FLOW AND ENERGY DISSIPATION OVER ON FLAT AND POOLED STEPPED SPILLWAY

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Graphical abstract
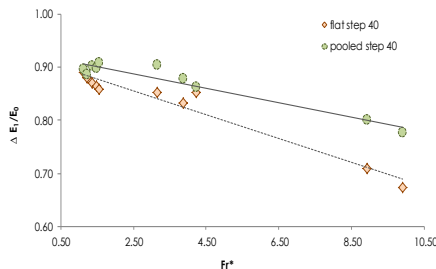
Abstract

The stepped spillway has increasingly become effective energy dissipation. The stepped spillway has been accepted to be the most powerful hydraulic structure to dissipate large flow energy downstream from spillway crest. The steps act as roughness elements significantly increase the dissipation energy rate. The physical study has performed on flat and pooled stepped spillways with a slope spillway ($\theta = 45°$) and number of steps (N): 20 and 40. The experiments were conducted for ten Froude number (Fr) run ranging from 1.117 to 9.909 with $0.700 < y_c/h < 3.00$. The focus of research to investigate the relationship between relative energy losses in skimming flow performance against Froude number on various stepped. The effect of number of steps is evident when the relative energy loss increases with the number of steps. In addition, the relative energy loss of flow on pooled steps is dissipating more energy than flat steps.

Keywords: Energy dissipation, flat steps, pooled steps

1.0 INTRODUCTION

The advantages of flat and pooled stepped spillway are the stepwise reduction of kinetic energy of water through transformation to heat, so that the size of the stilling basin can be reduced. These spillways were often used for river training, irrigation system, storm waterways, fish-way and step pool streams and improving natural surroundings. Each step in a pooled stepped corresponds to on isolated stilling basin for hydraulic jump. On stepped spillway the water falls from level to level and the optimal dissipation is expected if a hydraulic jump builds. For steeper stepped spillway and large discharges, so called skimming flow occurs in which the step acts as roughness element and causes a strong mixing of the water with air. The stepped profile allows an increased rate of energy dissipation on the spillway chute [2], [5] and the design engineers must assess accurately the turbulent kinetic energy dissipation down the staircase chute, in particular for the large discharges per unit width corresponding to the skimming flow regime. The stepped chutes are mostly equipped with flat horizontal steps. In some cases, the steps may be equipped with a sill at the step edge, creating a pool.

Several recent studies have been performed on flat and polled stepped spillways, namely [1], [4], [6], [8], [10]. Guenther [10] investigated energy dissipation on a 26.6° slope stepped chutes. Their result data are shown that the residual energy was the lowest for the flat steps. The energy dissipation on the spillway with flat horizontal steps compared to all the other configurations (pooled stepped spillway, two stepped spillway with in-line and staggered configurations of flat and pooled steps) in the skimming flow regime. It is consistent with the re-analysis of physical data down a 30° stepped chutes

[6], despite some quantitative difference in residual head level.

Chinnarasri [1] observed a comparatively smaller rate of energy dissipation on the flat stepped chute than on steps with end sill for chute slope 45°. Barani [4] investigated the energy dissipation of flow over the stepped spillway model with 41.41° slope and 21 steps. Comparison of flow energy dissipation over pooled stepped spillway has been dissipated more energy than flat stepped spillway. To find the best energy dissipation efficiency for flow on stepped spillways, the objective of the study is to compare the relative energy dissipation among flat stepped spillway and pooled stepped spillway. The effect of step geometry, number of steps and relative energy loss are presented and discussed. Experiments on physical model were conducted in the last decade to provide a better understanding of the characteristic flow and energy dissipation performances.

The energy dissipation can be observed and calculated from the energy between the inlet section at the approach channel of spillway, E_0, and any section of interesting step, E_i, as shown in Figure 1.
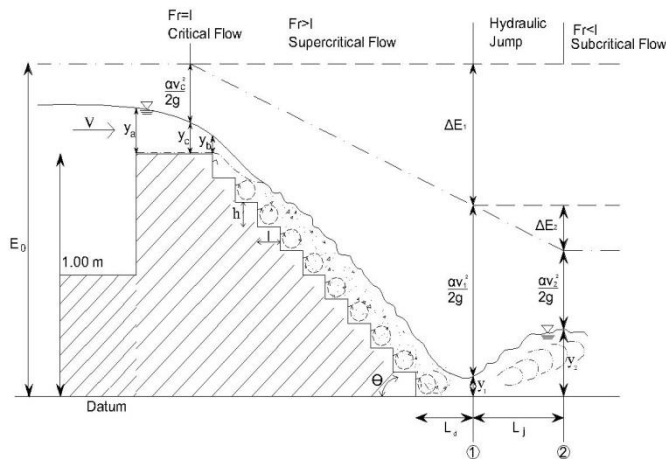

Figure1 Parameters of the calculation of energy dissipation

The energy E_0 consist of elevation head from datum to the inlet, H_{dam}, flow depth, y_c, and velocity head, $v_0^2/2g$.

$$E_0 = H_{dam} + y_c + \frac{v_0^2}{2g} \tag{1}$$

Where v_0 is velocity at the desired section (m/s), and g is acceleration of gravity of earth (m/s²). The term of velocity head can be changed to be in terms of flow as:

$$y_c^3 = \frac{q^2}{g} \tag{2}$$

The term of velocity head, then, can be written as:

$$\frac{v_0^2}{2g} = \frac{Q^2}{2gA^2} = \frac{q^2 B^2}{2gy_c^2 B^2} = \frac{q^2}{2gy_c^2} \tag{3}$$

Substitute q^2 from equation (2) into (3),

$$\frac{v_0^2}{2g} = \frac{gy_c^3}{2gy_c^2} = \frac{y_c}{2} \tag{4}$$

Then, equation (1) becomes

$$E_0 = H_{dam} + y_c + \frac{y_c}{2} = H_{dam} + 1.5y_c \tag{5}$$

The section of interesting step is also superimposed with the datum. Then, the energy E_i consist of flow depth measured, vertically, from the datum, y_i, and velocity head $v_i^2/2g$,

$$E_i = y_i + \frac{v_i^2}{2g} \tag{6}$$

The energy loss, ΔE_1, is the difference between energy at the inlet section, E_0, and the energy at the section of interesting step, E_1.

$$\Delta E_1 = E_0 - E_1 \tag{7}$$

The energy dissipation, $\Delta E_1/E_0$, is one of the dimensionless parameter which is widely used to study the energy dissipation characteristic.

The Froude similitude in open channel flow is considered sufficient for a similarity between the model and the prototype. The Froude number (Fr) is defined as the ratio of the inertia flow to gravity forces in the flow:

$$Fr = \frac{v}{\sqrt{\frac{gy}{a}}} \tag{8}$$

Based on previous research about the relative energy loss, this study analyzed the relationship of the relative energy loss to the increase of the Froude number for various configuration steps. The following equation were also proposed by Stephenson [9] in order to determine the amount of the relative energy loss in stepped spillway as function of the Froude number, so in this research using relation such as equation (9):

$$\frac{\Delta E_1}{E_0} = a - b\left(F_r^*\right) \tag{9}$$

Where a and b are the energy loss coefficient for each step and Fr* is a roughness Froude number $Fr^* = q_w / (g \sin\theta\, k_s^3)^{0.5}$.

The dissipation energy on flat and pooled stepped spillways ($\theta = 45°$) with Froude number (Fr*) < 10 were investigated with number of step 20 and 40, respectively. The results emphasize the dissipation energy on flat and pooled steps with different of the number step.

2.0 EXPERIMENTAL

The tests were carried out in a recirculating flume located at the hydraulic laboratory of Water Resources Engineering Department, Brawijaya University, Indonesia. Schematic of experimental apparatus is shown in Figure 2. Water was pumped from reservoir to upstream tank and flow to the Rehbock measurement and water entered the stepped channel through stilling tank. The flume is 7 m length and 0.5 m width. The stepped spillways are made of acrylic having thickness of 0.01 m and side walls with height of 0.6 m. The slope of the stepped spillway (θ) is 45° with number of steps 20 and 40,

respectively. The discharge varied from 3.457 – 30.669 l/s, the Froude number range (1.117< Fr < 9.909) and was measured by the Rehbock weir tank. Further details on the experimental configurations are listed in Table 1, and a sketch of the stepped configurations is provided in Figure 3.
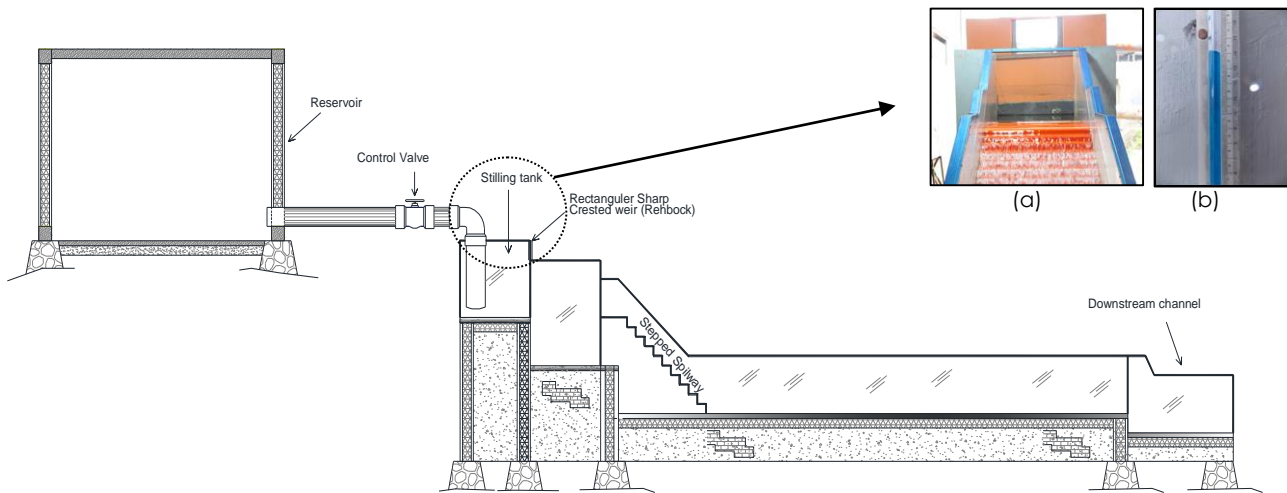

Figure 2 Experimental setup for stepped spillway facility, (a) the Rechbock weir, (b) the hosepipe

Two types of step were tested in the study, that is, flat and pooled steps. The dimensions of the step can be defined as h/l, where h = step height and l = horizontal length. For the case of pooled steps, the characteristic height (m) of end sill were 7.5 mm for number step (N) 20 and 3.75 mm for number step (N) 40. Configurations and notations of step used in the present study are shown in Figure 3. To investigate the effect of step geometry on the relative energy loss to Froude number are shown in Table 1.
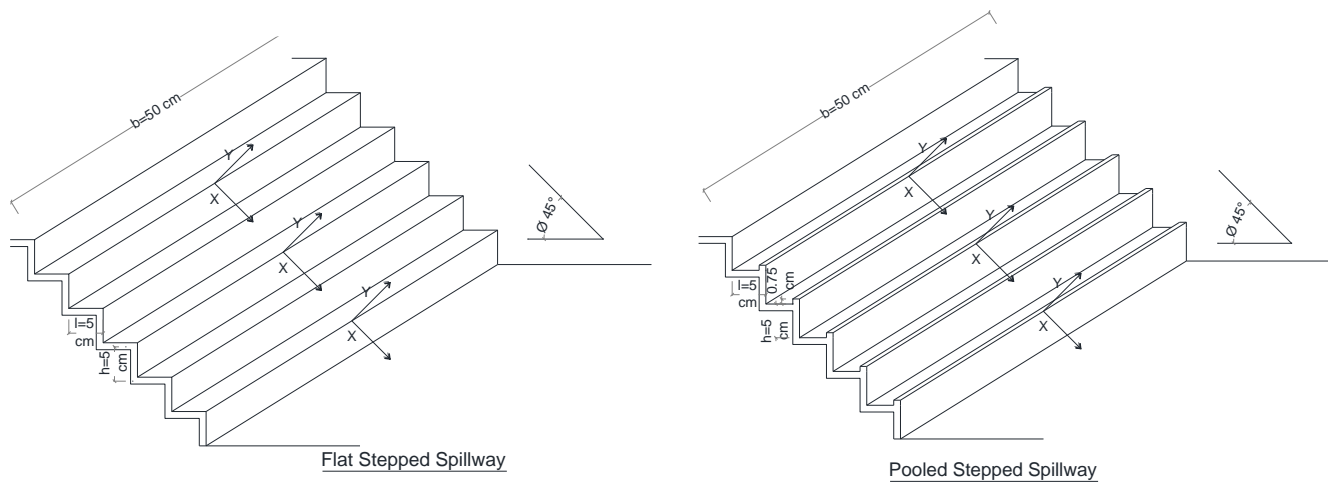

Figure 3 Sketch of the stepped configuration

The depth across the channel width was measured by a point gauge. The velocity was measured by two methods, first by a pitot tube and second by calculating discharge flow on the Rehbock measurement.

To measure the water level at the Rehbock weir is used a hosepipe connected out with stilling tank. So that the water level at the Rehbock weir can be read by a water pipe placed at the same height from the bottom of the tank (Figure 2).

Pitot tube was also used by [3] as an indirect method to measure the skimming flow depth in stepped spillways. The measured critical depth was compared with analysis from calculation of Rehbock formulas. The result showed relative error between both methods was under 10%.

Table 1 Experimental data for flat steps and pooled steps for spillway slope = 45°

Type of Steps	y_c (cm)	h (cm)	ks (cm)	q (cm²/s)	y_c/h	Fr*	$\Delta E_1/E_0$	Type of Steps	y_c (cm)	h (cm)	ks (cm)	q (cm²/s)	y_c/h	Fr*	$\Delta E_1/E_0$
1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Number of Step = 40								Number of Step = 40							
Flat Steps	1.750	2.500	1.768	69.135	0.700	1.117	0.891	Pooled Steps	1.750	2.500	2.033	69.135	0.700	1.117	0.896
	1.850			75.144	0.740	1.214	0.881		1.850			75.144	0.740	1.214	0.887
	2.000			84.466	0.800	1.364	0.871		2.000			84.466	0.800	1.364	0.902
	2.125			92.507	0.850	1.494	0.865		2.125			92.507	0.850	1.494	0.898
	2.187			96.585	0.875	1.560	0.859		2.187			96.585	0.875	1.560	0.908
	3.500			195.542	1.400	3.159	0.853		3.500			195.542	1.400	3.159	0.905
	4.000			238.907	1.600	3.859	0.833		4.000			238.907	1.600	3.859	0.880
	4.250			261.650	1.700	4.227	0.852		4.250			261.650	1.700	4.227	0.862
	7.000			553.077	2.800	8.935	0.709		7.000			553.077	2.800	8.935	0.800
	7.500			613.381	3.000	9.909	0.674		7.500			613.381	3.000	9.909	0.778
Number of Step = 20								Number of Step = 20							
Flat Steps	3.500	5.000	3.536	195.542	0.700	1.117	0.856	Pooled Steps	3.500	5.000	4.066	195.542	0.700	1.117	0.883
	3.750			216.863	0.750	1.239	0.847		3.750			216.863	0.750	1.239	0.885
	4.000			238.907	0.800	1.364	0.845		4.000			238.907	0.800	1.364	0.886
	4.125			250.192	0.825	1.429	0.846		4.125			250.192	0.825	1.429	0.881
	4.250			261.650	0.850	1.494	0.803		4.250			261.650	0.850	1.494	0.877
	4.375			273.278	0.875	1.561	0.794		4.375			273.278	0.875	1.561	0.873
	7.000			553.077	1.400	3.159	0.747		7.000			553.077	1.400	3.159	0.862
	7.500			613.381	1.500	3.503	0.733		7.500			613.381	1.500	3.503	0.835

3.0 RESULTS AND DISCUSSION

The visual observations of flow pattern were conducted for two type configurations of step for a broad range of discharge. The stepped spillway showed two typical flow patterns: transition flow (0.5 < y_c/h < 0.8) and skimming flow (y_c/h > 0.8) regimes depending upon the dimensionless flow rate y_c/h.

The limit of value was comparable with earlier studies of conducted by [7], that defined the onset of skimming flow for values of the ratio y_c/h = 0.8.
Flow over on flat stepped spillway for skimming flow conditions illustrated in Figure 4.

(a)

(b)

Figure 4 The flat stepped spillway 45° slope and (a) 20 steps; (b) 40 steps

The dissipated energy of flow over the flat stepped spillway with number of step 20 and 40, were plotted as a function of relative of critical flow depth on Figure 5. Where y_c is the critical depth (cm) and h is the height of the step (cm), which has been applied as dimensionless parameter y_c/h. Whereas,

the influence of increasing the Froude number toward a reduction the dissipated energy on flat step
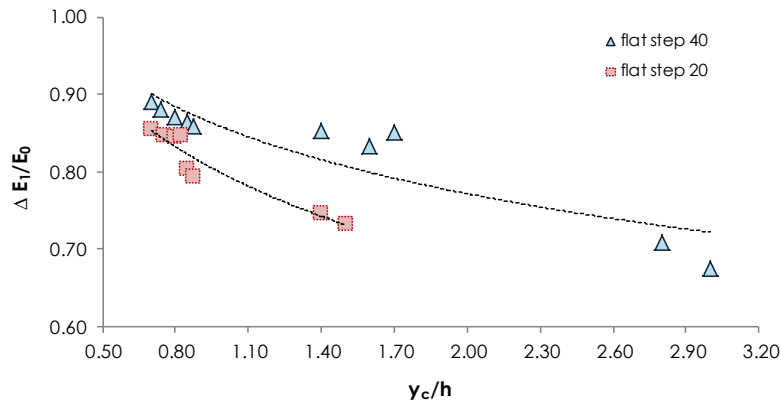
illustrated in Figure 6.

Figure 5 The relative energy loss against relative critical flow depth for flat steps
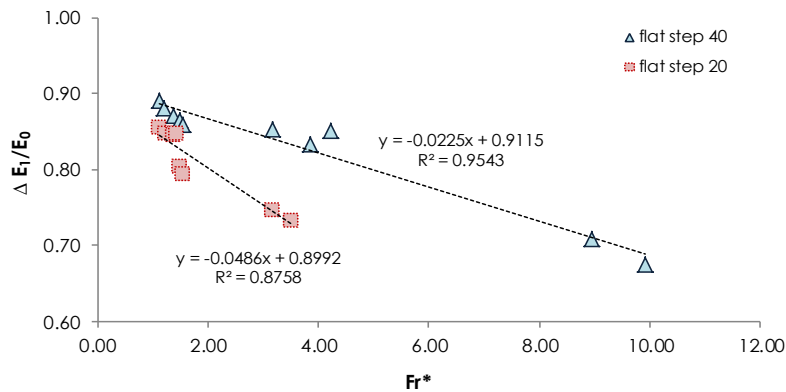

Figure 6 The relative energy loss against Froude number for flat steps

As shown on Figure 5, by increasing the discharge in flat steps, reduction of the amount of the energy dissipation can be seen. On the graph of the energy dissipation in terms of y_c/h for number steps 20 and 40 have also been implied by increasing the number of step, then the amount of the relative energy loss would be increased. It should be noted that the product obtained from this experiment is comparable with the results presented by [1].

The relative energy loss influenced by Froude number is shown in Figure 6. By increasing the Froude number, reduction of the relative energy loss for flat steps N=40 and N=20, respectively. The empirical correlation for the relative energy loss on flat steps is obtained by fitting the experimental data in linear regression form as follows:

$$\frac{\Delta E_1}{E_0} = 0.9115 - 0.0225 \left(F_r^*\right) \qquad \text{For } N = 40 \quad (10)$$

$$\frac{\Delta E_1}{E_0} = 0.8992 - 0.0486 \left(F_r^*\right) \qquad \text{For } N = 20 \quad (11)$$

The correlation may be used in design practice for initial estimates of the energy loss.

Figure 7 shows the flow over on pooled stepped spillway with different type of number of step, 20 and 40. The characteristic height (m) used have been 7.5 x 7.5 mm^2 for number of step 20 and 3.75 x 3.75 mm^2 for number of step 40.

The shapes of end sills have been formed rectangular. In the nappe flow, the characteristic height does not much effect the relative energy loss because most energy loss is due to the occurrence of the hydraulic jump and impact of the jet on the step face. In transition flow, the characteristic height has higher influence on the relative energy loss than in nappe flow. In the skimming flow, the effect of characteristic height is clearly observed.
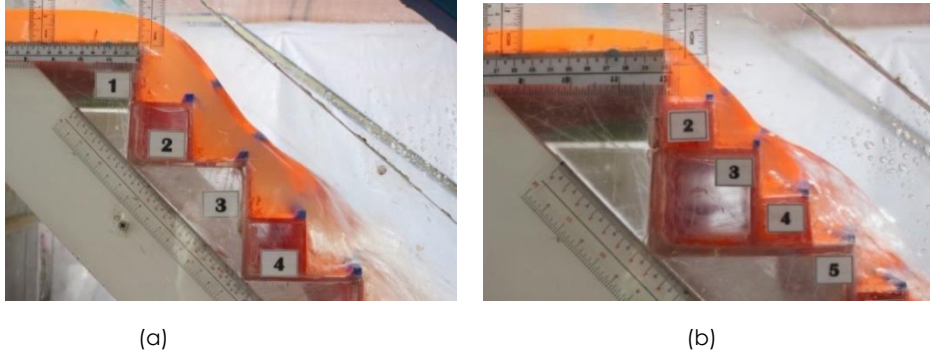
(a)   (b)

Figure 7 The pooled stepped spillway 45˚ slope and (a) 20 steps; (b) 40 steps
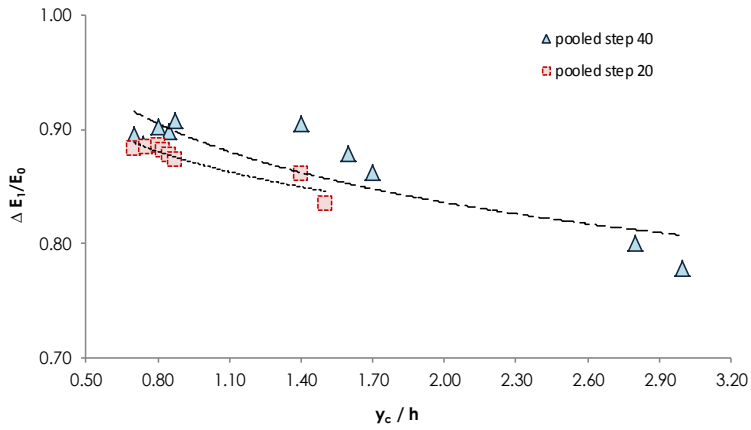

Figure 8 The relative energy loss against relative critical flow depth for pooled steps
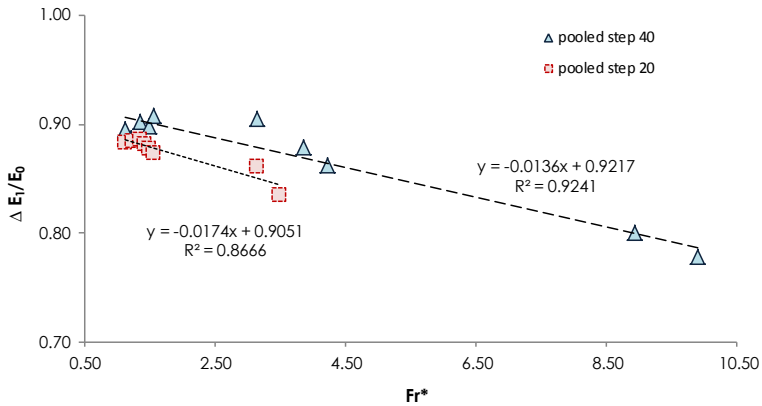

Figure 9 The relative energy loss against Froude number for pooled steps

For pooled steps, the relative energy loss of the number of steps 40 is higher more than number of steps 20. In figure above, energy loss of all the number of steps will be reduced with increasing relative critical flow depth for 45˚ (Figure 8).

The relative energy loss is directly proportional to Froude number can be expressed in linear regression form as follows:

$$\frac{\Delta E_1}{E_0} = 0.9217 - 0.0136 \left(F_r^* \right) \qquad \text{For N = 40} \quad (12)$$

$$\frac{\Delta E_1}{E_0} = 0.9051 - 0.0174 \left(F_r^* \right) \qquad \text{For N = 20} \quad (13)$$

Comparison of flow energy dissipation on Equation (10) with (12) and Equation (11) with (13) show higher dissipated energy for pooled steps. For pooled steps, the presence of the characteristic height has the effect of increasing the relative energy loss. For example, at y_c/h = 1.6 and Fr*=3.859, the relative energy loss for the flat steps is 0.833. For pooled steps (Table 1), the relative energy loss is 0.880.
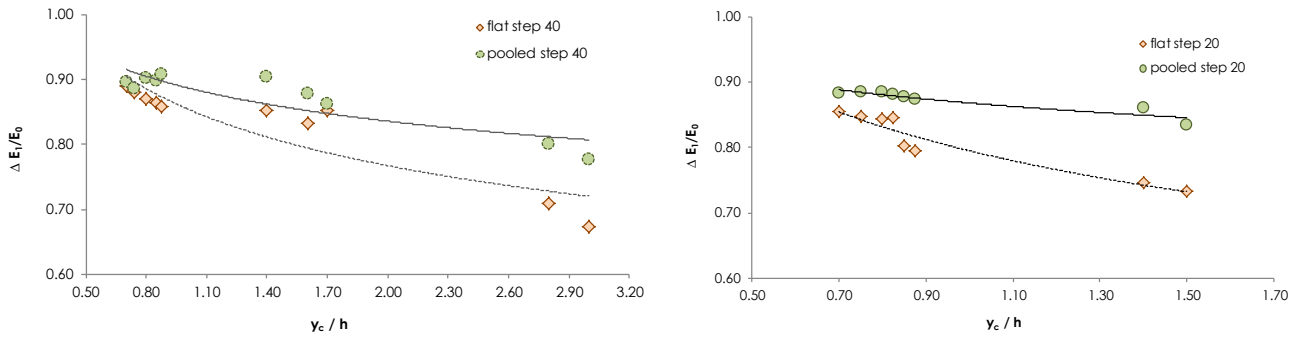
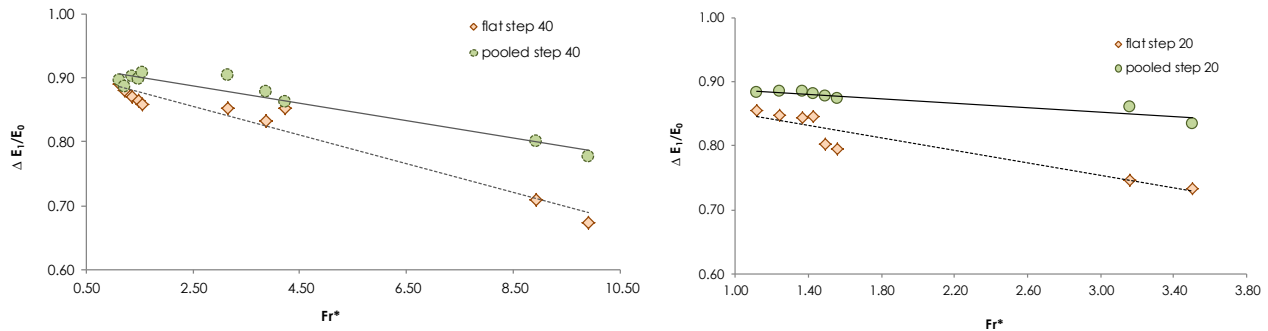**Figure 10** The relative energy loss against relative critical flow depth for N = 40 and N = 20

Figure 11 The relative energy loss against Froude number for N = 40 and N = 20

In Figure 10 and Figure 11 above, show that the pooled steps have been dissipate more energy than flat steps, respectively. Figure 10 shows that the relative energy loss increases of 4.283% with use end sill on steps. As for the number of step 20, the relative energy loss increases of 6.387% compared to flat steps.

The pooled steps have dissipater more energy than flat steps because the characteristic height of the end sill increases the volume of trapped water. Therefore, the circulating vortex was greatest compared to flat steps. Despite increases in the energy loss on pooled steps, but the use of this configuration in field has to be observed deeply if it does not provide any advantages significantly in the energy dissipation.

4.0 CONCLUSION

Result obtained from this experiments show that in the case of the number of steps increases, the relative energy loss is increased. This is due to the fact that steps act as macro-roughness that increase friction and then change the kinetic energy into thermal energy. Second, the relative energy loss will decrease with increasing relative critical flow depth. Similarly, the increase in the value of the Froude number will reducing the relative energy loss for flat step and pooled step. Third, the relative energy loss of flow on pooled steps is dissipating more energy than the flat steps. The characteristic height of the

end sill influences the relative energy loss on the pooled steps.

References

[1] Chinnarasri, C., and S. Wongwises. 2006. Flow Patterns And Energy Dissipation Over Various Stepped Chutes. *J. Irrig. Drain. Eng.* 132(1): 70-76.
[2] Chanson, H., and L. Toombes. 2001. Experimental Investigations Of Air Entrainment In Transition And Skimming Flows Down A Stepped Chute: Application To Embankment Overflow Stepped Spillways. Department of Civil Engineering: University of Queensland.
[3] Chanson, H., Y. Yasuda, and I. Ohtsu. 2002. Flow Resistance In Skimming Flows In Stepped Spillways And Its Modelling. *Can. J. Civ. Eng.* 29(6): 809-819.
[4] Barani, G. A., M. B. Rahnama, and H. Bagheri. 2005. Optimization Of Stepped Spillway Dimensions And Investigation Of Flow Energy Dissipation Over A Physical Model. *J. Appl. Sci.* 5: 878-882.
[5] Takahashi, M., Y. Yasuda, and I. Ohtsu. 2004. Flow Characteristics of Skimming Flows in Stepped Channels. *J. Hydraul. Eng.* 9: 860-869.
[6] M. A. Kökpinar. 2004. Flow Over A Stepped Chute With And Without Macro-Roughness Elements. *Can. J. Civ. Eng.* 31(5): 880-891.

[7]   N. Rajaratnam. 1990. Skimming Flow In Stepped Spillways. *J. Hydraul. Eng.* 116(4): 587-591.

[8]   Felder, S., and H. Chanson. 2013. Aeration, Flow Instabilities, And Residual Energy On Pooled Stepped Spillways Of Embankment Dams. *J. Irrig. Drain. Eng.* 139(10): 880-887.

[9]   D. Stephenson. 1991. Energy Dissipation Down Stepped Spillways. International Water Power and Dam Construction. 27-30.

[10] Guenther, P., S. Felder, and H. Chanson. 2013. Flow Aeration, Cavity Processes And Energy Dissipation On Flat And Pooled Stepped Spillways For Embankments. *Environ. Fluid Mech.* 13(5): 503-525.