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Research Paper

Comparative analysis for estimation of the height of training wall of convergent stepped spillway

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Abstract

For a dam system with inadequate capacity of spillway, provision of (RCC) roller compacted concrete stepped spillways with converging training walls prove to be an appropriate alternative. Sufficient number of guidelines and literature references are available on the design of straight side walled stepped spillways. The need was felt to conduct the experiments on stepped spillways with convergent training walls, as limited literature is available. This paper presents the comparative analysis of an experimentation conducted on flow over convergent stepped spillways having 1:1 chute slope with 45o convergence angle for different step height ratios leading to different step height variations. The findings are presented in the form of expressions for the maximum depth of flow through the training walls required to accommodate the flow rate. The observed maximum depth of flow along the training walls also compared with estimated maximum height of the training wall as per the criteria available within literature and percentage variation is worked out taking into account the step height variation. Outcomes of the experimental findings are expected to be useful for assessment of height of training walls by the hydraulic design engineers involved in rehabilitation of existing dam system and also in design of the modified spillway system that is necessarily associated with convergent training walls and stepped chute.

Keywords: *Convergence Angle; Percentage Variation; Step Height Ratio; Stepped Spillways.*

1. Introduction

A stepped spillway is a spillway provided with a series of steps from just below the crest up to the toe of the spillway. The advent of provision of steps on the downstream face of the spillway chute not only enhance the energy dissipation rate but also reduces the size of energy dissipater downstream which in turn reduces the cost of construction of stilling basin downstream of the stepped spillway. Figure 1 shows a typical cross-section of stepped spillway.
Lower flow velocities and occurrence of the high amount of air entrainment results in decrease in cavitation risk resulting from excessive sub-pressures. Aeration results into bulking of flow and therefore, the spillway requires taller training walls. The effect of convergence increases this effect due to shock waves, and higher training walls are required. With limited literature references available on stepped spillways with convergent training walls as compared to step spillways having straight training walls, the present study is proposed to determine experimentally the effect of converging training walls on flow characteristics of stepped spillway. Because of the topographical constraints, many of the stepped spillways are expected to be made with convergent training walls in due course of time. In the present study, The observed maximum depth of flow through the training walls also compared with estimated maximum height of the training wall as per HUNT and percentage variation is worked out taking into account the step height variation.

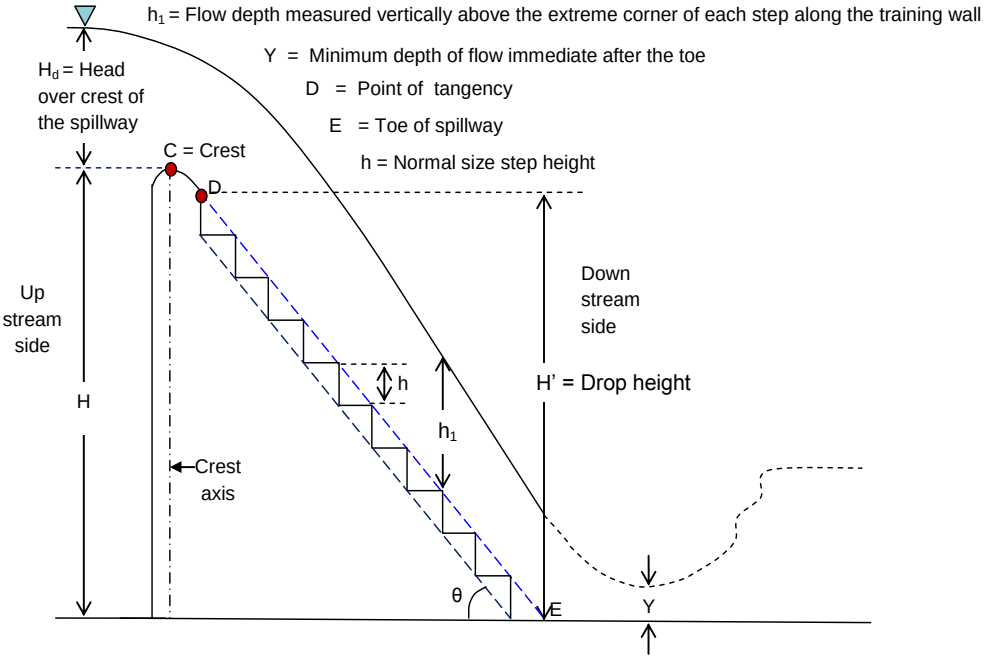

Fig. 1: Definition Sketch of Stepped Spillway.

Sorensen (1985) [1], Peyras et al. (1992) [2], Christodoulou (1993) [3], Chanson (1994) [4-5], Chamani and Rajaratnam (1999) [6], Barani et al. (2005) [7], Chanson (2006) [8], Chinnarasri and Wongwises (2006) [9], and many researchers highlighted the issues on study of stepped spillways.

Hunt et al. (2008) [10] evaluated the flow characteristics over a sloping stepped chute (3H: 1V) with varying training wall convergence angles based in the study conducted on a 1:22 scale three-dimensional physical model. He observed the required training wall height varied from the critical depth to thrice the critical depth for 15o convergence angle to at the 52o convergence angle respectively.

A major reference on a requirement of height of the training wall convergent stepped spillway was presented by Hunt et al. (2012) [11] as a follow-up work, wherein a simplified expression to predict the vertical height of the training wall was developed. This training wall height is a function of centerline depth of flow, and the generalized expression was developed on the basis of simplified control volume momentum analysis. Due to the requirement of an empirical adjustment associated with the force term during the derivation of the proposed expression, more testing of this expression was warranted. With this background, it was felt necessary to conduct the experiments to develop an expression for estimation of training wall height for 45o convergent stepped spillways.

Wadhai et al. (2014) [12] proposed the regression equation for prediction of training wall height of convergent stepped spillway based on the experimental study conducted over 1H:1V sloping stepped chute with 45 degree convergence angle normalized by a different step height ratio.

Cheng et al. (2014) [13] performed the exhaustive analysis to expand the available data from step geometry for estimation of surface roughness length z0, displacement height ds and the relationship of ds and z0. He summarizes that, ds and z0 depend on the key factor, i.e. hydraulic roughness height ks. Based on different flow rate, step height, step width and intake froude number, fixing the origin of vertical coordinates at the tip of the steps the relations z0/ks = 0.06 to 0.1, ds/ks = 0.22 to 0.27, and ds/z0 = 2.2 to four show good value along with the distance down the stepped spillways.

2. Experimental setup

Experimental setup consists of water recirculation system for optimal use of the available water from the existing underground sump. A centrifugal pump of 10 HP capacity lifts the water from underground sump and discharge into storage reservoir through delivering pipe. The delivery pipe provided with an arrangement of venturimeter with U-tube manometer for measurement of discharge. Storage reservoir with 9 square meter plan area and 1.75 m depth constructed on the upstream side of the convergent stepped spillway. Ogee type 2.66 m wide long crested weir and 1:1 slope stepped chute was followed by 0.5 m wide and 10 meter log toe channel.

Model step height (h) of 0.12 m, 0.06 m, 0.03 m and 0.015 m which in turn corresponds to respective step height ratios, H* = (H'/ h) of 10, 20, 40 and 80 were tested during the experimentation. Water allowed to flow over the convergent stepped spillway of drop height H = 1.23 m and consequently, through a toe channel and empties into a collecting tank for volumetric measurement of discharge. Discharge measured in a normal range of 20 liters /sec to 64 liters /sec. Vernier type point gauges were used as a sensitivity of 0.1 mm for measurement of water surface levels in x and y directions on the step and also for measurement of flow depths at other locations.

For clear visibility of flow over the stepped spillway and in a toe channel, the training walls of convergent stepped spillway and side walls of toe channel were fabricated with acrylic sheet. Venturimeter and a triangular notch was calibrated prior to begin with the experimentation.
Photographs of convergent stepped spillway experimental setup constructed at G. H. Raisoni College of Engineering, Nagpur in collaboration with VNIT, Nagpur, and Maharashtra State, India is shown in Figure 2.



Fig. 2: Photographs of Convergent Stepped Spillway Experimental Setup during Experimental Runs.

3. Experimental observations and computations

Table 1, Table 2, Table 3, Table 4 and Table 5 presents all the data sets of observations and computations for the experimental runs for the different step height ratios' H* = 10, 20, 40, 80 and for smooth ogee spillway respectively. These table show the maximum depth of flow h1max observed along the converging training walls compared with vertical training wall height above the chute floor formed by connecting the extreme corner of steps as per HUNT (2008) for the different experimental runs. These tables also shows the maximum depth of flow h1max observed along the converging training walls compared with vertical training wall height above the chute floor formed by connecting the extreme corner of steps as per HUNT (2012) representing the percentage variation for the different experimental runs.

Table 1: Experimental Observations and Computations for Θ = 45º, Ø = 45º, H* = 10 and H = 0.12 M.

Discharge, Q, m3/sec	Dimensionless critical depth of flow, Yc / H	Maximum depth of flow along the converging training wall, h1max, m		% Variation	Maximum depth of flow along the converging training wall, h1max, m		
		Observed	As per HUNT (2008)		Observed	As per HUNT (2012)	% Variation
0.020	0.0148	0.0960	0.0545	43.27	0.0960	0.0702	26.86
0.032	0.0198	0.1008	0.0709	29.63	0.1008	0.0914	09.28
0.044	0.0246	0.1062	0.0778	26.74	0.1062	0.1003	05.55
0.056	0.0289	0.1116	0.0836	25.13	0.1116	0.1077	03.47

Table 2: Experimental Observations and Computations for Θ = 45º, Ø = 45º, H* = 20 and H = 0.06 M.

Discharge, Q, m3/sec	Dimensionless critical depth of flow, Yc / H	Maximum depth of flow along the converging training wall, h1max, m		% Variation	Maximum depth of flow along the converging training wall, h1max, m		
		Observed	As per HUNT (2008)		Observed	As per HUNT (2012)	% Variation
0.025	0.0168	0.1140	0.0617	45.90	0.1140	0.0795	30.26
0.032	0.0200	0.1182	0.0732	38.06	0.1182	0.0944	20.14
0.040	0.0233	0.1226	0.0819	33.22	0.1226	0.1056	13.90
0.051	0.0272	0.1272	0.0921	27.63	0.1272	0.1187	06.70
0.060	0.0302	0.1320	0.1000	24.24	0.1320	0.1289	02.33

Table 3: Experimental Observations and Computations for Θ = 45º, Ø = 45º, H* = 40 and H = 0.03 M.

Discharge, Q, m3/sec	Dimensionless critical depth of flow, Yc / H	Maximum depth of flow along the converging training wall, h1max, m		% Variation	Maximum depth of flow along the converging training wall, h1max, m		% Variation
		Observed	As per HUNT (2008)		Observed	As per HUNT (2012)	
0.024	0.0165	0.1124	0.0526	53.23	0.1124	0.0678	39.71
0.035	0.0212	0.1156	0.0646	44.08	0.1156	0.0833	27.90
0.042	0.0239	0.1209	0.0712	41.09	0.1209	0.0918	24.06
0.052	0.0276	0.1264	0.0819	35.21	0.1264	0.1056	16.47
0.063	0.0315	0.1348	0.0939	30.35	0.1348	0.1210	10.21

Table 4: Experimental Observations and Computations for Θ = 45º, Ø = 45º, H* = 80 and H = 0.015 M.

Discharge, Q, m3/sec	Dimensionless critical depth of flow, Yc / H	Maximum depth of flow along the converging training wall, h1max, m		% Variation	Maximum depth of flow along the converging training wall, h1max, m		% Variation
		Observed	As per HUNT (2008)		Observed	As per HUNT (2012)	
0.025	0.0170	0.0598	0.0383	35.93	0.0598	0.0494	17.39
0.033	0.0206	0.0667	0.0464	30.50	0.0667	0.0598	10.40
0.041	0.0234	0.0706	0.0527	25.42	0.0706	0.0679	03.85
0.051	0.0272	0.0805	0.0612	24.03	0.0805	0.0788	02.05
0.064	0.0317	0.0925	0.0711	23.10	0.0925	0.0917	00.86

Table 5: Experimental Observations and Computations for Θ = 45º, Ø = 45º and Smooth Ogee Chute.

Discharge, Q, m3/sec	Dimensionless critical depth of flow, Yc / H	Maximum depth of flow along the converging training wall, h1max, m		% Variation	Maximum depth of flow along the converging training wall, h1max, m		% Variation
		Observed	As per HUNT (2008)		Observed	As per HUNT (2012)	
0.026	0.0172	0.0526	0.0387	26.42	0.0526	0.0499	05.14
0.035	0.0213	0.0596	0.0479	19.61	0.0596	0.0618	03.52
0.042	0.0239	0.0624	0.0537	13.94	0.0624	0.0692	09.88
0.052	0.0275	0.0664	0.0619	06.79	0.0664	0.0798	16.78
0.063	0.0315	0.0726	0.0708	02.49	0.0726	0.0913	20.45

4. Analysis of experimental data

The required training wall height is governed by the flow run-up due to convergence of chute walls. The flow depths along the wall shall form the basis to decide the minimum training wall height requirement so that the flow does not overtop the convergent training walls and maintaining the safety to the structure. Water surface profile was plotted along the centerline of the spillway and also along the convergent walls from the collected experimental data and observed that the flow depths near the wall were more than those at the centerline of the spillway. Observations indicated that there were no transverse waves for any of the step height ratios and as compared to ogee spillway the flow over the convergent stepped spillway was more bulked, and air entrainment occurred for nearly all the observations.

Figure 3 illustrates the observed water surface profiles along the side wall for different discharge for a step height ratio H* = 20.

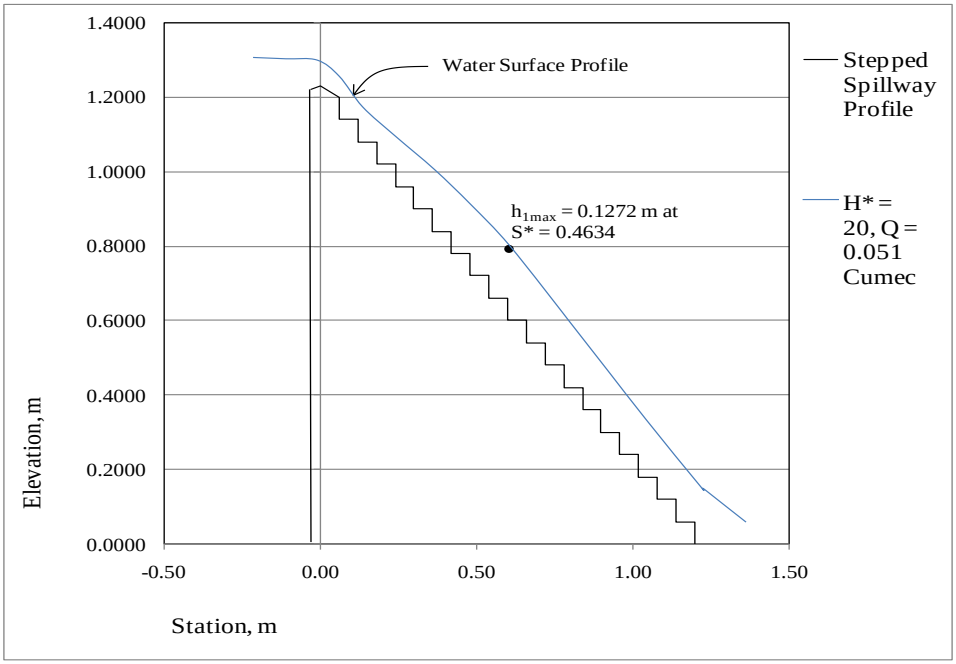

Fig. 3: (A): Water Surface Profiles Along the Side Wall of Spillway for Step Height Ratio, H* = 20, Q = 0.051 Cumec for Θ = 45°, Ø = 45°.

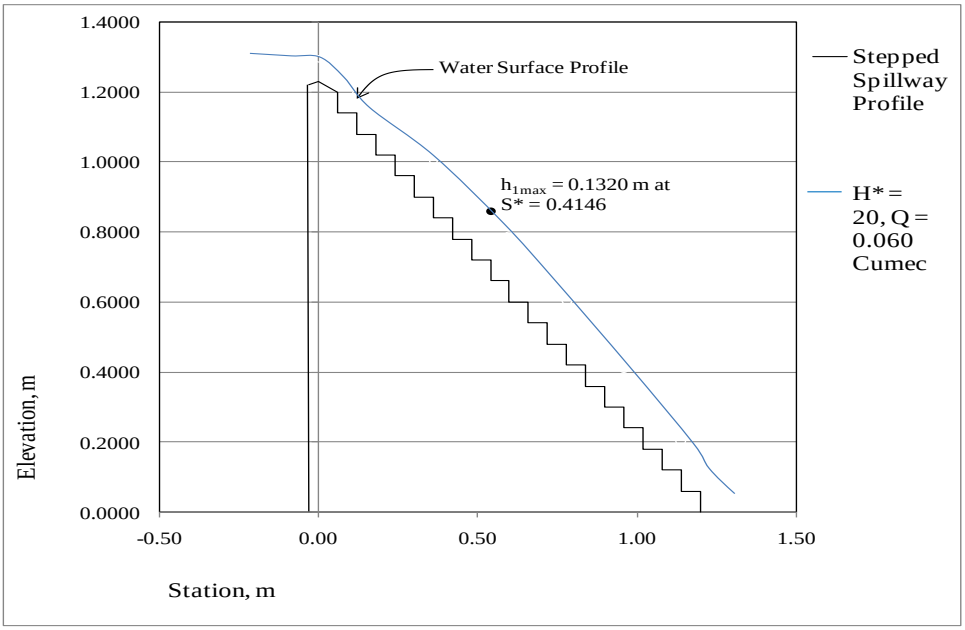

Fig. 3: (B): Water Surface Profiles Along the Side Wall of Spillway for Step Height Ratio, H* = 20, Q = 0.060 Cumec for Θ = 45°, Ø = 45°.

As the maximum depth of flow through the wall (h1max) would determine the training wall height, a plot showing variation of h1max {with reference to observed values, as per HUNT (2012) and as per HUNT (2012)} with discharge is presented in Figure 4 for the different step height ratio. The regression equations have been obtained and are as follows.

Maximum depth of flow observed along the side wall versus discharge for θ = 45° and ø = 45°.

$$For\ H^* = 10,\ [\,h_{1max}] = 0.441[Q] + 0.086\,,\ R^2 = 0.999 \quad (1)$$

$$For\ H^* = 20,\ [\,h_{1max}] = 0.506[Q] + 0.101\,,\ R^2 = 0.997 \quad (2)$$

$$For\ H^* = 40,\ [\,h_{1max}] = 0.580[Q] + 0.096\,,\ R^2 = 0.978 \quad (3)$$

$$For\ H^* = 80,\ [\,h_{1max}] = 0.836[Q] + 0.038\,,\ R^2 = 0.994 \quad (4)$$

$$For\ Ogee,\quad [\,h_{1max}] = 0.508[Q] + 0.040\,,\ R^2 = 0.988 \quad (5)$$

These expressions are proposed to be used for estimation of height of training wall of convergent stepped spillway with chute slope of 1:1.and convergence angle of 45o.

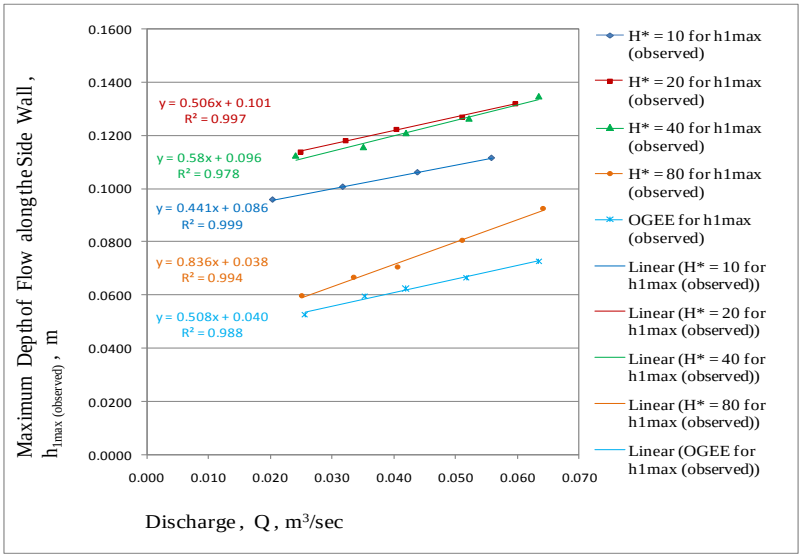

Fig. 4: (A): Maximum Depth of Flow Observed Along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and H* = 10, 20, 40, 80 & Smooth Ogee.

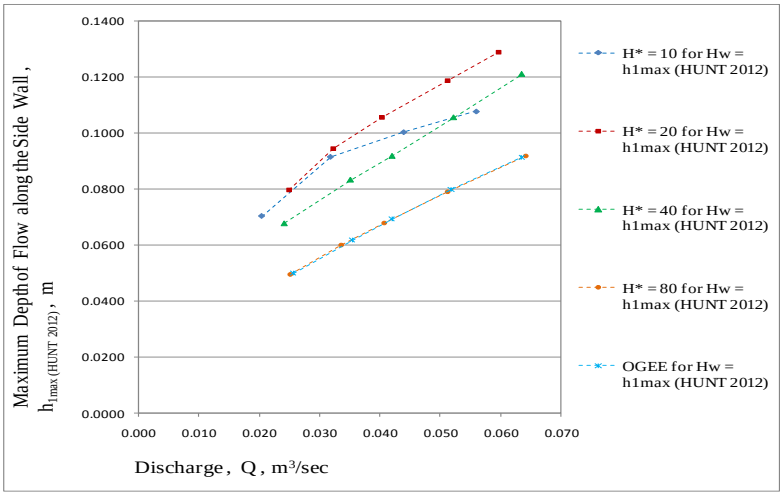

Fig. 4: (B): Maximum Depth of Flow (As Per HUNT 2012) Along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and H* = 10, 20, 40, 80 & Smooth Ogee.

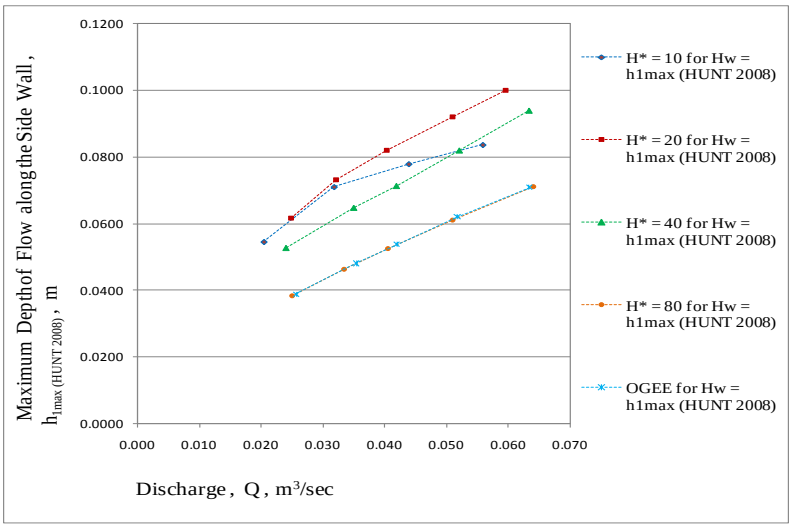

Fig. 4: (C): Maximum Depth of Flow (as Per HUNT 2008) Along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and H* = 10, 20, 40, 80 & Smooth Ogee.

The comparative plot of variation of h1max {corresponding to observed values, as per HUNT (2012) and as per HUNT (2012)} with discharge is presented in Figure 5.

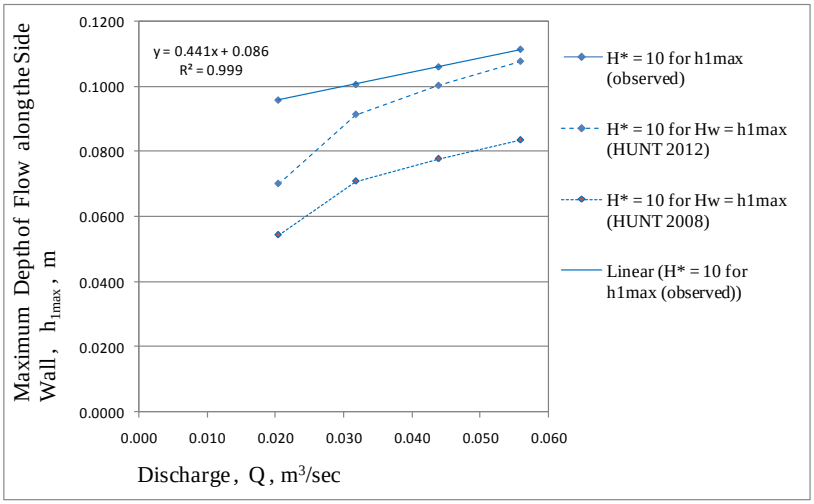

Fig. 5: (A): Maximum Depth of Flow along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and H* = 10.

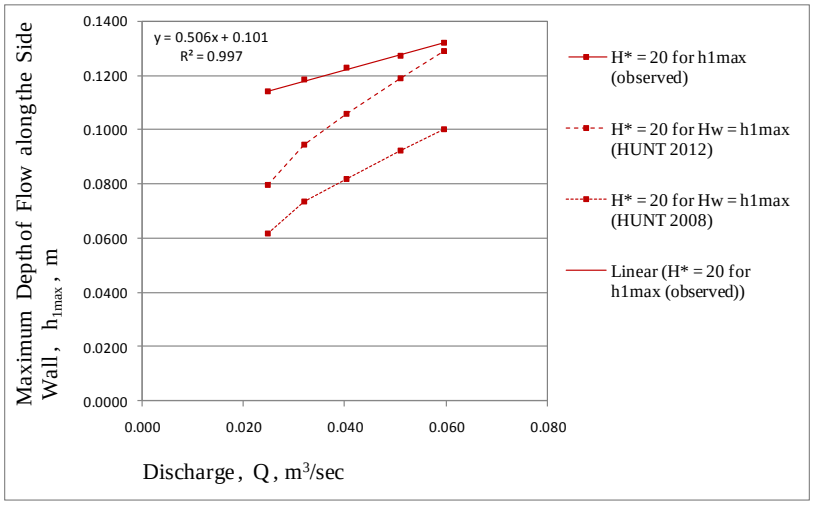

Fig. 5: (B): Maximum Depth of Flow along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and H* = 20.

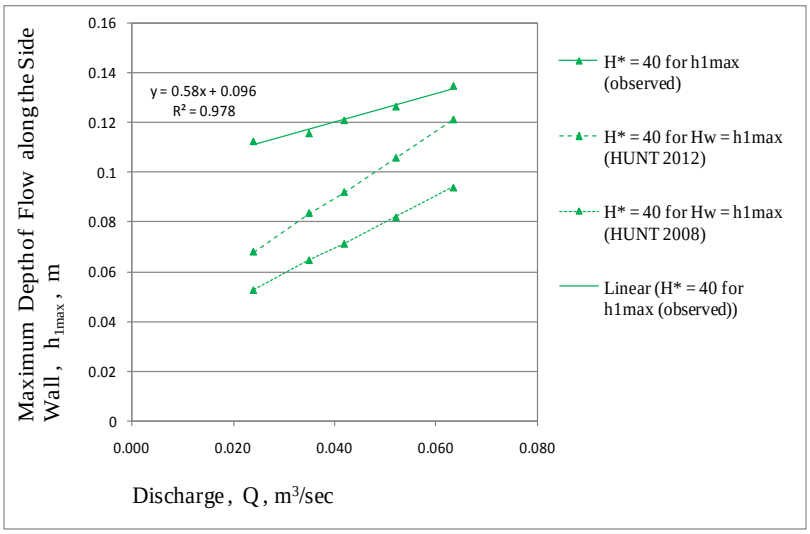

Fig. 5: (C): Maximum Depth of Flow along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and H* = 40.

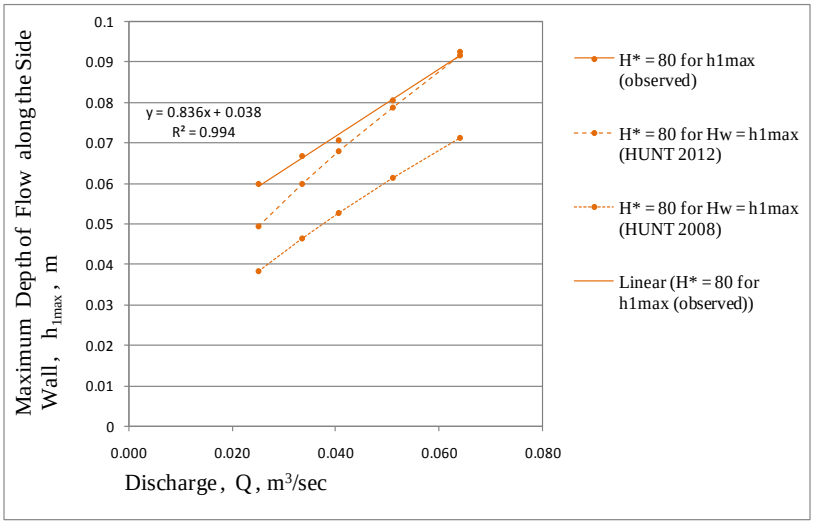

Fig. 5: (D): Maximum Depth of Flow along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and H* = 80.

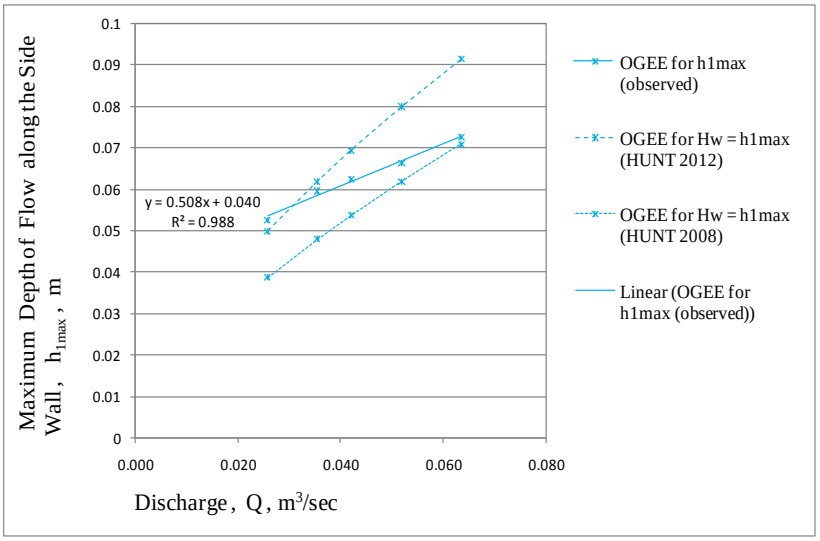

Fig. 5: (E): Maximum Depth of Flow along the Side Wall versus Discharge for Θ = 45°, Ø = 45° and Smooth Ogee.

The observed maximum depths of flow along the training wall were compared with the corresponding critical depths. Also percentage variations in observed maximum flow depths along the training wall were estimated as per HUNT (2008) and HUNT (2012) in Table 6.

Table 6: Comparative Analysis of Maximum Depth of Flow along the Training Wall for Θ = 45º, Ø = 45º.

Step height ratio, H*	Step height, h, m	Observed maximum depth of flow along the converging training wall, h1max, m	% Variation in observed maximum depth of flow along the converging training wall	
			As per HUNT (2008)	As per HUNT (2012)
10	0.120	3.10Yc to 5.30 Yc	25.00 to 43.00	03.50 to 27.00
20	0.060	3.55 Yc to 5.55 Yc	24.00 to 46.00	02.50 to 30.00
40	0.030	3.45 Yc to 5.55 Yc	30.50 to 53.00	10.00 to 40.00
80	0.015	2.35 Yc to 2.90 Yc	23.00 to 36.00	01.00 to 17.50
Smooth Ogee	Smooth Ogee	1.85 Yc to 2.50 Yc	02.50 to 26.50	00.0 to 05.00

5. Conclusions

An experimental study has been carried on convergent stepped spillway having 1:1 chute slope and 45o convergence angle for different step height ratios. As compared to ogee spillway the flow over the convergent stepped spillway was observed to be more bulked and air entrained. For spillway, rehabilitation works with inadequate availability of downstream space, provision of stepped spillways with convergent training walls will have to be made. The observed maximum flow depth at the convergent training wall normalized by the step height was found to increase with an

increase in discharge. The observed maximum depth of flow through the training wall found to vary in a range of 23 % to 53 % and 1 % to 40 % when compared with HUNT (2008) & HUNT (2012) respectively for chute slope of 1:1 and convergence angle of 45o depending upon the step height ratio. Depending upon the step height, the maximum flow depth near the convergent training wall was found to lie between 2.35 to 5.55 times the critical depth of flow. The regression equations {Eq. (1) To (5)} for observed maximum depth of flow near the converging walls have been proposed on the basis of experimental observations and its analysis. A good correlation was obtained for all the regression equations, as the value of a coefficient of determination is very high. The regression equations presented within this paper, may be useful for the hydraulic design engineers associated in estimation for deciding the appropriate height of training wall for convergent stepped spillways. To formulate more generalized expressions for estimation of a requirement of appropriate height of training wall for convergent stepped spillways, more experimental studies with different convergence angles shall be required.

Acknowledgements

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Notations

The following symbols are used in this paper:

A = L * Hd = Area of flow at crest of spillway;
A1 = B * Y = Area of flow at toe of spillway;
B = Width of flow channel;
C = Discharge coefficient;
ds = Displacement height;
Er = ΔE / Eo = Relative energy dissipation;
Eo = H + 1.5 Yc = Energy at crest of spillway;
Et = Y + (V12/ 2.g) = Energy at toe of spillway;
g = Acceleration due to gravity;
h = Normal size step height;
h1max = Maximum depth of flow observed along the converging training wall;
h1 = Depth of flow observed along the converging training wall;
H = Datum head measured from toe up to crest of Spillway;
Hd = Head over crest of spillway;
H' = Drop height;
H* = H' / h = Step height ratio;
ks = Hydraulic roughness height;
L = Length of crest;
Lr = Lp /Lm = Scale ratio;
n = Number of regular size steps;
q = Q / L = Intensity of Discharge;
Q = C * L * (Hd)1.5 = Rate of flow i.e. Discharge over crest of spillway;
R = Hydraulic radius;
V = Q / A = Velocity of flow at crest of spillway;
V1 = Q / A1= Velocity of flow;
Y = Depth of flow;
Yc = Critical depth of flow;
zo = Surface roughness length;
ΔE = Eo - Et = Energy loss due to stepped spillway;
Ø = Convergence angle;
θ = Chute angle;

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