Nappe flow regime energy loss in stepped chutes equipped with reverse inclined steps: experimental development

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Nappe Flow Regime Energy Loss in Stepped Chutes Equipped with Reverse Inclined Steps: Experimental Development

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ABSTRACT: With advances in technology and the invention of the Roller-Compacted Concrete (R.C.C) technique, stepped spillway construction has become much faster than in the past. Due to this, designers have become more interested in using this kind of chute as one of the best energy dissipaters. Along with the increasing use of stepped spillways, researchers have focused on increasing the efficiency of this hydraulic structure. They have proposed different methods to achieve this. Step geometry optimization, regarding flow regime type, is one of these efforts. In this experimental research, reverse inclined steps have been applied for three degrees (7°, 10°, and 12°) to investigate their effect on the energy dissipation rate in the Nappe Flow Regime of stepped spillways. Energy loss rates obtained from the reverse inclined steps have been compared with the energy loss rate in a horizontal step. Results indicate a slight increase in the energy loss rate when the reverse inclined steps have been applied in the Nappe Flow Regime of stepped spillways.

INTRODUCTION

Dissipating the flow energy, passing through the spillway, is crucial to avoid downstream damage. Using a stepped spillway is one of the best approaches for dissipating flow energy. This kind of chute gives designers an opportunity to reduce the stilling basin dimension, downstream, due to its high performance in dispersing energy [1]. In recent decades, many studies have addressed different aspects of stepped spillways; and have made them known as an efficient energy dissipater [1, 2]. The discharge rate in the stepped spillways leads to three different flow regimes. Nappe flow that is observed in the low-rate flows, Transition flow can be represented when the discharge rate increases and Skimming flow that is caused by high rates of discharge. [1, 2] performed extensive experiments on the Nappe Flow Regime and devolved experimental formulas to determine energy loss in this flow regime. Other work has been conducted on flow condition, and

energy loss in stepped spillways with horizontal steps: [3, 4] considered the characteristics of flow conditions on stepped channels. [5, 6] worked on the air entrainment inception point and energy dissipation in the case of a stepped spillway equipped with baffles and sills.

Moreover, other work on the flow condition, and energy dissipation in stepped spillways equipped with inclined steps or an end sill, have been conducted by [7-9] who investigated the effect of inclined steps and an end sill together on the flow pattern and energy loss rate. Among all investigations conducted on spillways, the research performed by [10, 11] can be singled out. In his research, the height of the applied end sills was considered at 5, 10 and 15 mm on various step slopes and this led to presenting a relationship between the relative energy loss and the drop number. The result of his investigation demonstrated that relative energy loss increased 8% due to the existence of an end sill. The drop number, which is equal to q2/gHT3 (where q is the flow discharge per channel width, g is gravity acceleration, and HT its total drop height), is one of the most important energy dissipation parameters. [12-14] examined three inclined steps degrees (10o, 20 o, and 30o) and end sill to determine the energy dissipation rate separately. They noted that using an end sill is the best approach to increase the energy dissipation rate.

Although end sills increase the energy loss rate more than inclined steps, preparing and installing an end sill is much harder than using inclined steps. Moreover, end sills should tolerate high pressure due to impact force from the flow. Therefore, one of their issues is instability. In light of this, reverse inclined steps have been selected to be investigated in this study, because their preparation is simpler than an end sill. They also don't have an instability problem. Three reverse inclined step angles (7o, 10o, and 12o) have been used in the Nappe Flow Regime of stepped spillways to investigate the energy loss rate.

ENERGY LOSS EQUATIONS

The experimental relationships and formulas for the Nappe Flow Regime are discussed in this section. Among the proposed equations, the equations designed by [1, 15, 16] are considered to be the best ones for the Nappe Flow Regime. The following equation was proposed by [15, 17] to determine the energy dissipation rate in the Nappe Flow, along with the hydraulic jump in stepped spillways:

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

Where Hmax is total energy (Hdam+3/2hc); ΔH is energy dissipated in the length of the chute; dc is the critical depth of the flow (m); Hdam is the height of the dam and h is the height of the step (m). [1], also presented the subsequent equation to obtain the energy dissipation rate in all Nappe Flows in stepped spillways:

$$\frac{\Delta H}{H_{\max}} = 1 - \frac{\left\{ (1-\alpha)^N \left[1 + 1.5\left(\frac{h_c}{h_s}\right) \right] + \sum_{i=1}^{N-1}(1-\alpha)^i \right\}}{N + 1.5\left(\frac{h_c}{h_s}\right)} \tag{2}$$

Where α = the coefficient of the energy loss for each step and N = number of steps and ls = horizontal step length (m).

$$\alpha = a - b\log\left(\frac{h_c}{h_s}\right) \tag{3}$$

$$a = 0.3 - 0.35\left(\frac{h_s}{l_s}\right) \tag{4}$$

$$b = 0.54 + 0.27\left(\frac{h_s}{l_s}\right) \tag{5}$$

[12] introduced equations (6) to (8) to estimate energy dissipation rate in steps spillways equipped with inclined steps.

$$\frac{E_L}{E_0} = \eta\left(\frac{d_c}{h}\right)^\xi \tag{6}$$

$$\eta = -0.034\ln\left(\frac{h}{m}.\frac{h}{l}\right) + 0.767 \tag{7}$$

$$\xi = -0.015\ln\left(\frac{l}{m}\right) - 0.216 \tag{8}$$

EXPERIMENTAL SET UP

The research was conducted at the Water Research Institute in Iran on a stepped spillway. The steps and walls were made of Plexiglass and mounted on a steel frame. The chute spillway that was used was a broad-crested weir with 60 steps. In the present investigation, only four steps were reverse inclined; all were placed after the middle of the chute (steps 39-42). The horizontal length of the steps was 14 cm; the step height was 4.66 cm and the chute width were 1.33 m. The height of the broad-crested weir to the first step was 5 cm. Measured parameters during the test include depth and velocity. The experiments have been conducted for four discharges (20, 25, 30, and 35 L/s) in the Nappe Flow Regime. Flow depth and velocity have been measured by using a liminimeter (with a precision of 1 millimeter) and a pitot-tube, respectively. Flow discharge has been measured by the sharp crested weir at the end of the downstream chute. Three slopes of 7°, 10°, and 12° about the horizon were used.

Depth along the spillway width was measured by a liminimeter across each line of piezometers. This measurement included three depths of Jet 1 (only water), Jet 2 (a mixture of water and air),

and Jet 3, which is spraying of the water flow. Finally, an average of the three depths across each line of the piezometer was used as the step width. The pitot-tube was used to measure velocity. This measurement was difficult since the flow was two-phase and bleeding had to be performed regularly. In the Nappe Flow Regime, flow depth was not high enough to measure velocity at different depths; the velocity was measured on both sides and in the middle at 0.6 m depth. Finally, the depth in the left, right, and middle sections was averaged and set as the average velocity of that step. In this chute, only four steps (39-42) were reversely inclined. The depth and velocity values were measured at these steps, as well as at the 38th step. To determine energy loss, data from the 38th and 42nd steps was sufficient. Velocity and depth values were recorded on other steps for future investigations.

Flow enters the chute from the reservoir. The flow enters transferring pipes from the pumps and falls into the reservoir. When the reservoir is filled, the vent is opened, and flow falls into the chute. The employed pump has a pumping capacity of 220 liters per second. To determine energy upstream and downstream from the amended steps, the following equations have been used:

$$H_1 = y_1 + \frac{v_1^2}{2g} + z \tag{9}$$

$$H_2 = y_2 + \frac{v_2^2}{2g} + z \tag{10}$$

Where H is flow energy, y is flow depth, V is flow velocity in proper sections, g is gravity acceleration, and Z is the height from the baseline (The bottom of the last modified step has been assumed to be the baseline and Z=0).

RESULTS AND DISCUSSION

The results obtained from the experiments for all applied reverse inclined slopes (i.e., 7o, 10o, and 12o) and the horizontal slope also all discharges (20, 25, 30, and 35 L/s) are presented in this section. Figure 1a shows the flow pattern in the horizontal steps. Figure 1b illustrates the energy loss rate versus the dimensionless parameter "dc/h." Where dc is the critical depth and h is the step height. As can be seen in Figure 1b, when the discharge increases, the energy loss rate decrease.
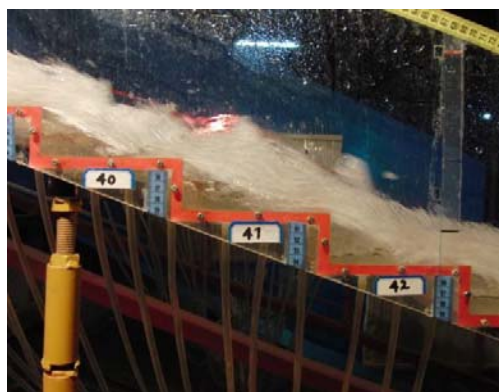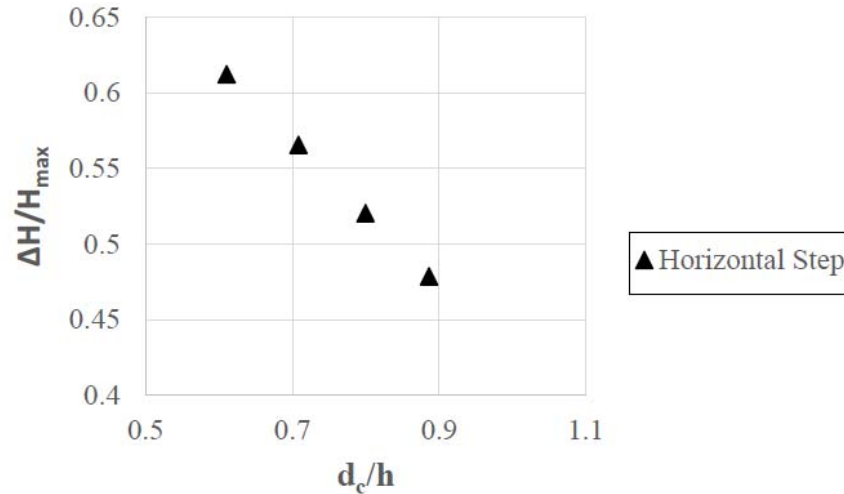

FIGURE 1a. Horizontal step

FIGURE 1b. Energy loss rate

The energy loss rate versus the "dc/h" graph is also provided for reverse inclined steps 7o, 10o, and 12o (Figures 2b, 3b, and 4b). The results indicate that, in reverse inclined steps, the energy loss rate decreases when the discharge increase which is following the same trend in horizontal steps. The results demonstrate that when the steps are reversely inclined, the energy loss rate increased. The equation suggested by [13] cannot be used to compare the results, because they did not include the effect of the number of steps in their equation. Figures 2a, 3a, and 4a show flow patterns in reverse inclined steps 7o, 10o, and 12o respectively. Table 1 illustrates all energy loss rates obtained from the experiments.
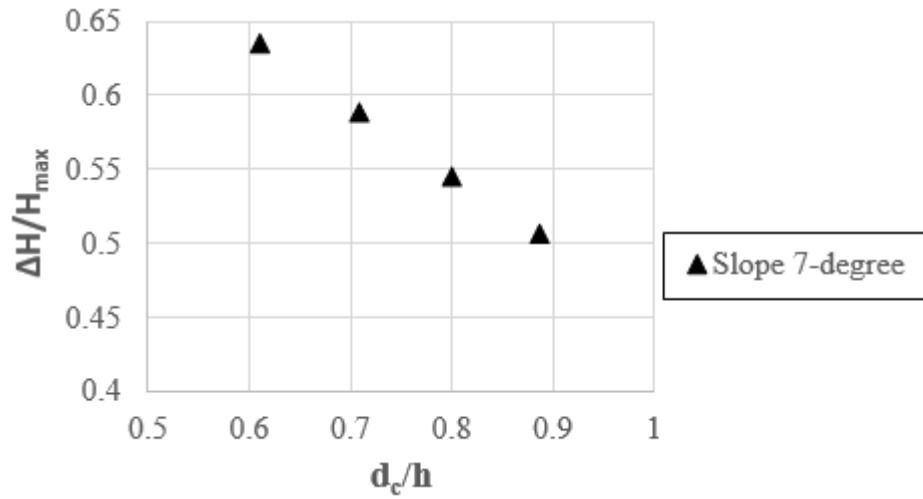

FIGURE 2a. Slope 7º
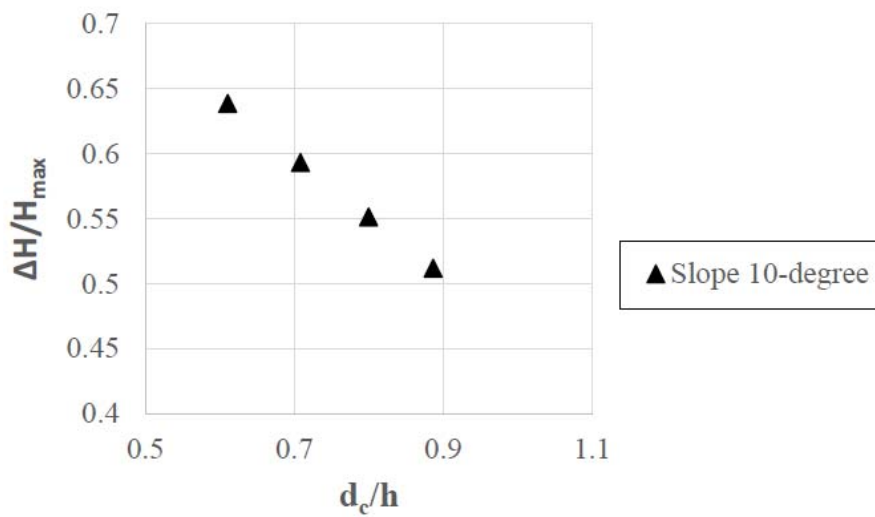
FIGURE 2b. Energy loss rate

FIGURE 3a. Slope 10º

FIGURE 3b. Energy loss rate
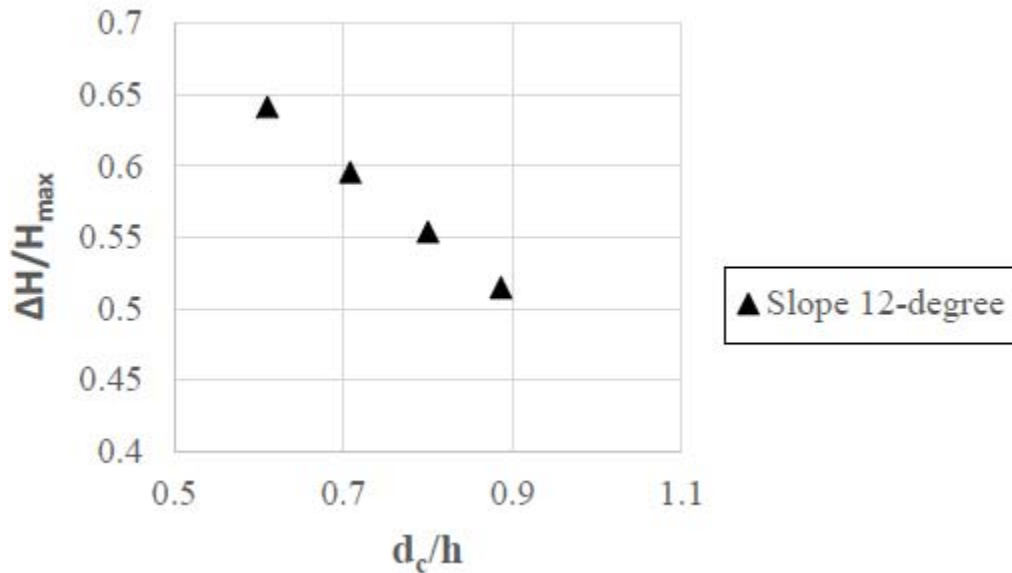
FIGURE 4a. Slope 12°

FIGURE 4b. Energy loss rate

Based on the obtained results and the energy loss rate graphs, it can be concluded that increased discharge leads to an energy loss rate decrease for both horizontal and reverse inclined steps. Also, results indicate that the energy loss rate is higher at reverse inclined steps than for horizontal steps. Moreover, the higher the reverse inclined slopes leads to a higher energy loss rate. However, this increase is not considerable. Figure 5 shows the energy loss rate for all slopes and Table 2 indicates the energy loss rate for various discharges.

Table 1. Energy Loss Rate for Various Slopes

Test Number	Discharge (L/s)	Slope(degree)	dc/h	Energy loss rate
1	20	0	0.611	0.612
2	25	0	0.709	0.566
3	30	0	0.800	0.521
4	35	0	0.887	0.479
5	20	7	0.611	0.635
6	25	7	0.709	0.589
7	30	7	0.800	0.545
8	35	7	0.887	0.506
9	20	10	0.611	0.639
10	25	10	0.709	0.593
11	30	10	0.800	0.551
12	35	10	0.887	0.512
13	20	12	0.611	0.641
14	25	12	0.709	0.596
15	30	12	0.800	0.554
16	35	12	0.887	0.515
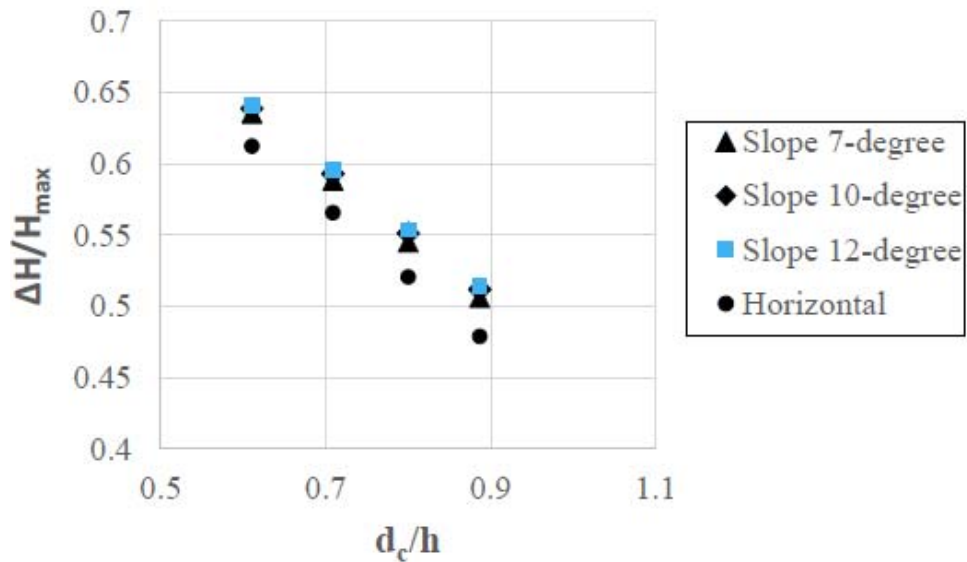
FIGURE 5. Energy loss rate for all slope

Table 2. Energy Loss Rate for Various Discharges

	Discharge (L/s)			
	20	25	30	35
Horizontal	0.612	0.566	0.521	0.479
7-degree Slope	0.635	0.589	0.545	0.506
10-degree Slope	0.639	0.593	0.551	0.512
12-degree Slope	0.641	0.596	0.554	0.515

CONCLUSION

Three reverse inclined step angles (7º, 10º, and12º) have been used in the Nappe Flow Regime for stepped spillways to investigate the energy loss rate experimentally. Four discharges (20, 25, 30, and 35 liters per second) have been used in this research. All these discharges belong to the Nappe Flow Regime. The results indicate that discharge is the most important factor that affects the energy loss rate. In the 7-degree slope, discharge changed from 20 L/s to 35 L/s and the energy loss rate dropped 20.32%, whereas in a constant discharge (20 L/s), the change in the slope from horizontal to a 7-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 7-degree to 10-degree only increases the energy loss rate 0.52%.

ACKNOWLEDGMENTS

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