2nd International Conference

DAM SAFETY EVALUATION

November 26-30, Trivandrum, India

Volume 1

Editors

C.V.J. VARMA

A.R.G. RAO

Central Board of Irrigation and Power
New Delhi

INCOLD

Committee for International Commission on Large Dams (India)
New Delhi

OXFORD & IBH PUBLISHING CO. PVT. LTD.
New Delhi Calcutta

2nd International Conference on Dam Safety Evaluation
26 – 30 November 1996, Trivandrum, India

MODEL INVESTIGATIONS OF STEPPED SPILLWAY

D. Nagesh Kumar, P.C. Nayak and C.R.S. Pillai

Civil Engineering Department, Indian Institute of Technology
Kharagpur, India

ABSTRACT

Stepped block protection has considerable potential as a low-cost method for the construction of chute spillways and the protection of embankments from erosion by overtopping flow. Stepped spillways are structurally stable, resistant to water loads and significantly increase the rate of energy dissipation on the spillway face thus eliminating or greatly reducing the need for a large energy dissipation basin at the spillway toe. It can also be readily adopted for use in diversion works during dam construction and for providing additional spillway capacity to existing dams. While constructing stepped spillway over embankment dam, the stepped block is used in conjunction with an under layer which incorporates a free draining medium and a lower zone which has the function of filtering seepage flow out of the subsoil and also protecting the subsoil from erosion by flow in the draining layer. Blocks are laid in stretcher bond configuration. It is proposed to construct stepped precast concrete block spillway over the truncated embankment dam to be constructed at Jambhira in Orissa on Subarnarekha river. In the present study, model investigations are carried out to study the energy dissipation efficiency of the monolithic stepped spillway and the negative slope of the toe wall to be provided for the spillway. The stepped spillway is found to be very efficient in energy dissipation. It was observed that with the increase in discharge, the amount of energy dissipated is reducing. For additional energy dissipation, a toe wall with a negative slope of 8^0 to 12^0 is found to be suitable.

INTRODUCTION

A stepped spillway is an energy dissipator having profile made up of steps. It dissipates much more energy than other types of spillways, when water is flowing over the spillway profile. The stepped spillways are structurally stable, resistant to water loads and significantly increase the rate of energy dissipation on the spillway face thus eliminating or greatly reducing the need for a large energy dissipation basin at the spillway toe. Many of the existing stepped spillway structures in countries like Russia, USA, UK, and South Africa were mentioned in (1), (2) and (3). Experimental studies on stepped spillways were reported in (3), (4), (5) and (6).

While constructing stepped spillway over embankment dam, the stepped block is used in conjunction with an under layer which incorporates a free draining medium and a lower zone which has the function of filtering seepage flow out of the subsoil and also protecting the subsoil from erosion by flow in the draining layer. Blocks are laid in stretcher bond configuration. Design aspects of Stepped spillway over embankment dam were given in (6) and (4). According to (1), the step height needs to be atleast two or three times the critical flow depth and the horizontal tread of the steps needs to be two or three times the step height.

Generally two types of flow occur when water flows over stepped spillway. They are nappe or jet flow and skimming flow. Hydraulics of skimming flow over stepped spillways was studied in (2). A comparative study of energy dissipation between nappe and skimming flow regimes on stepped chutes was made in (7). Based on the experimental results in (2), for nappe flow, the nappe impinges on the whole surface of the lower step at small discharges. Again nappe flow is further classified as isolated nappe and partial nappe. Isolated nappes may exhibit alternating sub and supercritical flow or be entirely supercritical. In the partial nappe flow, the nappe does not fully impinge on the step surface, and it disperses with considerable turbulence. Flow is supercritical down the whole length of the spillway. In the partial nappe flow, energy is dissipated in two stages, on impact with the flat surface and more importantly, in the turbulence created by dispersal of the nappe, with or without the formation of hydraulic jump. For the case of jet flow, the energy loss was calculated in (9), based on the remaining energy on each step .

Skimming flow occurs at moderate to high discharges. No nappe is visible and the spillway is submerged beneath a strong, relatively smooth current. The water flows down the stepped face as a coherent stream, skimming over the steps and cushioned by the recirculating fluid trapped by the momentum transfer to the recirculating fluid. The energy dissipation in the flow appears to be enhanced by the momentum transfer to the recirculating fluid. It was found that the skimming flow sets in when the critical depth is greater than about 0.8 times the height of the steps (10). Two factors were introduced for analysis, viz., C_f (the coefficient of fluid friction) and τ (shear stress equal to $C_f \gamma V^2/2g$). Here, τ is the average Reynold's shear stress between the skimming stream and the recirculating fluid. For fully developed flow with a constant mean velocity of V and normal depth y, shear stress will be equal to $\tau = \gamma y \sin\alpha$ ($\sin\alpha$ is constant slope of stepped spillway and γ is the unit weight of fluid). From the above two shear stress equations, we get

$$C_f = (2 g y \sin\alpha)/V^2 \quad (1)$$

Velocity, V, from Eq. 1 is

$$V = (2 g y \sin\alpha / C_f)^{1/2} \quad (2)$$

Discharge per unit width (q) is

$$q = (2 g \sin\alpha / C_f)^{1/2} y^{3/2} \quad (3)$$

Energy of flow at the toe of the stepped spillway, E_t, is given by

$$E_t = y + V^2/2g$$

$$E_t = \{C_f q^2 / (2 g \sin\alpha)\}^{1/3} + \{(q \sin\alpha / C_f)^2 / (2 g)\}^{1/3} \quad (4)$$

If y_s and V_s are the corresponding depth and velocity at the toe of smooth spillway without steps, the energy at the toe E_s, is given by

$$E_s = y_s + V_s^2/2g \quad (5)$$

The additional energy loss caused by the steps over that caused by the smooth spillway face is

$$\Delta E_s = E_s - E_t$$

If the relative energy loss is defined as $\Delta E_s/E_s$, it can be shown as (10)

$$\Delta E_s/E_s = \frac{(1-A) + F_s^2 (A^2-1)/(2A^2)}{1 + F_s^2/2} \qquad (6)$$

where $A = (C_f/C_{fs})^{1/3}$ and F_s is the Froude number at the toe of the smooth spillway.

SPILLWAY MODEL

When water is flowing over the spillway, total resistance of flow is a function of velocity, viscosity, density, length and acceleration due to gravity. Froude model law is considered when the force of gravity can be considered to be the only predominant force which controls the motion in addition to the inertia force. The similarity of the flow in any two such systems can be established if the Froude number for both the systems is same. So according to Froude model law,

$$F_{model} = F_{prototype}$$

or

$$V_m/(g_m L_m)^{0.5} = V_p/(g_p L_p)^{0.5} \qquad (7)$$

From Eq. 7, it follows that (assuming $g_m = g_p$)

$$V_r = L_r^{0.5} \qquad (8)$$

Here subscripts m, p and r indicate model, prototype and ratio respectively.

Dynamic similarity exists between model and prototype which are geometrically and kinematically similar and the ratio of all forces acting at homologous points in two systems ie., the model and prototype are equal. As the gravity force is the only predominant force in the stepped spillway model, it should obey froude model law. As per this law, Eq. 8 is the sufficient criteria for the dynamic similarity to be established in the model and the prototype for the spillway.

The peak design flood of 1167 cumecs at the Jambhira earth dam site, when routed through unabated spillway will cause a peak outflow of 510 cumecs which is proposed to be passed over the truncated earth dam through a 75m wide spillway (11). The height of the spillway is 13m and stepwise slope is 1 in 6. The size of each step block is 1.2 x 1.2 x 0.2 m. The stepped spillway was designed as per the guide lines cited in (6), (4) and (10). From the field data, discharge per unit width of the spillway (discharge intensity, q_p) is 6.8 cumecs per meter.

Based on the maximum discharge intensity possible in the Hydraulics laboratory of IIT, Kharagpur, a scale ratio (L_r) of 16.76 was adopted for the lab model. Considering the same vertical and horizontal model scale ratio (Undistorted model), the dimensions of the height and size of the step are as follows.

Height of the spillway model = $h_m = h_p L_r$ = 13 x 1/16.76 = 0.776m or say 780 mm

Width of the step = 1.2/16.76 = 71.59mm say 72mm

Depth of the step = 0.2/16.76 = 11.93mm say 12mm

Instead of stepped blocks, monolithic construction is adopted for the model with 65 steps of size 1250 x 72 x 12 mm with a total height of 780mm and length of 7.53m. Monolithic construction was adopted since the objective of the present study is to evaluate the energy dissipation characteristics of the stepped spillway. If the stability studies are to be made, then the model should have stepped blocks with an underlying inverted filter. The model studies are conducted for unit width of spillway (1.25m width is provided to avoid the side wall effects). Sectional view of spillway model is shown in Fig. 1. The model is constructed in a rectangular flume with cement mortar and sand filling. For uniform passage of water wave breakers were fixed upstream of the spillway model. Water is allowed into the flume through a calibrated V-notch. With the help of V-notch, various discharges passing over the spillway were measured.

For the measurement of depth of flow over each step of the spillway, two rolling bridges each with a point gauge were installed. The bridges were capable of moving in the direction of flow. The rolling bridges were placed over two parallel rails on the side walls of the flume. The point gauge was arranged in such a way that it is capable of sliding over the measuring bridge in lateral direction. These movements in both the directions facilitated taking observations for cross profile at any desired section. A general layout of the experimental flume is shown in Fig. 2.

EXPERIMENTS ON SPILLWAY MODEL

The experiments on the present model were conducted on two sets of settings. The objective of the first set of experiments was to study the flow profile and the energy dissipation characteristics of the spillway. The first set of experiments consists of 9 runs with discharges 0.012, 0.0234, 0.034, 0.04, 0.05, 0.06, 0.071, 0.08 and 0.11 cumecs. The objective of the second set of experiments was to study the additional effect of toe wall at the toe of the spillway with various negative slopes, in energy dissipation. The toe wall width is fixed as 120 mm as proposed in the prototype. The second set of experiments consist of 20 runs after construction of the toe wall having negative slopes of 4°, 6°, 8°, 10°, 12°. For each negative slope of the toe wall, flow profiles were studied for discharges of 0.04, 0.05, 0.06 and 0.08 cumecs.

Observations for each run consisted of measuring flow profile at different steps along the spillway profile. The depth of flow was measured at the end of each step. Downstream depths were also measured by the movable measuring bridge after the water passes over the toe wall of the spillway. Discharge was measured from V-notch calibration curve. From the depth of flow observed at each step, velocity head, $V^2/2g$, is calculated. The flow and velocity head profiles over the spillway were thus obtained for each run. A typical data set of the run no. 6 for a discharge of 0.06 cumecs is given in Table 1.

FIG. 1 SECTIONAL VIEW OF SPILLWAY

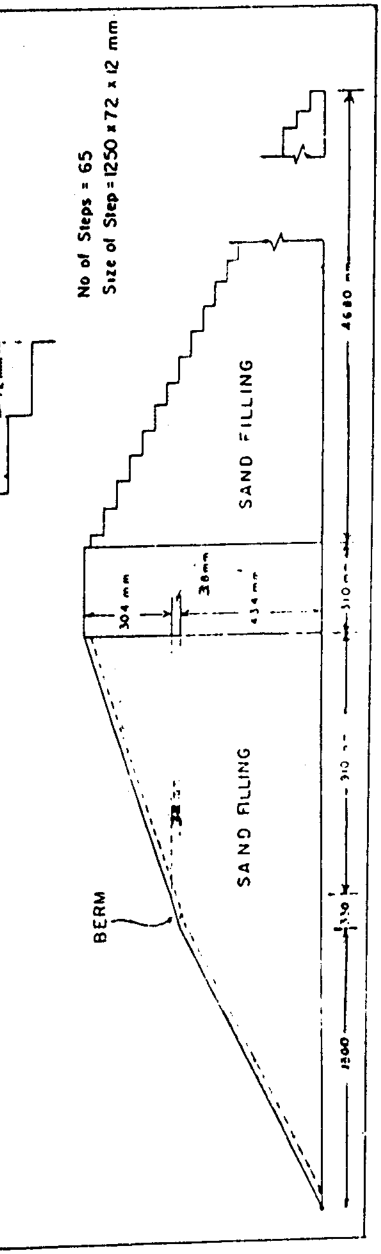

FIG. 2 GENERAL LAYOUT OF EXPERIMENTAL FLUME INDICATING LOCATION OF MODEL

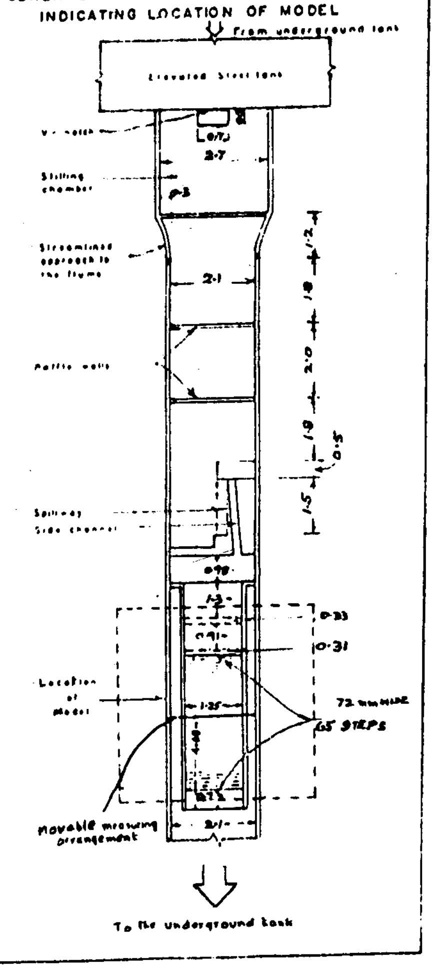

Table 1. Observations for run no. 6 with a discharge of 0.06 cumec
(Depth of flow in mm)

Step no.	Depth	Step no.	Depth	Step no.	Depth	Step no.	Depth
1	52.2	18	31.2	35	33.0	52	31.4
2	47.6	19	32.0	36	33.5	53	36.0
3	43.5	20	31.0	37	33.8	54	34.0
4	39.6	21	31.0	38	32.3	55	39.5
5	34.3	22	32.0	39	31.7	56	37.0
6	35.4	23	29.0	40	34.8	57	33.0
7	31.4	24	31.4	41	32.0	58	32.5
8	33.7	25	31.0	42	35.0	59	30.5
9	36.6	26	29.0	43	34.8	60	33.0
10	34.0	27	30.5	44	34.0	61	33.0
11	35.0	28	30.7	45	33.0	62	33.0
12	37.0	29	36.7	46	32.8	63	29.0
13	34.0	30	32.7	47	33.2	64	33.5
14	32.0	31	31.4	48	33.5	65	39.0
15	29.7	32	30.5	49	31.7	d/s	33.5
16	33.0	33	29.0	50	33.0	d/s	36.0
17	32.0	34	34.2	51	30.5	d/s	36.0

For different toe walls, the readings were observed at an interval of ten steps and the observations for toe wall with a negative slope of 6° is furnished in Table 2 for various discharges.

Table 2. Observations for Toe wall with a negative slope of 6°
(Depth of flow in mm)

Step no.	For discharge 0.08 cumecs	For discharge 0.06 cumecs	For discharge 0.05 cumecs	For discharge 0.04 cumecs
1	59.7	51.5	44.3	38.7
10	40.0	33.0	31.0	26.0
20	36.0	29.2	27.2	26.7
30	37.2	31.2	28.7	26.2
40	39.8	34.8	31.8	27.3
50	41.0	33.0	32.0	26.0
60	38.0	34.0	31.0	29.0
65	40.3	33.8	32.6	28.3
d/s of toe wall	45.0	36.0	31.0	28.0

ENERGY DISSIPATION

The energy at the spillway crest, E_o (considering downstream bed level as datum) is given by

$$E_o = n\,h + 1.5\,y_c$$

where n is the number of steps, h is the height of the step and y_c is the critical depth which is given by $(q^2/g)^{3/2}$. The energy at the toe of the spillway, E_t is given by

$$E_t = y_t + V_t^2/2g$$

where y_t is the depth of flow at the toe of the spillway and V_t is the velocity of flow at the toe of the spillway. The energy loss is $\Delta E = E_o - E_t$. The percentage of energy loss or the percentage of energy dissipated over the stepped spillway with respect to the energy at the spillway crest is $\Delta E/E_o$

RESULTS AND DISCUSSIONS

Results obtained from the present study are discussed for the two sets of experiments conducted ie., without the construction of toe wall and with the construction of toe wall.

(i) Without the construction of Toe wall

This set of experiments consist of 9 runs with discharges 0.012, 0.0234, 0.034, 0.04, 0.05, 0.06, 0.071, 0.08 and 0.11 cumecs. The amount of energy dissipated for various discharges are computed. For all the discharges, the flow was found to be skimming flow. For a discharge of 0.08 cumec (or 0.064 cumec/m), the amount of energy dissipated is 80.89%. At the lowest discharge of 0.01 cumec the energy loss is 95.23%. It was observed that there was air entrainment on each step at the lowest discharge which is not seen for higher discharges. The energy loss versus discharge curve is shown in Fig. 3.

(ii) With the construction of Toe wall

This set of experiments consist of 20 runs with toe walls having negative slopes of 4°, 6°, 8°, 10°, 12°. For each negative slope of the toe wall, flow profiles were studied for discharges of 0.04, 0.05, 0.06 and 0.08 cumecs. The additional amount of energy dissipated due to the construction of toe wall was calculated for all these runs. The effect of 4° negative slope toe wall is found to be insignificant. For a specific discharge of 0.08 cumec, the additional energy loss due to the toe wall are shown in Table 3. Total energy dissipated for various discharges and for different negative slopes of toe wall are shown in Fig 4.

Fig.3 Energy Dissipated without Toe wall

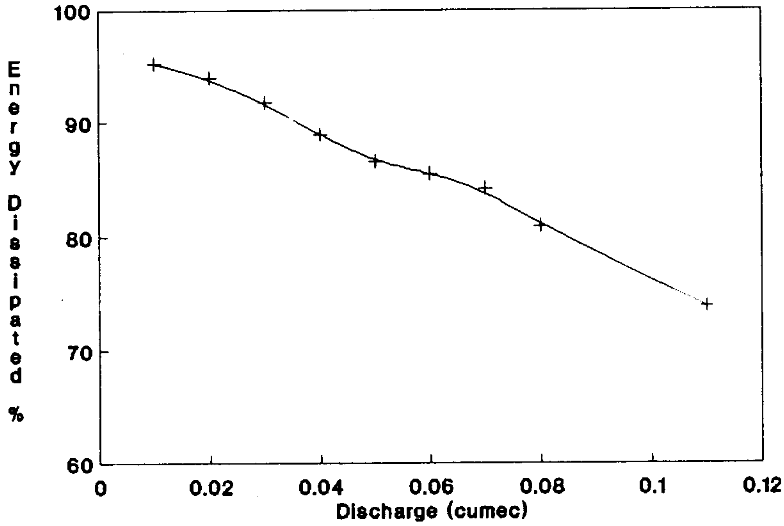

Fig.4 Energy Dissipated with Toe wall

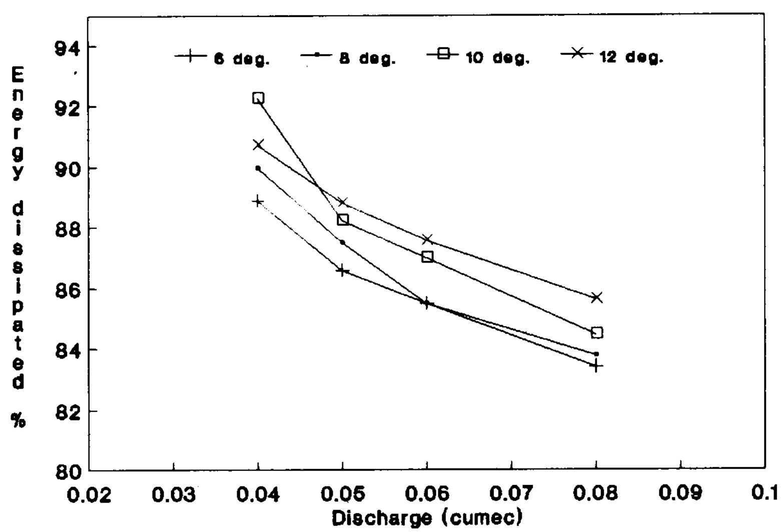

Table 3. Additional energy dissipation for a specific discharge of 0.08 cumec

Negative slope of Toe wall	Additional energy dissipated (%)
4°	Not significant
6°	2.50
8°	2.88
10°	3.57
12°	4.63

CONCLUSIONS

Experimental studies were conducted on a physical model of Stepped spillway to study the energy dissipation characteristics of the spillway. From the experimental study, it is concluded that the stepped spillway is an efficient and technically sound alternative to conventional spillway structures and dissipates maximum amount of energy on the spillway structure itself. For additional energy dissipation, a toe wall with a negative slope of 8° to 12° is found to be suitable. The stepped spillway is more suitable over embankment dams where the downstream slopes are relatively flat. Although stepped spillways are presented as efficient energy dissipators, extensive research must be carried out, in the field of air entrainment and stability, before their adoption at a specific location.

REFERENCES

1. Stephenson, D. 1991. Energy dissipation down stepped spillway. J. Water Power and Dam Construction, 43(9): 27-30.
2. Chanson, H. 1994. Hydraulics of skimming flow over stepped channels and spillways. Canadian J. of Civil Engg., 445-460.
3. Sorenson, R.M. 1985. Stepped spillway hydraulic model investigation. J. Hydraulic Engg., ASCE, 111(2): 1461-1472.
4. Pravdivets, Y.P. and Branley, M.E. 1989. Stepped protection blocks for dam spillways, J. Water Power and Dam Construction, 49-56.
5. Dieez-Cascon, J., Lanco, J.L., Revilla, J. and Garcia, R. 1991. Studies on the hydraulic behaviour of stepped spillways. J. Water Power and Dam Construction, 22-26.
6. Pravdivets, Y.P. and Slissky, S.M. 1981. Passing flood waters over embankment dams. J. Water Power and Dam Construction, 30-32.
7. Chanson, H. 1994. Comparison of energy dissipation between nappe and skimming flow regimes on stepped chutes. Canadian J. of Civil Engg.
8. Pyras, L. and Degoutte, G. 1992. Flow and energy dissipation over stepped gabion weirs. J. Hydraulic Engg., ASCE, 118(5): 707-717.
9. Chamini , M.R. and Rajaratnam, N. 1994. Jet flow on stepped spillways. J. Hydraulic Engg., ASCE, 120(2): 254-259.
10. Rajaratnam, N. 1990. Skimming flow in stepped spillways. J. Hydraulic Engg., ASCE, 116(4): 586-590.
11. Dept. of Water Resources, Govt. of Orissa. 1994. Preliminary feasibility study on construction of truncated Jambhira earth dam, Preliminary report.