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Experimental Study of Energy Loss in a Stepped Spillway Equipped with Inclined Steps in the Nappe and Skimming Flow Regimes

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Abstract: Scrutinizing the considerable flow energy in a spillway plays a significant role in maintaining downstream dam safety, and due to this fact, the dimension of the stilling basin will be enormously reduced, and from an economical point-of-view, construction costs will dramatically reduce. This phenomenon may even result in the removal of the stilling basin. A stepped spillway is one of the best structures for this purpose. In this experimental study, steps in the stepped spillway are equipped with inclined steps with various slopes, to find out how they influence their relative energy loss. Results illustrate that using inclined steps, considerably affect both the nappe and skimming flows; however, the energy loss in nappe flows is greater than that in skimming flows. Analyzing the results of experimental tests side-by-side with the results obtained from other researchers makes clear that the method used in the current investigation is more efficient than previous ones.

Keywords: stepped spillway; nappe flow; skimming flow; energy loss; inclined step

1. INTRODUCTION

The remnants of ancient structures show that stepped spillways have been used for 3500 years. As a matter of fact, these spillways were not only used as a dissipater but had various other applications. As a case in point, between the 16th and 18th centuries, they served decorative and aesthetic purposes [1]. In the early twentieth century, these spillways became practically unused and were replaced with other options due to their long construction time, high maintenance cost, and low hydraulic efficiency. However, in recent years, due to technological advances and the use of the R.C.C. technique, the construction time for spillways and their maintenance cost has been dramatically reduced and their hydraulic efficiency has been significantly boosted. Due to the abovementioned reasons, the tendency to reuse spillways has interestingly increased. Furthermore, with the utilization of these spillways, the energy of the flow is substantially dissipated by the time of the arrival to the toe of the spillways. As a consequence, the size of the stilling basin is remarkably reduced.

In stepped spillways, the flow pattern does not remain constant as the discharge is changed. For instance, in low-rate flow, nappe flow, in high-rate flow, the skimming flow and between these two flow regimes, a transition flow is observed. One of the most important parameters in energy dissipation is the drop number which is q2/gHT3; where q= flow discharge per channel width; g= gravity acceleration and HT = total drop height. Investigations (Peyras et al.1992; Israngkura and Chinnarasri 1994) show that by increasing the drop number the relative energy loss ratio decreases. [8], [10]

Some relevant equations concerning the estimation of the dissipation energy rate in various flows in horizontal steps have been proposed by different researchers.

2. THE NAPPE FLOW REGIME

Among the proposed equations, the equations belonging to Chanson, Chamani, and Fratino and Rajaratnam are considered to be the best for nappe flow.

The following equation was proposed by Chanson (1994) to determine the dissipation energy rate in nappe flow, along with the hydraulic jump in stepped spillways [1]:

$$\frac{\Delta H}{H_{max}} = 1 - \left[\frac{0.54\left(\frac{d_c}{h}\right)^{0.275} + \frac{3.43}{2}\left(\frac{d_c}{h}\right)^{-0.55}}{\frac{3}{2} + \frac{H_{dam}}{d_c}}\right] \qquad (1)$$

Where Hmax=total energy (Hdam+3/2hc); ΔH = energy dissipated in the length of the chute; dc=critical depth of flow (m); Hdam = height of dam and h: height of step (m).

Moreover, the equation proposed by Frantino and Colleagues (2000) pertaining to nappe flow is as follows [7]:

$$\frac{\Delta H}{H_{max}} = 1 - \frac{H_r}{H_{max}} = 1 - \frac{y_1 + \frac{1}{2}\frac{y_c^3}{y_1^2}}{H_d + \frac{3}{2}y_c} = 1 - \frac{\lambda + \frac{1}{2}\lambda^{-2}}{\frac{H_d}{y_c} + \frac{3}{2}} \qquad (2)$$

Where λ is the dimensionless parameter and shows the relation between y_1 and y_c.

$$\lambda = \frac{\sqrt{2}}{\frac{3}{2\sqrt{2}} + \sqrt{\frac{h}{y_c} + \frac{3}{2}}} \qquad (3)$$

Chamani and Rajaratnam (1994) also presented the subsequent equation to obtain the dissipation energy rate in all nappe flows in stepped spillways [4]:

$$\frac{\Delta H}{H_{max}} = 1 - \frac{\left\{(1-\alpha)^N\left[1 + 1.5\left(\frac{h_c}{h_s}\right)\right] + \sum_{i=1}^{N-1}(1-\alpha)^i\right\}}{N + 1.5\left(\frac{h_c}{h_s}\right)} \qquad (4)$$

Where α = coefficient of energy loss for each step and N = the number of steps.

$$\alpha = a - b\log\left(\frac{h_c}{h_s}\right) \quad (5)$$

$$a = 0.3 - 0.35\left(\frac{h_s}{l_s}\right) \quad (6)$$

$$b = 0.54 + 0.27\left(\frac{h_s}{l_s}\right) \quad (7)$$

Where l_s = horizontal step length (m).

All material on each page should fit within a rectangle of 18 x 23.5 cm (7" x 9.25"), centered on the page, beginning 2.54 cm (1") from the top of the page and ending with 2.54 cm (1") from the bottom. The right and left margins should be 1.9 cm (.75"). The text should be in two 8.45 cm (3.33") columns with a .83 cm (.33") gutter.

3. SKIMMING FLOW REGIME

Chanson presented an equation to calculate the estimation of the dissipation energy rate in the skimming flow in stepped spillways [1]:

$$\frac{\Delta H}{H_{max}} = 1 - \frac{\left(\frac{f}{8sin\theta}\right)^{\frac{1}{3}}cos\theta + \frac{1}{2}\left(\frac{f}{8sin\theta}\right)^{\frac{-2}{3}}}{\frac{H_D}{h_c} + \frac{3}{2}} \quad (8)$$

Where *f* can be obtained as follows:

$$\frac{1}{\sqrt{f}} = 2.43 - 0.2676 ln\left(\frac{h_s \cos\cos\theta}{D_H}\right) \quad (9)$$

Where DH = hydraulic depth of flow. That equation is applicable for mild slope chutes. ($\theta \leq 20°$)

Another equation which can be used to determine the dissipation energy rate in the skimming flow regime is Chanson's equation, which can be used to calculate the energy remaining at the end of the chute. [1]

$$H_{res} = ycos\theta + \frac{q^2}{2gy^2} + z \quad (10)$$

Where y = depth of fresh water and H_{res} = energy remaining at the end of the chute.

The following equation is used to calculate y:

$$\frac{y}{h_c} = \sqrt[3]{\frac{f}{8\sin\sin\theta}} \quad (11)$$

f is calculated from (9).

The following equation has been also offered by Chamani and Rajaratnam to estimate the energy remaining at the end of the chute. [5]

$$H_{res} = y_m cos\theta + \frac{u_m^2}{2g} + z \quad (12)$$

Where y_m= mixed depth (air and water); um= mixed flow velocity and z = height from the baseline.

Among all investigations conducted on spillways; the research performed by Chaturabul (2002) can be singled out. [6]

Chinnarasri and Wongwises examined the inclination of the step brink to determine the increase in energy loss in 2004. [3]

4. ENERGY DISSIPATION

4.1 Model Specification

Recent research has been conducted at the Institute of Water Research on a stepped spillway with a scale of 1:15. Steps and walls are made of Plexiglas and have been mounted on the steel structure. Wall thickness is 10 mm. The number of steps is 60. Four steps shortly after the middle of the spillway have been changed. The horizontal length of the steps is 14 cm; the step height is 4.66 cm; and the chute width is 1.33 m. The height of the step inclination to the first step is 5 cm. Measured parameters during the test, including depth, velocity, static pressure imposed on the steps, and pressure fluctuations were tested at four different discharges: 20 and 25 liters per second (the nappe flow regime) and 95 and 100 liters per second (the skimming flow regime).

Water depth, flow velocity, and static pressure has respectively been measured by liminimeter, pitot tube, and piezometer. In addition, to record pressure fluctuations, a transducer has been used. For each piezometer 200 data in seconds 30 seconds have been recorded. To measure the water level in the reservoir, a scale bar has been used and flow discharge has been measured by a thin-plate weir at the end of the downstream chute. The flow that passed over the spillway has been calculated and compared with the discharge rate. Pegram et al. (1999) conducted some experiments on stepped spillways with scales of 1:10 and 1:20 and concluded that models with a scale of 1:20 and higher can represent actual spillway behaviour by Froude number similitude. [9] Considering this, the results of the recent study are applicable for models 15 to 20 times greater than this spillway. Three slopes were used: 5°, 8° and 11° during the current investigation.

5. NAPPE FLOW REGIME

Before applying the changes on the stairs, tests were conducted on the horizontal steps to observe and also calculate the effects of the step incline with the end sill on increasing the energy dissipation rate. Numbers obtained for the dissipation energy rate from the test were 0.5128 and 0.5112, which were derived from the Chamani and Rajaratnam correlation, showing suitable agreement.

Then, changes were applied on the steps and energy dissipation was measured for different slopes and end sills. The results have been presented in Table 1.

The obtained results show that the height, thickness, and upward angle of the end sills, as well as the height of the inclined step, affect the energy dissipation rate.

In this section, the parameter w is used, where w = height of step inclination. (see Fig. 1)

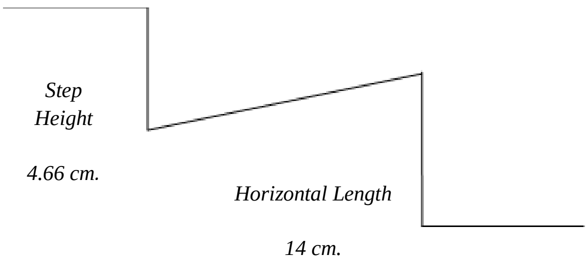

Figure 1. Schematic representation of the step

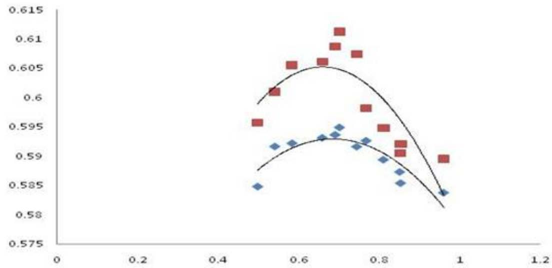

Figure 2. Dissipation energy loss per m for all examined slopes

In the abovementioned figure, the overall conclusion for all slopes have been presented. Additionally, the fitted curve between different points has been shown. As can be seen, the curve is quadratic. If the w/h ratio increases up to 0.7, the energy dissipation rate increases and after that it decreases. This graph suggests that the best ratio for m/h is about 0.7 and an excessive increase negatively impacts the dissipation energy rate.

The reason underlying the decrease in the energy dissipation rate as we increase the w/h ratio to values greater than 0.7 may be the fact that as the slope (w) and the height of the end sill increases the flow jumps from one of the steps. This step plays practically no role in energy dissipation. As a consequence, the energy dissipation rate decreases.

Figure. 3 Step: slope=5°

Figure. 4 Step: slope=11°

The table below presents increased dissipation energy rates within the experimental range:

Table 1. Comparison of energy derived from the test

	Energy Loss		
Run number	**Test**	**w/h**	**Inclined step angle θ (degrees)**
1	0.595675	0.4972	5
2	0.600957	0.5401	5
3	0.605484	0.5829	5
4	0.606066	0.6580	11
5	0.608699	0.6901	5
6	0.611219	0.7008	11
7	0.584767	0.4972	5
8	0.591643	0.5401	5
9	0.592178	0.5829	5
10	0.593122	0.6580	11
11	0.593628	0.6901	5
12	0.594898	0.7008	11
13	0.592959	0.5829	5
14	0.584457	0.5829	5

6. SKIMMING FLOW REGIME

Like with the nappe flow regime, the energy dissipation rate is obtained in horizontal steps. The numbers obtained for the dissipation energy rate from the test were 0.3514 and 0.3508 derived from the Chansun correlation, which show good agreement. Changes were then imposed on the steps and the energy dissipation rate was measured for different slopes and end sills. The results are presented in Table 2. The results show that the height, thickness, upward angle of the end sills, and also the height of the step incline, affect the energy dissipation rate slightly.

In this section, the effects of the w/h ratio on the energy dissipation ratio per total energy is examined for the skimming flow.

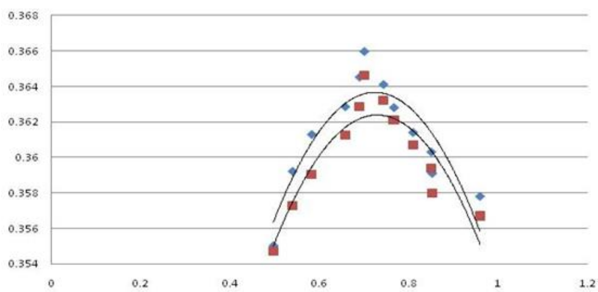

Figure. 5 Energy loss per w for all tested slopes

In Fig. 5, the energy loss per w/h ratio is presented. As with the nappe flow, an increase in the dissipation energy rate continues up to 0.7 and after that it decreases. Once again, this demonstrates that an excessive increase in the w/h ratio w/h negatively impacts the dissipation energy rate.

As a matter of fact, in the nappe flow, some steps have no role in dissipating energy due to the flow jumping over them.

Figure. 6 Step: slope=5°

Figure. 7 Step: slope=11°

Table 2 presents experimental dissipation energy rate increases.

Table 2. Comparison of energy derived from the test

	Energy Loss		
Run number	**Test**	**w/h**	**Inclined step angle θ (degrees)**
1	0.355022	0.4972	5
2	0.359207	0.5401	5
3	0.361285	0.5829	5
4	0.362848	0.6580	11
5	0.364517	0.6901	5
6	0.365962	0.7008	11
7	0.354725	0.4972	5
8	0.357268	0.5401	5
9	0.359039	0.5829	5
10	0.361264	0.6580	11
11	0.362863	0.6901	5
12	0.364622	0.7008	11
13	0.360696	0.5829	5
14	0.358607	0.5829	5

7. CONCLUSION

Our thanks to the experts who have contributed towards development of the template.

To recap, energy loss is associated with the geometry of steps. The results show that the incline of steps dramatically influences energy loss. In both flow regimes, nappe flow and skimming flow with a w/h ratio less than or equal to 0.7, the incremental trend of energy loss can be seen. However, greater than that, it decreases due to the flow jumping over several steps.

Three reverse inclined step angles (5°, 8°, and 11°) have been used in the Nappe and Skimming Flow Regimes for stepped spillways to experimentally investigate the energy loss rate. Four discharges (20, 25, 95, and 100 liters) were used in this research. Two of these discharges belong to the Nappe Flow Regime and the other two to the Skimming Flow Regime. The results indicate that discharge is the most important factor affecting the energy loss rate.

In the 5-degree slope, discharge changed from 20 L/s to 25 L/s and the energy loss rate dropped 20.32%, whereas with a constant discharge (20 L/s), the change in the slope from horizontal to a 8-degree slope increased the energy loss rate only 3.76%. The change in the inclined slope degree minimally impacts the energy loss rate. As Table 2 illustrates, modifying the slope from 8-degrees to 11-degrees only increases the energy loss rate 0.52%.

Current investigation demonstrates that using inclined steps increases the energy dissipation rate approximately 15% on average for nappe flow and 2% on average for skimming. In the skimming flow, changes imposed on steps have no tangible impact on the energy loss.

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