kinematic wave flows.

Similarly, Reynold's number also plays a very important role in deciding the turbulences and the nature of flows and flow regimes under different conditions. For flows of water in open channels, Reynold's number can be given by below given generalized eq.3,

$$Re = \frac{vD}{10^{-5}}\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3).$$

In a simplistic and direct format the 'v' is the velocity 'D' is hydraulic depth, and 10^{-5} is the value of kinematic viscosity of water placed directly here.

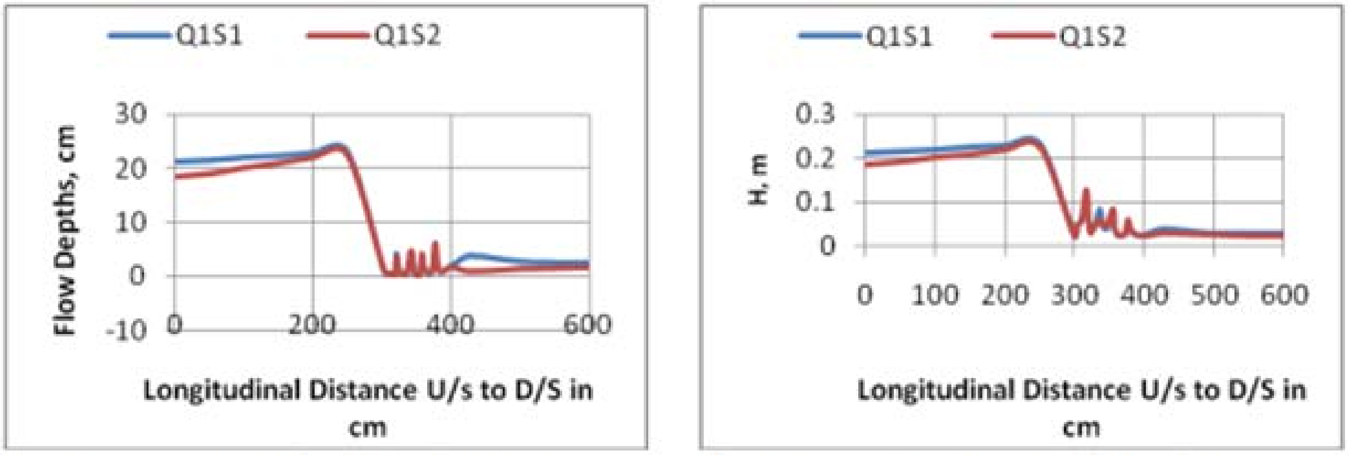
Table 2: Overall range of hydraulic parameters during flume test runs using Steped Spillway (Wooden)

Flow Parameters	Low Discharge Conditions (1.875 l/s)								High Discharge Conditions (3.35 l /s)							
	Low Bed Slope (0.5%)				High Bed Slope (1.5%)				Low Bed Slope (0.5%)				High Bed Slope (1.5%)			
	Max	Min	Avg.	Deviation in%	Max	Min	Avg.	Deviation in%	Max	Min	Avg.	Deviation in%	Max	Min	Avg.	Deviation in%
h	23.20	0.50	6.61	97.84	22.60	0.40	6.06	98.23	24.30	0.80	7.25	96.71	23.70	0.90	6.75	96.20
v	1.25	0.03	0.46	97.84	1.56	0.03	0.50	98.23	1.40	0.05	0.53	96.71	1.24	0.05	0.56	96.20
E	0.23	0.02	0.09	89.75	0.23	0.02	0.08	89.48	0.24	0.04	0.10	85.56	0.24	0.04	0.09	85.23
n	0.53	0.002	0.13	99.70	0.89	0.002	0.20	99.78	0.32	0.002	0.08	99.38	0.53	0.004	0.13	99.22
Fr	5.74	0.03	1.70	99.50	7.99	0.03	1.87	99.63	5.11	0.05	1.50	99.06	4.30	0.05	1.59	98.85
Rey No	604.8	245.4	487.32	59.4	608.8	249.3	495.89	59.0	1059.5	426.0	845.99	59.8	1052.9	432.6	856.90	58.9

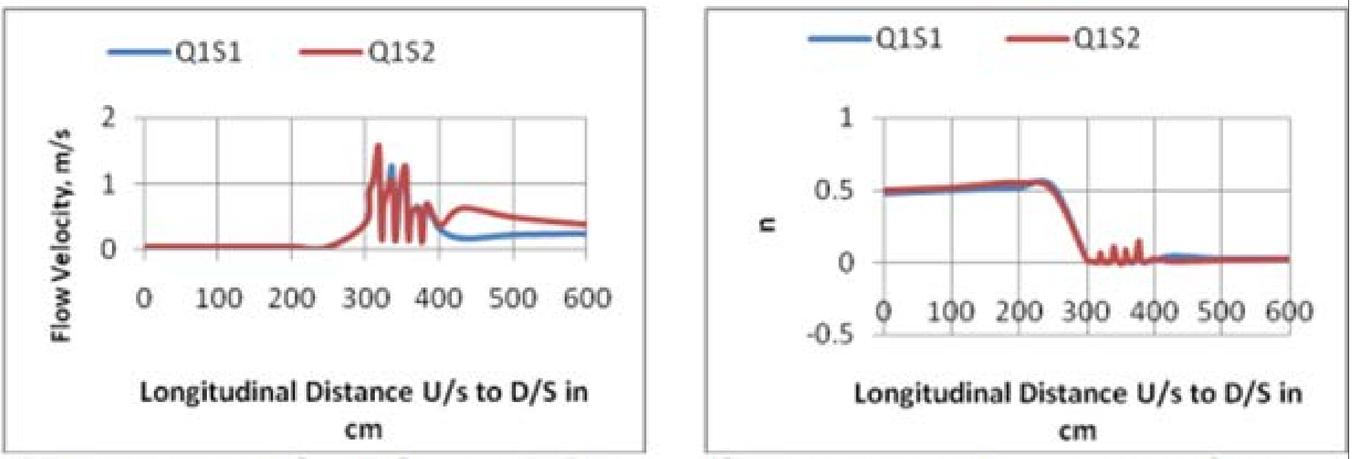
Note: h - Flow Depths (cm), v - Flow Velocities (m/s), H - Potential Head (m) n - Manning's Roughness, Fr - Froude Number, Re - Reynold's Number

Test Run Configurations : Channel Bed Slope = 0.5, 1.5 %
Discharge, Q_1 = 1.875 L/s

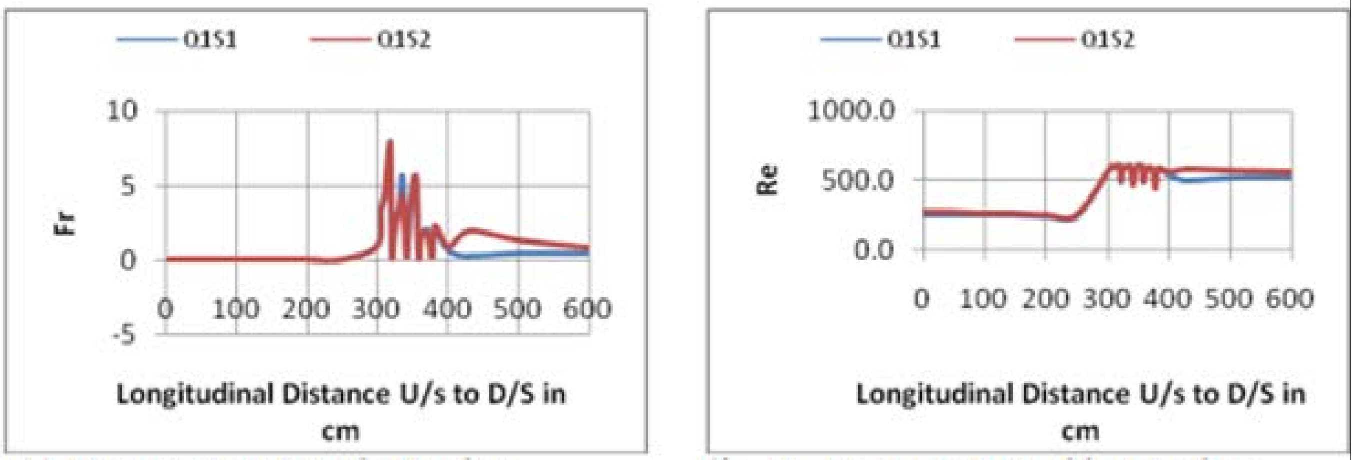
Hydraulic Structure : Stepped Spillway



(a) Variations in Flow Depths (cm) *(b) Variations in Potential Head (m)*

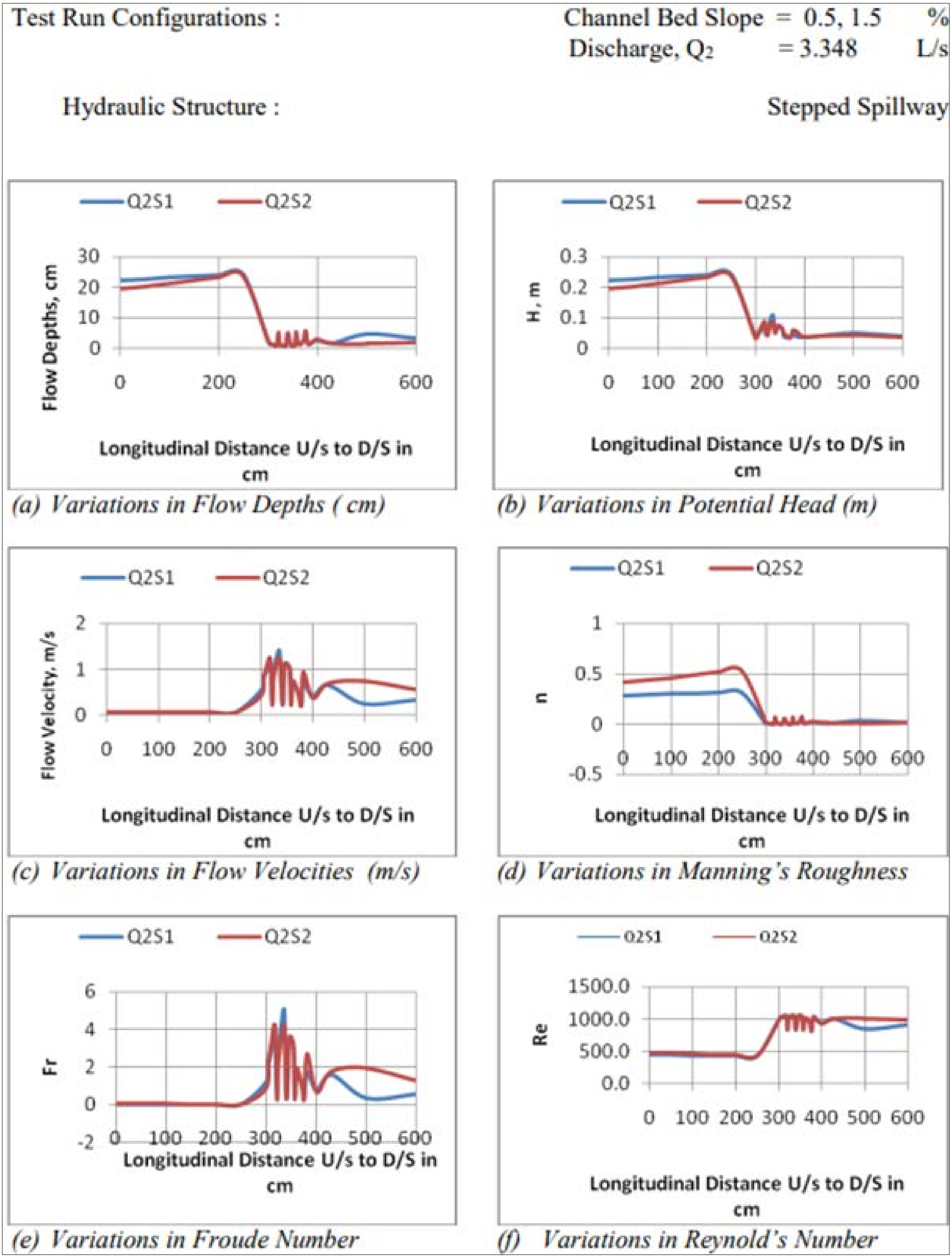


(c) Variations in Flow Velocities (m/s) *(d) Variations in Manning's Roughness*



(e) Variations in Froude Number *(f) Variations in Reynold's Number*

Fig 7: Observed Hydraulic Parameters for Flows in Channel having Stepped Spillway with 1.875 L/s Discharge on 2 Different Channel Bed Slopes



(a) Variations in Flow Depths (cm)

(b) Variations in Potential Head (m)

(c) Variations in Flow Velocities (m/s)

(d) Variations in Manning's Roughness

(e) Variations in Froude Number

(f) Variations in Reynold's Number

Fig 8: Observed Hydraulic Parameters for Flows in Channel having Stepped Spillway with 3.348 L/s Discharge on 2 Different Channel Bed Slopes

Result and Discussion

The averaged values of h under low discharge conditions changed from 6.61 to 6.06 cm when the channel bed slope enhanced from 0.5 to 2%. Similarly, under high discharge conditions these values remained at 7.25 & 6.75 cm respectively. The avenged values of v under low discharge conditions remain 0.46 m/s, moreover, when the channel bed slope is enhanced from 0.5 to 2% it is enhanced to 0.50 m/s. Under high discharge conditions, it was found to be 0.53 to 0.56 m/s. similar values and changes in regard to other flow parameters are well depicted in Table 2 which are self-explanatory. The detailed values of all the flow parameters in respect of 2 specific discharge rates 1.875 and 3.349 L/se under 2 different slopes are well shown in Figures 7 and 8, where the trends of variations as well as the net values of 6 different flow parameters (as observed under present experimental set up) is clearly depicted showing significant variations and uniqueness with regards to respective hydraulic structures and associated flow conditions.

Coefficients of Discharges and Predictive Equations for Different Flow Conditions

The whole scenarios in regards to flow depths, flow velocities, roughness, Fr values, Re values, and over all flow regime during these additional runs is elaborately depicted in Figures 4.1 to 4.24, giving a broad range of flow conditions. The Cd values for each categorized hydraulic structure under different sets of flow regimes/ conditions showed significant variations in accordance to type of structures as well as the flow conditions. The Cd values for the stepped Spillway were found the be in the range of 0.004 to 0.107. Quadratic equation was found most easy and most suitable function among the variety of alternate equations and models, hence the final shape of Cd predictive equations for hydraulic structures under study is shown in eq.(4), incorporating the numerical values of associated coefficients/parameters.

Stepped Spillway (wooden) $Cd = -0.0134 + 7.967\,H - 141.29\,H^2$ … (4)

Where, Cd = Coefficient of Discharge; H = Total potential Head (m)

The Predictive performance of the above-cited equations was tested and categorical comparisons of observed and predicted values of Cd values under different sets of conditions in regards to flows as well as hydraulic structures are illustrated in Figure 9, where the qualitative performance of these synthesized equations is well demonstrated.

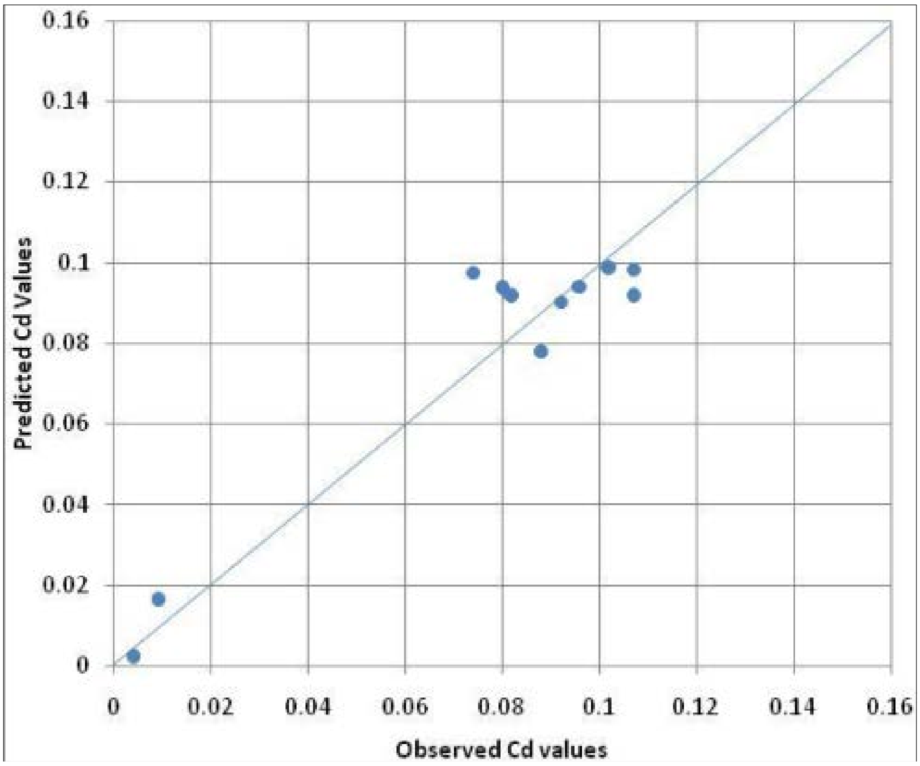


Fig 9: Validation Results of Cd Predictive Equations for Stepped Spillway

The predictive equations were derived for down-scaled models under generalized conditions with a pooled data set earmarked for calibration. Detailed predictive performances of these C_d equations are reported in the chapter reflecting their possible utilities in some of a like ungauged situations.

Conclusion

A considerable time and effort were made in reviewing, screening, designing, and fabricating some of the hydraulic structures for use in this flume-based experimentation. Stepped Spillway with overall net slope (15 degree i.e. 1: 3.75 H: V ratio, Height 20 cm, Base Width 75 cm with 4 equal steps @ 5 cm). A stepped Spillway was utilized in the flume channel (pacing it at middle reach i.e. at about 3 meters from the upstream end of the flume) to control or regulate the flows all along the channel length of 6 meters, the observed averaged values of h under low discharge conditions changed from 6.61 to 6.06 cm when the channel bed slope enhanced from 0.5 to 2%. Similarly, under high discharge conditions these values remained at 7.25 & 6.75 cm respectively. The avenged values of v under low discharge conditions remain 0.46 m/s, moreover, when the channel bed slope is enhanced form 0.5 to 2% it is enhanced to 0.50 m/s. Under high discharge conditions it was found to be 0.53 to 0.56 m/s.

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