Experimental survey of energy dissipation in nappe flow regime in stepped spillway equipped with inclined steps and sill

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Experimental Survey of Energy Dissipation in Nappe Flow Regime in Stepped Spillway Equipped with Inclined Steps and Sill

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Abstract—**Stepped spillway increases the hydraulic resistance against flow by using of step-made spillway floor and when the flow of water passing on steps, a significant part of energy dissipates and also reduces the risk of cavitation. In this experimental research, in order to increase the energy dissipation of stepped spillway, Steps has a reverse gradient and in other part of this tests in addition to create a reverse gradient in the steps at the same time the sill is also installed on the edge of the steps. Height, thickness of the sills is considered variable. The results show that in both Nappe Flow Regime and Skimming Flow Regime Change of gradient, sills height, thickness are effective to increase the energy loss but the effect of these parameters on the Nappe Flow Regime is much greater than Skimming Flow Regime. By analyzing the results of the experiments and compared with results from other studies, the research showed that the method used in this study has a better energy loss than other methods used in prior researches.**

Keywords—**stepped spillway; Nappe Flow Regime; Skimming Flow Regime; energy loss; experimental method.**

I. INTRODUCTION

Stepped spillway, consists of the steps which starts close to the spillway crest and continues to lower heel. Stepped spillway is like energy dissipation structures, especially in Roller Compacted Concrete Dam, health of the downstream spillway ensures and the need of stilling basin at the spillway terminal reduces and even causes that the use of the stilling basin at the toe of spillway being not necessary which cause economic saving in dam construction [1-6]. Rajaratnam offered a measure according to the experiments and analysis that based on the ratio of the step height to its length (h/l). Thus, in facing relationship:

$$0.4 < \frac{h}{l} < 0.9$$

A procedure is created [7]. Azhdary, M. examined Hydraulic flow on stepped spillway with 4 different forms and 3 slope and according to the shape and slope of the spillway evaluated friction and energy loss factors an d also determined optical shape of steps [8, 9]. Ohatsu et al. examined the stepped spillway flow resistance parameter and Stated that flow resistance at high rates depends on the vortex formed in the corner of steps and maximum resistance obtained at spillways with a slope of 19 degrees [10, 11]. Pegram and Mottram examined the effect of step height in energy loss; thus, in the spillway slope of 59 degrees and a step height of 0.5 to 2 m, energy losses were almost equal. The result obtained from this research was that in slope of 59 degrees, step height has no effect in energy losses. By the way the energy loss of about 60% has been achieved in these spillways, but on slopes of 40 to 50 degrees step height has a large impact on energy dissipation [12, 13]. Chafi et al. compared the results from experiences and models in other research works and Concluded that the relative energy loss in the falling stream depends on the number of steps and the flow rate, and the relative energy loss in the falling stream is greater than in flow without falling stream [14]. Hamedi et al. also examined the existence effect of reverse slope and sill at same time, on amount of energy loss, in this research they used reverse slope of 7,10 and 12 degrees and sill with different Height and thickness [15, 16]. Dermawa n, V. and .Legono,D. studied amount of remaining energy and relative energy loss on stepped spillway with 45 degrees slope, 100 centimeter height and 30 centimeter width. In the following the surface of stepped spillway from its crest up to claws have been splitted to 2, 4, 8, 16 and 32 steps in 5 stages and have achieved flow rate in 5 types from 1.73 to 6.15 liters per second for each process, achieved results show that for each number of process, amount of relative energy loss reduces with increase in Yc/h ratio [17]. Darvish et al., Ketabdar and Hamedi, Kamyab 2017a,b [18-25] ,proposed several numerical and materials simulation, which are currently considered in current work.

II. NAPPE FLOW REGIME (HISTORY AND EQUATIONS)

From among presented equations for stepped spillway we can mention equations of Chanson, Fratino, Chamani and Rajaratnam. Chanson presented equation below for examining amount of energy dissipation in nappe regime with hydraulic jump of stepped spillway. Zeidi et al. [26-31], defined different mathematical models for flow which were utilized in the current study.

$$\frac{\Delta H}{H_{\max}} = 1 - \left[\frac{0.54\left(\frac{d_c}{h}\right)^{0.275} + 1.175\left(\frac{d_c}{h}\right)^{-0.55}}{1.5 + \frac{H_{dam}}{d_c}} \right] \quad (1)$$

Which in this equation total energy is Hmax = (Hdam+3/2hc), energy dissipation in shot length is ΔH, critical depth is dc, dam height is Hdam and step height is h.

And also Franito et al. presented equation below for Nappe flow:

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

Which λ is dimensionless parameter and represent relation between and as below [16 -21]:

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

Chamani and Rajaratnam, presented equation below for examining amount of energy dissipation in all nape flows of stepped spillway:

$$\frac{\Delta H}{H_{\max}} = 1 - \frac{\left\{ (1-\alpha)^N \left[1 + \frac{1}{5\left(\frac{h_c}{h_s}\right)} \right] + \sum_{i=1}^{N-1} (1-\alpha)^i \right\}}{N + \frac{1}{5\left(\frac{h_c}{h_s}\right)}} \quad (4)$$

Which α is energy dissipation factor for each step, N is number of steps. Chamani and Rajaratnam presented equation (5) to calculate α, as below:

$$\alpha = \frac{0}{3} - \frac{0}{35\left(\frac{h_s}{l_s}\right)}$$

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

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

III. ATERIALS AND METH ODS

At the institute of water research, recent research has been done on the 1:15 scale modeled stepped spillway. Material of steps and walls of stepped spillway are plexiglass and has been mounted on metal frame. Wall thickness is 10 mm. Used a wide-brimmed shot spillway and the numb er of shot steps is 60, among these 4 steps have been change d shortly after the middle of the spillway. Step length is 14 cm, the step height is 4.66 cm, width of spillway is 1.33 m and height from spillway crest to the bottom of the first step is 5 cm. The measured parameters in research included flow depth, speed, static pressure on the bottom of the steps and pressure fluctuations. Water's depth is measured by Point gauge, velocity by Pitot tube and static pressure is measured by pi ezometers. Also a transducer was used to register the pressurre fluctuations, so that for every piezometer, 200 data is recordded per second for 30 seconds. To measure the water surface le vel in the tank, bar measurement is used and flow rate is meas ured with the help of a sharp-edged rectangular spillway at the end of downstream channel of the shot. Of course, to ensure the accuracy of flow rate, compared it with the flow over the spillway that has been calculated. Pegram et al. experimented stepped spillways on the scale of 1:10 and 1:20 and concluded that models with a scale of 1:20 or greater can present a real spillway behavior by the similarity of Fr oude number [5]. According to this, recent study results, can be used for spillway 15 to 20 times larger. The shape and slope characteristics of sills which have been us ed are as follows: Three dip includes 7, 10 and 12 degrees were used.

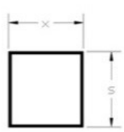

Fig. 1. Schematic of vertical sills and their characteristics

TABLE I. CHARACTERISTIC OF VERT ICAL SILLS

Millimeter (s-x)	
6-5	6-10
8-5	8-10
10-5	10-10
15-5	15-10

IV. NAPPE FLOW REGIME

Before the changes on steps, tests were performed on horizontal steps to determine the amount of increase in energy dissipation due to slope-made and sill-made steps, after the changes. The value resulting from tests for energy loss is 0.5128 and energy loss resulting from the relationship of Chamani and Rajaratnam i s 0.5112 which shows good agreement.

Then changes were applied to the steps, and the energy loss for different dips and sills is achieved, which results are presented in Table 2. The results show that height, thickness and angle of sills upstream and height of the slope are effective on the amount of energy loss. The parameter m which is equal to p+w, is used in this section. P is sill's height and W is height of the slope. Figure (2).

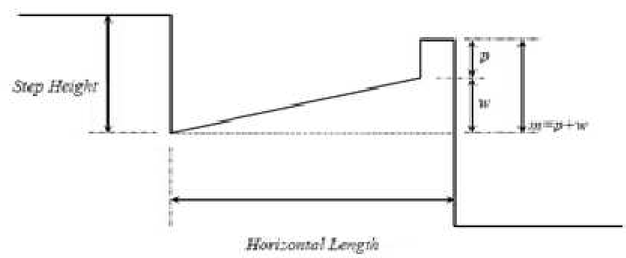

Fig. 2. P sill's height and W height of the slope

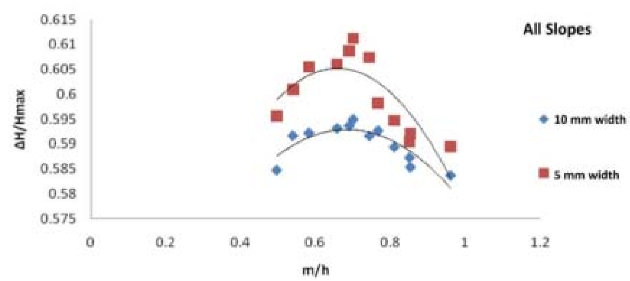

Fig. 3. Energy loss in meter for all testing slopes

In the figure above conclusions presented an overview of all slopes and the fitted curve bet ween specified points, which is aquadratic function. As shown in the graph by increasing $\frac{m}{h}$ to 0.7 the upward trend seen for the energy loss and then the energy loss has downward trend and This could indicate that the best amount of $\frac{m}{h}$ is in the range of 0.7 and increasing $\frac{m}{h}$ too much would have a negative impact on energy losses. The reason that we have decrease in energy loss due to increasing the height of $\frac{m}{h}$ more than 0.7, can be that due to the increase in the sill's height and slope (increasing m), flow gets up, and passes 1 or 2 steps and this steps are not actually play a role in energy dissipation, so the energy loss is reduced.

Fig. 4. Steps with 12 degrees slope and 15 mm sill's height and 5 mm width

Fig. 5. Figure 4-steps with 7 degrees slope and 6 mm sill's height and 5 mm width

The following table proposes energy obtained from tests in the areas that are causing increasing loss (effective sills):

TABLE II. COMPARE THE ENERGY OBTAINED FROM EXPERIMENTS ENERGY LOSS

Num	Test	Width(mm)	m/h	slope	Sill's
1	0.595675	5	0.4972	7	6
2	0.600957	5	0.5401	7	8
3	0.605484	5	0.5829	7	10
4	0.606066	5	0.6580	10	6
5	0.608699	5	0.6901	7	15
6	0.611219	5	0.7008	10	8
7	0.584767	10	0.4972	7	6
8	0.591643	10	0.5401	7	8
9	0.592178	10	0.5829	7	10
10	0.593122	10	0.6580	10	6
11	0.593628	10	0.6901	7	15
12	0.594898	10	0.7008	10	8

V. DATA OBTAINED FROM TESTS

The results of tests for different slopes are as follows:

Fig. 6. Horizontal steps with flow rate of 30 liters per second

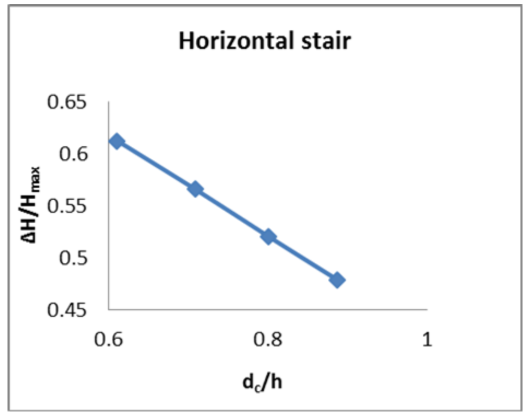

Fig. 7. Energy loss graph obtained from tests of horizontal steps

Which dc is critical depth and h is step height that has been handled as a dimensionless parameter which is dc/h. As shown in the graph by increasing the flow rate on the horizontal steps, the amount of energy dissipation is reducing. In the following graphs energy losses in terms of dc/h for 7, 10 and 12 degrees gradient have been drawn and has been shown that in the steep steps with increasing the flow rates of spillway here also the energy dissipation is reduced and as shown in the diagrams, by steep steps, energy dissipation is also increased. It should be noted that the results from the relationship provided by Chinarasri and Wongwises because of that the effect of the number of steps have not been seen, results of these tests are not comparable.

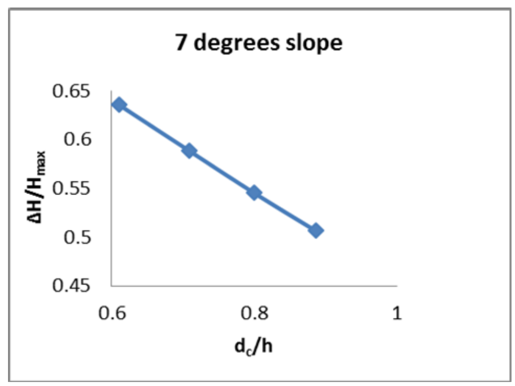

Fig. 8. Energy loss obtained from 7 degrees slope

Fig. 9. 7 degrees slope and 30 liter per second flow rate

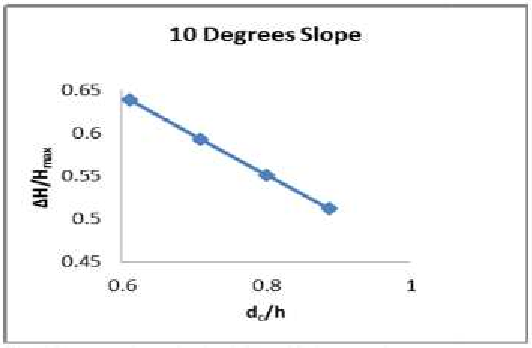

Fig. 10. Energy loss obtained from 10 degrees slope

Fig. 11. 10 degrees slope and 30 liter per second flow rate

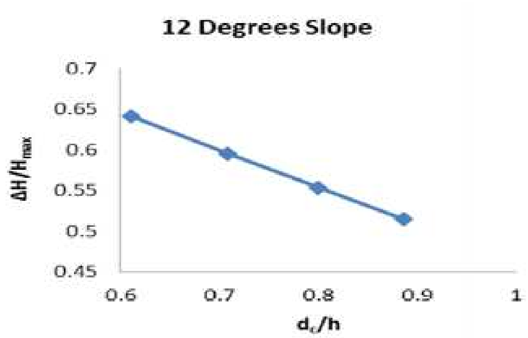

Fig. 12. Energy loss obtained from 12 degrees slope

Fig. 13. 12 degrees slope and 30 liter per second flow rate

TABLE III. ENERGY LOSS FROM EXPERIMENT FOR VARIOUS SLOPE

Energy loss	Flow rate (l/s)	dc/h	Step slope (deg)	Test num
0.5206	30	0.8003	0	3
0.5451	30	0.8003	7	7
0.5512	30	0.8003	10	11
0.5539	30	0.8003	12	15

Table III shows energy losses obtained from experiment for various slope and flow rates.

VI. Conclusion

According to the results of the tests and also the drawing diagrams, changes in energy loss is determined, so that by increasing flow rate in both horizontal and steep steps, amount of energy dissipation is reduced and the results also shows that by applying the reverse slope on the steps, amount of energy dissipation compared to horizontal steps, increases and also by increasing the amount of the reverse slope, energy dissipation increases but the increasing process is not so much.

TABLE IV. EXPERIMENTAL ENERGY LOSS COMPARED IN TERM OF FLOW RATE CHANGE

Flow rate (l/s)			
35	25	20	Energy loss
0.4789	0.5658	0.6124	Horizontal step
0.5063	0.5886	0.6354	7-degree slope
0.5119	0.5931	0.6387	10-degree slope
0.5146	0.5956	0.6414	12-degree slope

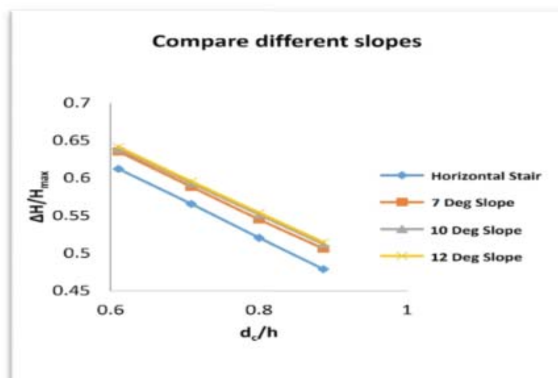

Fig. 14. Compare experimental energy loss obtained from various slopes

In Figure 14 and Table III energy loss achieved by all slopes have been brought together to compare and shows that the flow rate changes will have the greatest impact on the amount of energy loss, so that it is clear, for example, in the slope 7 degrees, the change of flow rate for 20 liters per second to 35 liters per second reduces energy loss by as much as 20.32 % while in the constant flow rate of 20 liters per second, with step change from horizontal to slope 7 degrees, the energy loss only increases up to 3.76 % and reverse changeable slope also will have the least impact on the energy loss for example from Table II it is clear that in the constant flow rate of 20 liters per second, slope shift from 7 degrees to 10 degrees only has 0.52 % increases in energy loss.

Energy loss associated with the geometry of the steps and the results show that the steep and sill steps will affect the amount of energy loss. So that both Nappe Flow Regime and Skimming Flow Regime for the range which m/h is smaller and equal to 0.7 we will see that the energy loss has an increasing trend and for over this range because of that flow jumps over some steps we will see that energy loss has a decreasing trend. In both flow regime, thickness of the sill is effective in increasing energy loss so that by reducing the thickness energy loss increases, in general, the impact of all of these parameters in Nappe Flow Regime is much more than Skimming Flow Regime.

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