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Effect of Slope Geometry on Energy Dissipation for Stepped Spillway

Prachi Dharmadhikari [1,*], Sumit Gandhi [2]

[1]Research Scholar, Department of Civil Engineering, JUET Guna-473226, India
[2]Associate Professor & Head, Department of Civil Engineering, JUET Guna-473226, India

*Corresponding author email: prachidm786@gmail.com

ABSTRACT

Experimental study has been done for the analysis of flow over stepped spillway with three different models. Study reflects the behavior of flow characteristics namely sequent depth ratio, relative energy loss and relative length of jump against varying Froude number. Effect of height, width and length of steps plays a significant role in dissipating maximum energy under nappe and skimmimg flow conditions. Importance of air entrapment and entrainment were also discussed to protect the structure against cavitaion damage. Difficulties faced during the prediction of length and roller jump due to presence of turbulence and eddies at the channel bottom were discussed with existing literatures. Comparison has been made between non-aerated flow zone and point of inception against reduction of step height under same discharge. Also, pseudo-bottom air concentration is explained for entrapped and entrained air concentration. Present approach represents the flow properties in dimensionless form and hence can be applied to the field condition directly.

Keywords - Stepped Spillway, Relative Energy Loss, Skimming flow, Air Entrainment, Cavitation.

ABBREVIATIONS

E_1	Energy before the jump (m)
E_2	Energy before the jump (m)
E_L/E_1	Relative energy loss (-)
F_{r1}	Froude number (-)
g	Acceleration due to gravity
H_p	Height of Spillway
ΔH	$Y_2 - Y_1$
L_r	Length of roller (m)
L_j	Length of jump (m)
L_j/Y_1	Relative length of jump (-)
n_s	Number of steps (-)
Q	Discharge or flow rate (m^3/s)
Re	Reynolds's number
S_h	Step height (cm)
S_w	Step width (cm)
S_l	Step length (cm)
V	Mean velocity of flow
Y_1	Pre jump depth (m)
Y_2	Post Jump depth (m)
Y_c	Critical depth (m)
Y_2/Y_1	Sequent depth ratio (-)
ρ	Density of water (kg/m^3)
μ	Dynamic viscosity of water (Ns/m^2)
α	Slope of spillway steps

1. INTRODUCTION

Recent advancement in construction of compacted concrete dams necessitated the increased energy dissipation. Safe dissipation at downstream of flow is achieved by providing steps in the spillway structure called stepped spillway (Tozzi 1992). Steps contribute to some dissipation of the turbulent kinetic energy, thereby reducing the length of downstream stilling structure. Highly turbulent flows are experienced down a stepped spillway (Rajaratnam 1990). One of the advantages of good spillways is to provide overall structural stability and energy dissipation through water aeration during its passage over the spillway. Among the other benefits of using a stepped spillway compared with equivalent smooth spillway is its efficiency through which a significant increase in energy dissipation takes place (Chanson, H. and Gonzalez C.A., 2005). Other design advantages of stepped spillways are ease of construction, application to the existing embankment slope, and the significant nappe and skimming flows noted by Chanson (1994), Boes (2000), Ohtsu et al. (2004), Meireles & Matos (2009), and Hunt & Kadavy (2009).

Energy dissipation can be estimated by the indirect method through the hydraulic jump formation and measuring the sequent depths in a channel. The flow over the stepped spillway in nappe flow proceeds in a series of plunges from one step to another. Flow from each step hits the step below as a falling jet, with the energy dissipation occurring by breaking of jet. The transition from the jet (nappe) flow to the skimming flow occurs when critical depth to step height (Y_c/S_h) is approximately equal to 0.8 (Rajaratnam,N. 1990).

Christodoulou (1993) found that it depends on the ratio of critical depth to step height (Y_c/S_h) as well as on the number of steps (n_s). Location where water is discharged through gates or spillway crest is generally accomplished by causing a hydraulic jump formation in stilling basin. Certain structural arrangements like baffle blocks or sills permit the hydraulician for economic benefits through reduction in size of stilling basin and favorable flow conditions. These arrangements become more significant were channel faces an inclined bed and or faces design constraints of lateral and bottom expansion.

2. THEORY

Young (1982) studied the feasibility of a stepped spillway for a particular dam and managed greater than 75% energy reduction. Sorensen (1985) performed a model investigation for energy dissipation, were other author found it is advantageous to add few steps to the face of the spillway in order to optimize overall efficiency of spillway.

Guideline published (CIRIA, 1978) by Degoutte et al. (1992) provides no indication up to what degree the spillway step configuration may impact the energy dissipation. Chamani & Rajaratnam (1999a, b) developed an equation to predict the incipient value of the ratio of the critical depth to step height through experimental study. Chanson (1999) proposed a pre-design calculation method that provides a general trend for preliminary designs. Chafi (2010) observe that number of steps have no significant influence on the energy dissipation but Christodoulou (1993) evoked dependency of the energy dissipation on variation of number of steps; former had got around 63 % energy dissipation whereas later had got 50 %. Rajaratnam (1990), Chanson (1993, 1994) and Christodoulou (1994) reveal that the average friction factor for this type of structure is varying between 0.24 to 0.30 which helps in more energy dissipation.

Barani et al. (2005) investigated energy dissipation of flow over stepped spillway experimentally for different types of step shape with sills. The energy dissipation increases by increasing the thickness of end sill and by providing adverse slope size. Dissipation of energy is more in horizontal channel and it increases with different size of end sills i.e. increases from 1 cm to 4 cm.

Mohammad et al. (2015) used flow 3D model to ascertain the effect of different parameters such as number of steps (n_s), step height (S_h), step length (S_l) and discharge on energy dissipation in stepped spillway. Author established the relationship between energy dissipation and critical depth in their model study. On the basis of dimensional analysis, function among the parameters (H_p, n_s, S_l, S_h, V, Y_c, g, ρ, μ) = 0 has been established for energy dissipation with ρ, V, Y_c has been chosen as repetitive variables.

$$\frac{E_1-E_2}{E_1} = f\left(\frac{Y_c}{S_l},\frac{Y_c}{S_h},n_s,Re,F_{r1}\right) \tag{1}$$

Fig. 1(a) shows variation in relative energy dissipation with change in step height of spillways. Relative energy increases with increasing in step height. Fig. 1(b) indicates the effect of step length in spillways in which dissipation of relative energy is more due to increase in surface area.

Awada et al. (2018) has done empirical study and concluded that the maximum relative scour depth increases with increasing Froude number and discharge; further Flow 3D program resulting that the scour increase with the relative step height of spillway (S_h/n_s). Fig. 2(a) shows the relationship between $(E_1-E_2)/E_1$ and upstream Froude number for the different relative stepped spillways with different relative stepped height (S_h/n_s = 0.5, 0.33, 0.25, 0.17, 0.11). It shows maximum relative scour depth achieved with the increment in Froude number. Whereas from fig. 2(b) variation with critical depth (n_s/Y_c) shows that with the increase of critical depth relative scour depth increases simultaneously.

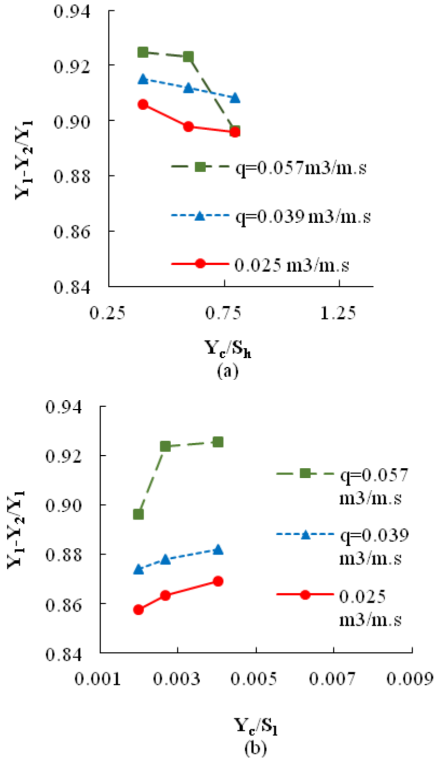
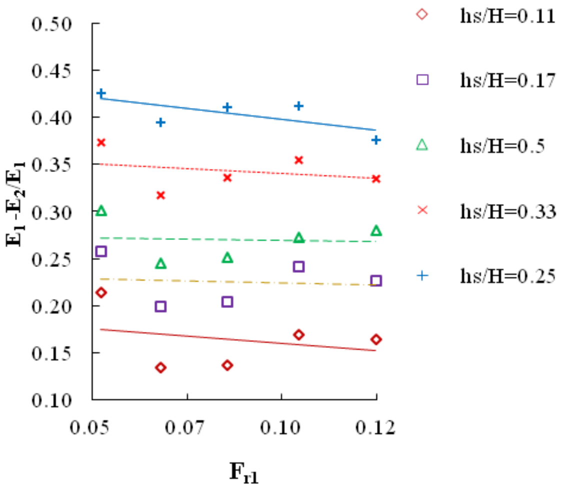
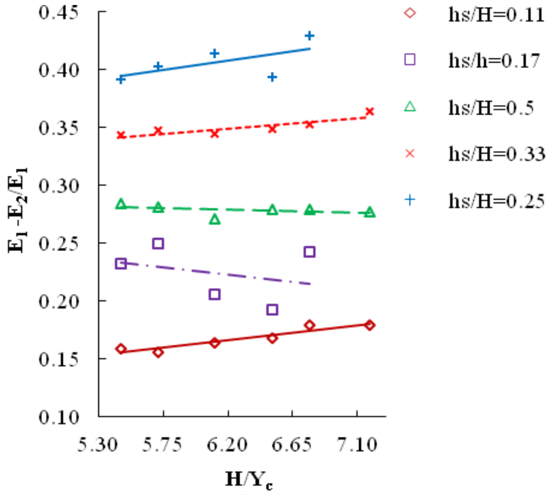


Fig. 1: (a), (b) Variation of relative energy with relative step height and with relative step length



(a)

Fig. 2 (a): Variation of relative energy loss against Froude number



(b)

Fig. 2 (b): Variation of relative energy loss against H/Y_c with different relative stepped height of spillways (S_h/n_s).

Tabbara et al. (2005) presented numerical simulations of water flow with different steps. Computational fluid dynamics module of the ADINA software was utilized to model flow over spillway and it is qualitatively consistent with general flow characteristics. Chatila et al. (2005) experimental investigation is done for efficiency in reducing the downstream energy and length of jump. It shows that more steps on the spillway face provide better expenditure of energy and a shorter hydraulic jump. Authors concluded that stepped spillways with maximum number of steps are efficient and desirable alternative over traditional spillways. A similar conclusion reached by Chamani & Rajaratnam (1994), where they reported that the size of steps is more important than number of steps.

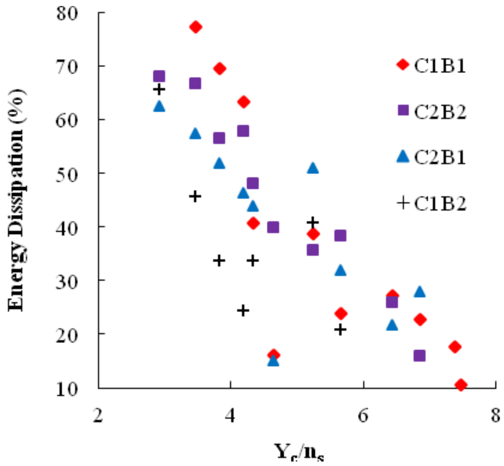


Fig. 3: Variation of percentage energy dissipation with Y_c/n_s

Fig. 3 shows variation between percentage of energy dissipation and Y_c/n_s ratio. For value of Y_c/n_s = 2.89 higher amount of energy dissipated in stepped surface. It gradually decreases up to value 8 from C1B1 model with 33 steps shows highest energy dissipation as compare to another model (C2B2, C3B3 and C4B4). Energy dissipation is efficient mainly due to the fact that steps act as roughness elements which increase friction and changes kinetic energy.

Amin (2021) et al. investigated the effect of roughness screen and porous obstacle with different arrangements on steps. Putting of the porous obstacle as well as the continuous obstacle on the edge of the spillway at 1: 2 slopes does not have a positive effect on the energy dissipation but for spillway with a 1:3 slope, the dissipation performance of the spillway increased with an average of 5 %.

Chanson (1993) discussed the effects of air entrainment and presented new calculation method for flow aeration on flow characteristics and for rate of energy dissipation. When the flow is uniform at downstream end of spillway, the energy dissipation along stepped spillway with aerated flow is written in terms of friction factor, spillway slope, critical depth and the spillway height:

$$\frac{E_1-E_2}{E_1}=1-\frac{\left(\frac{f}{8Sin\alpha}\right)^{1/3}cos\alpha+\frac{E}{2}\left(\frac{f}{8Sin\alpha}\right)^{-2/3}}{\frac{H_p}{Y_c}+1.5} \qquad (2)$$

Stefan & Chanson (2011) conducted study in a moderate slope stepped spillway (1V: 2H) and detailed air water flow measurements were performed for each configuration. Results were compared in terms of flow patterns, energy dissipation and flow resistance. The basic findings showed minor differences between all configurations and indicated that rate of energy dissipation is same for uniform and non-uniform step configurations. Pinheiro & Fael (2000) summarized and compared the energy dissipation theories developed by many researchers and found the equation presented by Chamani & Rajaratnam (1994) provided the best agreement among those evaluated:

$$\frac{E_1 - E_2}{E_1} = (1-A)^n \left[1 + \frac{1.5Y_c}{S_h}\right] + \sum_{i=1}^{n=1} (1-A)^i \tag{3}$$

$$A = \left[0.3 - 0.35\left(\frac{S_h}{S_l}\right)\right] - \left[0.54 - 0.27\left(\frac{S_h}{S_l}\right)\right] \log\left(\frac{Y_c}{S_h}\right)$$

In the nappe flow regime, the total energy loss is highly dependent on the number of steps. The total energy loss in nappe flow decreases with number of steps, with more slope and with discharge (Chanson, 1994a; Matos & Quintela, 1995b; Peruginelli & Pagliara, 2000).

3. EXPERIMENTATION

Experiments were performed in the hydraulics laboratory at JUET Guna, MP, India in a 5 m long, 20 cm wide recirculating open channel flume with flow velocity ranging from 0.2 m/s to 1 m/s. Two sluice gates are provided at the inlet & end of the channel to create hydraulic jump under different flow conditions. Geometrical features of stepped spillway model are mentioned in table 2. Pitot tube and point gauges were used to measure the velocity and depth of flow at desired locations. In the case of a fluctuating water surface profile, average values of depths were taken based on several measurements. Pump with valve control supplied the flow into the channel through tank provided at the inlet; and collection tank is provided at outlet to measure the total discharge. The walls of the flume are made of perspex sheet to visualize the flow profile on both sides. Proper care has been taken to control the side wave reflection and surface undulation so that a stabilized flow is generated in main channel.

Table 1: R^2 values of different jump characteristics for all three models

Spillway Model	**Y_2/Y_1**	**E_L/E_1**	**L_j/Y_1**
Model 1	0.93	0.99	0.84
Model 2	0.96	0.99	0.91
Model 3	0.95	0.99	0.86

4. RESULTS AND DISCUSSION

Fig. 4 shows a linear variation of sequent depth ratio (Y_2/Y_1) against the approach Froude number (F_{r1}), which was varied between 1 to 6.5 for all the three models. The R^2 values (0.88, 0.89, 0.89) of the linear fit shows that linear variation holds good between Y_2/Y_1 and F_{r1}. Linear variation of Y_2/Y_1 with F_{r1} has been well reported in the literature [Chafi (2010), Barani et. al (2005) and Stefan & Chanson (2011)]. Also, a good agreement between the experimental results and the best fit line can be seen at higher values of Froude numbers ($1 \leq F_{r1} \leq 6.5$). The U.S. Bureau of Reclamation (1955, 1957) suggested that steady jump is formed when approach Froude numbers lie between 4.5 to 9. The best fit line shows that approximately 85% data are lying within ± 10% of the best fit line. Few data points are seen deviating from the best fit line which may be due to inaccurate measurement of sequent depths. Therefore, the sequent depth ratio of stepped spillway for rectangular channel seems to be linearly related to the approach Froude number.

From the Table 2, it is clear that with the increase in rise (i.e step height) sequent depth ratio decreases which indicates that most of energy get dissipated during the stepping of water at spillway and less energy is to be dissipated further near the toe (i.e at jump formation). There is significant effect of more step height is noticed with model-3 than model-2 in dissipating energy at spillway; this may be attributed to skimming and nappe flow effect at low and high Froude number respectively.

Table 2. Details of stepped spillway and range of measured & calculated parameters

Spillway	**Step Geometry**				**Y_1**	**Y_2**	**Q**	**F_{r1}**	**L_r**	**L_j**	**Flow Characteristics**		
	Numbers (n_s)	**Width (S_w cm)**	**Length (S_l cm)**	**Rise (S_h cm)**	**(m)**	**(m)**	**X 10^{-3} (m^3/s)**	**-**	**(m)**	**(m)**	**Y_2/Y_1**	**L_j/Y_1**	**E_L/E_1**
Model -1	6	19.5	3	3	0.013-0.072	0.05-0.11	2.0 - 26.0	1.0-6.5	0.11-0.70	0.33-0.73	1.07-4.05	5.78-36.15	0.06-39.11
Model -2	5	19.5	3.5	3.5	0.024-0.069	0.07-0.26	6.30 - 40.0	1.0-6.5	0.22-0.68	0.43-0.89	1.66-4.07	7.29-30.69	0.02-15.39
Model -3	5	19.5	2.6	4	0.02-0.08	0.07-0.12	6.55-20.0	1.0-6.5	0.13-0.35	0.25-0.87	1.20-3.98	6.62-21.77	0.01-23.69

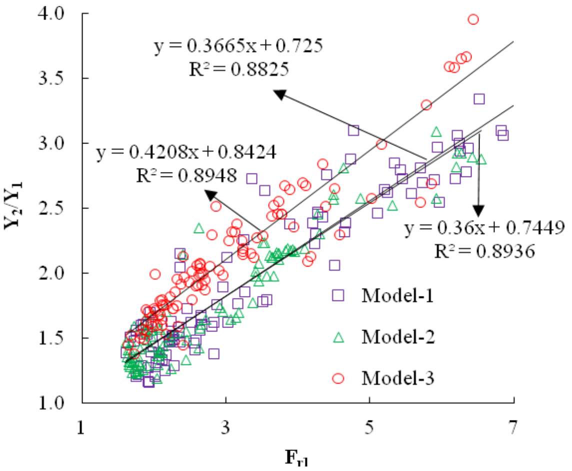


Fig. 4: Variation of sequent depth ratio with Froude number

Fig. 5 shows an increasing trend of relative energy loss ‘E_L/E_1’ with Froude number ‘F_{r1}’. A quadratic fitting of experimental data with R^2 value of 0.99 shows that relative energy loss is related to the Froude number with good agreement. About 95 % data points are lying within the range of ± 6 % of the best fitted curve drawn; slight variation in data may be limit to the error involved in measurement. It can be seen that the efficiency of jump decreases with increase in Froude number. Similar trend have also been noted & presented by Ranga Raju (1993) Chanson (1994), Boes (2000), Ohtsu et al. (2004), Meireles & Matos (2009), and Hunt & Kadavy (2009) for relative energy loss against Froude number.

Further from table 2, it is clear that energy dissipation is more for more number of step geometry (i.e. for model-1) because of flow recirculation, with or without air entrainment. Similar interpretation has been presented by Chanson (1994) and Rajaratnam (1990) for energy dissipation due to pseudo-bottom caused by the flow on each step of spillway. Therefore, for a given stepped spillway geometry, the nappe flows are common for small discharges at each step. They are characterized by a succession of free-falling nappes. At little higher discharge, flow becomes transition and it starts skimming over each step edge. Skimming flow characteristics is mostly observed for the largest discharges, in which falling waters converted to coherent turbulent flow.

Fig. 6 shows a non-linear variation of relative length of jump (L_j/Y_1) against approach Froude number (F_{r1}) between 1 to 6.5 for all three types of spillway arrangements. From this figure, it can be seen that logarithmic variation is plotted with less significant R^2 value. Reason for the low R^2 value may be attributed to inaccuracy in the measurement of the length of the jump as it is very difficult to judge the correct position of starting and end of the jump precisely due to presence of high turbulence, rollers and eddies. Because of these effects, measurement of length of roller which is less than length of jump is also difficult to predict. Theoretically and on the basis of experiment also, length of hydraulic jump is generally considered to be 5 to 7 times that of the height of the jump for all hydraulic design of spillway.

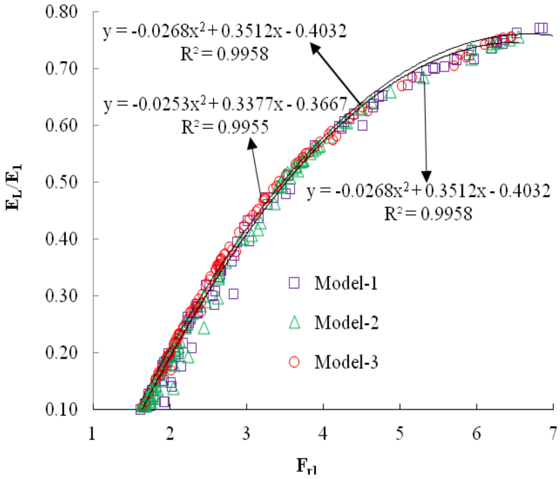


Fig. 5: Variation of relative energy loss with Froude number

From table 2, it is clear that length of jump is more for model 2 which having more & uniform tread and rise dimensions than the other two models. Similar trend is seen for length of roller also. So, it can be deduce that model 1 and model 3 are more efficient in reducing the jump length for the considered condition of flow. More importantly, entrapment of air rollers and eddies at the bottom of the channel near the toe of spillway is to be protected as it causes unstability and cavitation problem to the structure.

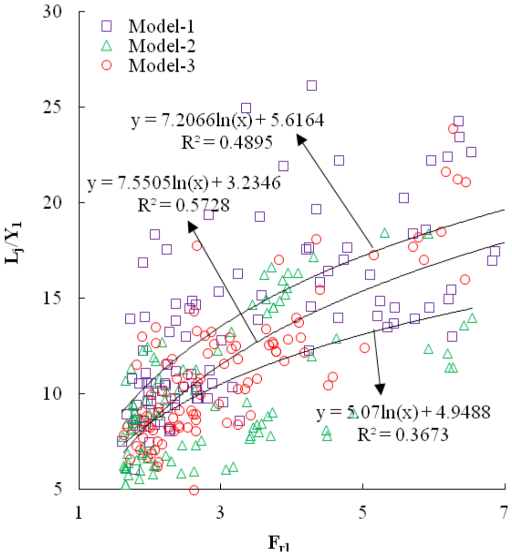


Fig. 6: Variation of relative length of jump against Froude number

5. CONCLUSION

The formation and development of the flow over stepped spillway was investigated through experimental study. Amount of air entrapment in a stepped spillway is very important to protect the spillway from cavitation damage. It is concluded that with the increase in step height, sequent depth ratio decreases which indicates most of energy get dissipated during the stepping of water at spillway. More step height becomes significant in dissipating energy at spillway due to skimming and nappe flow at low and high Froude numbers respectively.

On the other hand, efficiency of jump decreases with increase in Froude number. Also, from table 2, energy dissipation increases with more number of steps (i.e. model 1) because of flow recirculation and air entrainment. Therefore, flow can be classified as nappe, transition and finally as skimming flow at low and higher discharges respectively. Nappe flow is characterized by a succession of free-falling jets and skimming flow is characterized with falling jets converted to coherent turbulent flow.

It is very difficult to predict exactly the length and roller of the jump due to presence of high turbulence, rollers and eddies at the channel bottom. The length of the non-aerated flow zone increases with the discharge. It is observed that inception point moves downwards with the reduction of step height at the same discharge. Also, pseudo-bottom air concentration is suddenly changes from entrapped to entrained. Entrained air circulates within the flow, while entrapped air moves near the water surface.

The present approach can represent the evolution of flow properties in the hydraulic jump, about which the existing knowledge is relatively scarce. Moreover, results presented are in dimensionless form and hence can be applied to field condition directly irrespective of dam height.

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