Optimum flow depths prediction along the convergent stepped spillways side walls

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Abstract. Stepped spillway designs are popularly adopted in dam systems due to their distinct advantage of enhanced energy dissipation of flow. Several references and literature are available for the design of stepped chute with straight side walls. For spillway modification works or due to site-specific situations, spillways may sometimes be provided with convergent training walls. But very few literature references are available on spillways having stepped chute provided with convergent side walls instead of straight side walls. The outcome of comprehensive experimental investigations carried out on spillway experimental set up with 0.7H:1V (i.e. \(\theta = 55^\circ\)) slope of stepped chute and side walls with 15\(^\circ\) convergence on both sides is presented. This paper described expressions for estimation of optimum depth of flow and decide the height of sidewall in spillways having stepped chute required to be provided with symmetrically converging side walls.

Keywords. Step height ratio (H\(^s\)), stepped chute, convergence angle

1. Introduction

A stepped chute constitutes a normal ogee spillway profile modified with successive series of steps fabricated from just below the crest up to the toe of the spillway. This provision of series of steps on spillway chute at the downstream face significantly enhances the energy dissipation rate and results into the reduction in the size of energy dissipater. This ultimately decreases the overall construction cost of energy dissipation arrangement of the spillway. Aeration produces flow bulking and hence the stepped chute typically requires high side walls. The convergence effect further enhances the effective flow depth due to shock waves and still higher side walls are necessary. Literature survey reveals that, very few literature references are available on stepped chute with convergent side walls in comparison with the references and literature available for stepped chute with straight side walls. Urbanization results in to limited scope for right-of-way, and because of geological or topographical constraints, some of the stepped chute may be required with convergent side walls. The proposed experimental study, presented to analyze the effect of moderate convergence of flow over stepped chute with special reference to the occurrence of maximum flow depth on the chute, which would help the designer to arrive at the appropriate side wall height.
The hydraulic research aspects related to stepped spillways are highlighted by the several researchers viz. Sorensen [1]; Peyras et al. [2]; Christodoulou [3]; Chanson [4]; Chamani and Rajaratnam [5]; Barani et al. [6]; Chanson [7]; Chinnarasri and Wongwises [8] amongst other authors. Experimental study performed by Hunt et al. [9] on 1:22 scale three-dimensional, physical model. They analyzed the characteristics of flow over a sloping stepped spillway with chute slope (3H: 1V) in conjunction with varying convergence angles of training wall and it was observed that, the height of training wall required ranges from a value equal to critical depth of flow for convergence angle of 15° to around a value of three times the critical depth of flow for convergence angle of 52°. Based on the control volume momentum analysis and as a part of follow up experimental study, Hunt et al. [10] presented a simplified generalized expression to estimate the vertical side wall height as a function of flow depth at the centerline of chute. However, the association of a force term at the time of proposed expression derivation, and necessity of an empirical adjustment, more testing of this generalized expression was recommended. It was felt necessary, looking to this background to conduct an experimental study to develop and suggest an expression to predict the flow depths at side walls for convergent stepped spillway with varied convergence angles. Experimental study performed by Wadhai et. al. [11] over sloping stepped chute with a chute slope of 1H:1V having different step height ratios with 45° side wall convergence angle and proposed the regression equations for estimation of side wall height for stepped chute with convergent side wall. Wadhai et. al. [12] provided a comparative analysis of the results obtained by their expressions for training wall height with those obtained by approaches provided by Hunt et al. [9], [10].

2. Experimental Concepts and Testing Methodology

In order to experimentally investigate the performance of stepped spillway a convergence angle (Ø) of 15° was selected to account for practically occurring convergence scenarios. The stepped chute slope was decided as 0.7(H):1(V) (i.e. θ = 55°). “Figure 1”, shows the schematic of convergent stepped spillway used in present research.

The experimental facility included a recirculation arrangement of water. Water is lifted from existing underground sump by means of a centrifugal pump of 10 HP capacity and discharges through delivery pipe in to upstream storage reservoir of 15750 liter capacity. The delivery pipe is provided with a calibrated venturimeter for measurement of flow rates. The storage reservoir is followed by ogee type 2.02 m wide crest and a stepped chute with 0.7(H):1(V) uniform slope and side wall convergence angle (Ø) of 15°, leading to a 0.5 meter wide toe channel and 10 meter length.

Stepped chute had a convergence angle Ø = 15° for both the side walls from the point of tangency further down the chute up to toe. For clear visibility, the side walls of toe channel and the side walls of the spillway are fabricated with flexi glass panels. For verification of flow rates, a ‘V’ notch was also installed in the downstream end of the toe channel. The spillway had a total height (H) of 1.26 m above the floor of toe channel. Initially, steps of height (h) 0.12 m were constructed, which resulted in step height ratio (H*) of 10. The step height ratio was successively increased during further experimentation by reducing the step height. The step height ratios of 10, 20, 40 and 80 was maintained and tested for flow rates varied broadly for each of the step height ratio in the range of 0.02 m²/s to 0.065 m²/s. For measurement of water levels over the steps at the centerline as well as at the side walls while running all the discharges, Vernier type pointer gauges with 0.1 mm sensitivity were used.
3. Analysis of Experimental Data

The observed data and subsequent calculations for the different experimental runs with respect to varying range of step height ratios ($H^*$) and also for normal ogee spillway are presented in table 1 and table 2 respectively. These tables also show the observed maximum depth of flow in dimensionless form along the converging side walls and the corresponding observed flow regimes for the different experimental runs.

The experimental data and observed flow pattern for the convergence angle i.e. $\theta = 15^\circ$ and for normal ogee spillway is shown in table 1 and table 2.

### Table 1. Observed data and calculations for $\theta = 55^\circ$, $\theta = 15^\circ$, Step Height Ratio $H^* = 10, 20, 40$ and $80$, Total Drop Height ($H$) = 1.26 m

| Intensity of discharge at crest of spillway $q = Q/L$ (m$^3$/s) | Critical depth of flow $Y_c = (q^2/g)^{1/3}$ (m) | Dimensionless discharge $Q/(H_d^{5/2}g^{1/2})$ | Optimum depth of flow in dimensionless form along the sidewall | Observed flow regime |
|---------------------------------------------------------------|-----------------------------------------------|---------------------------------------------|-------------------------------------------------|---------------------|

Figure 1. Schematic of convergent stepped spillway for convergence angle, $\theta = 15^\circ$
As expected, the depths of flow observed near the sidewall were more than the depth of flow observed at the spillway centerline. However, the flow depths near the side walls do form the basis for assessment of requirement of minimum height of side wall, so that the safety of the structure to be maintained and preventing the flow from overtopping the convergent sidewalls. Figure 2 show the water surface profiles observed for one of the step height ratios i.e. H* = 40 for a 0.7H:1V (i.e. $\theta = 55^\circ$) slope of stepped chute and convergence angle of 15° for different flow rates on single plot.

Table 2. Observed data and calculations for $\theta = 55^\circ$, $\varnothing = 15^\circ$, Normal ogee chute, Total Drop Height (H) = 1.26 m
Intensity of discharge at crest of spillway

\[ q = \frac{Q}{L} \quad (m^2/s) \]

Critical depth of flow

\[ Y_c = \left( \frac{q^2}{g} \right)^{1/3} \quad (m) \]

Dimensionless discharge

\[ \frac{Q}{(H_0^{5/2}g)^{1/2}} \]

Observed Flow Regime

| q (m²/s) | Y_c (m) | Dimensionless discharge | Observed Flow Regime |
|---------|---------|-------------------------|----------------------|
| 0.0275  | 0.0426  | 11.73                   | Skimming flow        |
| 0.0386  | 0.0533  | 9.37                    | Skimming flow        |
| 0.0465  | 0.0605  | 8.26                    | Skimming flow        |
| 0.0576  | 0.0697  | 7.17                    | Skimming flow        |
| 0.0715  | 0.0804  | 6.21                    | Skimming flow        |

**Figure 2.** Profile of water surface along the side wall of spillway for \( \theta = 55^\circ \), \( \Omega = 15^\circ \) and \( H^* = 40 \) for varying discharges

The requirement of training wall height determined based on the maximum flow depth along the side wall (\( h_{1\text{max}} \)), a plot showing variation of maximum flow depth along the side wall (\( h_{1\text{max}} \)) with discharge in dimensionless form for all the four experimentally investigated step height ratios for 0.7H:1V (i.e. \( \theta = 55^\circ \)) slope of stepped chute and training walls with 15° and 0° convergence on both sides is presented in figure 3 and figure 4, respectively.
4. Summary and Discussion

It is observed that the dimensionless optimum flow depth along the side wall decreases with increase in dimensionless discharge for all the step height ratios. From the plot showing variation of observed dimensionless maximum flow depth along the side wall with dimensionless discharge for $\theta = 55^\circ$, $\phi = 15^\circ$ and $\phi = 0^\circ$ presented in Figure 3 and 4, the regression equations have been obtained and are proposed in the form of "(1)":
For $H^* = \frac{H_1}{h}$, \[ h_{\text{max}} = A \left( \frac{q}{(H_1^{1/2})^{1/2}} \right)^{B} \] \[ R^2 = \text{Coefficient of determination} \]

Where, $A$ and $B$ are coefficient of equation,

$H^* = $ Step height ratio,

$H_1 = $ Drop height up to point of tangency,

$h = $ Normal size step height.

The proposed expressions to be used for deciding the height of side wall for convergent stepped chute with side wall convergence angle of $\phi = 15^\circ$ and $0^\circ$ and chute slope of $\theta = 55^\circ$.

Table 3, summarizes the coefficient of equation (A and B) along with coefficient of determination ($R^2$) for different step height ratios ($H^*$) each corresponding to varying range of convergence angle of $\phi = 15^\circ$ and $0^\circ$ for spillway experimental set up with chute slope of $0.7H:1V$ (i.e. $\theta = 55^\circ$).

| Sr. No | Convergence angle $\phi$ | Step height ratio $H^* = (H_1/h)$ | Step height h (m) | Coefficient A | Coefficient B | Coefficient of determination $R^2$ | Regression equation No. |
|--------|--------------------------|---------------------------------|------------------|---------------|---------------|-------------------------------|-----------------------|
| 1      | $15^\circ$               | 10                              | 0.12             | 4.667         | -             | 0.61                          | 0.999                 |
| 2      | $15^\circ$               | 20                              | 0.06             | 12.46         | -             | 0.71                          | 0.999                 |
| 3      | $15^\circ$               | 40                              | 0.03             | 30.14         | -             | 0.74                          | 0.999                 |
| 4      | $15^\circ$               | 80                              | 0.015            | 32.10         | -             | 0.62                          | 0.996                 |
| 5      | $0^\circ$                | 10                              | 0.12             | 2.757         | -             | 0.73                          | 0.994                 |
| 6      | $0^\circ$                | 20                              | 0.06             | 7.136         | -             | 0.81                          | 0.996                 |
| 7      | $0^\circ$                | 40                              | 0.03             | 13.03         | -             | 0.78                          | 0.996                 |
| 8      | $0^\circ$                | 80                              | 0.015            | 21.72         | -             | 0.81                          | 0.999                 |

Table 4, summarises the comparison of observed maximum depths of flow along the side wall ($h_{\text{max}}$) in terms of the corresponding critical depths of flow ($Y_c$) for different flow rates. It is observed that, the range of observed maximum flow depth significantly reduces for step height ratio of 80 as compared to other lesser values of step height ratios.

| Sr. No | Convergence angle $\phi$ | Step height ratio $H^* = (H_1/h)$ | Step height h (m) | Range of observed maximum flow depth along the converging side wall $h_{\text{max}}$ (m) |
|--------|--------------------------|---------------------------------|------------------|----------------------------------|
5. Conclusion

The results of an experimental study on convergent stepped spillway having 0.7H : 1V chute slope and convergence angle of $\phi = 15^\circ$ and $0^\circ$ for different step height ratios have been presented. It was observed that, the flow over the convergent stepped spillway to be air entrained and more bulked as compared to normal ogee spillway as well as observed for straight walled stepped spillway. Stepped chute with convergent side walls will have to be employed for rehabilitation of spillway works with constraint of availability of inadequate downstream space. Very few guidelines available in the literature so far for the design of stepped chute with convergent side wall. Based on normalization of step height ratio, it was observed that, with increase in dimensionless discharge, the maximum depth of flow at the convergent side wall decreases. On the basis of experimental observations and analysis for different step height ratios, the regression equations “(1) to (8)”, corresponded to {Sr. No. (1) to (8)}, for prediction of maximum flow depth near the converging side walls have been proposed. High value of determination coefficient indicated that, correlation obtained was good for all the regression equations. Maximum flow depth near the convergent side wall was found to lie between 1.60 $Y_c$ to 3.05 $Y_c$ and 1.27 $Y_c$ to 2.00 $Y_c$ for the different step height ratios for convergence angle of $\phi = 15^\circ$ and $0^\circ$, respectively. It is also noted that the range of observed maximum flow depth is significantly less in case of step height ratio of 80 as compared to other investigated smaller step height ratios. Presented regression equations may be useful to the hydraulic engineers associated in design and estimation of the appropriate height of side wall for convergent stepped chute with similar chute slope and convergence angle. However, results from more experimental investigations with different convergence angles, shall be necessary to formulate more generalized expressions for the estimation of requirement of sufficient side wall heights for stepped chute with convergent side walls.

Notations

The following symbols are used in this paper:

| No. | Step Height Ratio | Step Height | Normal Size Step Height | Max Depth of Flow at Converging Side Wall |
|-----|-------------------|-------------|-------------------------|------------------------------------------|
| 1   | 15°               | 10          | 0.12                    | 2.33 $Y_c$ to 3.05 $Y_c$                  |
| 2   | 15°               | 20          | 0.06                    | 2.54 $Y_c$ to 3.04 $Y_c$                  |
| 3   | 15°               | 40          | 0.03                    | 2.89 $Y_c$ to 3.42 $Y_c$                  |
| 4   | 15°               | 80          | 0.015                   | 1.88 $Y_c$ to 2.38 $Y_c$                  |
| 5   | 15° Smooth ogee   | 10          | 0.12                    | 1.60 $Y_c$ to 1.98 $Y_c$                  |
| 6   | 0° Smooth ogee    | 10          | 0.12                    | 1.54 $Y_c$ to 1.83 $Y_c$                  |
| 7   | 0° Smooth ogee    | 20          | 0.06                    | 1.79 $Y_c$ to 2.00 $Y_c$                  |
| 8   | 0° Smooth ogee    | 40          | 0.03                    | 1.68 $Y_c$ to 1.93 $Y_c$                  |
| 9   | 0° Smooth ogee    | 80          | 0.015                   | 1.38 $Y_c$ to 1.55 $Y_c$                  |
| 10  | 0° Smooth ogee    | 10          | 0.12                    | 1.27 $Y_c$ to 1.41 $Y_c$                  |
\( S^* \) = Dimensionless distance at location of occurrence of maximum flow depth (along chute from crest)

\( V \) = \( Q / A \) = Velocity of flow at crest of spillway;

\( Y \) = Depth of flow;

\( Y_c \) = Critical depth of flow;

\( \bar{\theta} \) = Convergence angle;

\( \theta \) = Chute angle

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