Jahad, Udai A., Al-Ameri, Riyadh and Das, Subrat 2016, Energy dissipation and geometry effects over stepped spillways, *International journal of civil engineering and technology*, vol. 7, no. 4, pp. 188-198.

International Journal of Civil Engineering and Technology (IJCIET)
Volume 7, Issue 4, July-August 2016, pp. 188–198 Article ID: IJCIET_07_04_015
Available online at
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

ENERGY DISSIPATION AND GEOMETRY EFFECTS OVER STEPPED SPILLWAYS

Udai A. Jahad, Riyadh Al-Ameri, Subrat Das
School of Engineering,
Deakin University, 3216 Australia

ABSTRACT

The energy dissipation process is the major significant point in the design of hydraulic structure. The dissipation of high energy on stepped weirs prevents any damage in the weir itself and channels the energy downstream to reduce the stilling basin size. In this study, four physical models are used to evaluate the impact of adding end sills that have a quarter circle shape at step edges. The amount of energy loss on weirs under different flow regimes is investigated by experimental work. Stepped weirs have a suitable number of steps and two different ratios of the width to height (2.22, and 2.40). The scale of the physical models is 20:1. The outcomes of the dimensional analyses refer to the critical depth for flow in weirs to the height of step yc/h, the end sill radius, and the number of steps N are more effective parameters than others in the energy loss process. Moreover, for small values of yc/h, the energy dissipation is the greatest. Any increase in yc/h leads to a decrease in the energy dissipation, while the energy dissipation increases with the number of steps (N).

Key words: Energy Dissipation, Discharge, Weir, Stepped, Step Height, Step Number.

Cite this Article: Udai A. Jahad, Riyadh Al-Ameri, Subrat Das, Energy Dissipation and Geometry Effects over Stepped Spillways. *International Journal of Civil Engineering and Technology*, 7(4), 2016, pp.188–198.
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=7&IType=4

1. INTRODUCTION

For more than 3000 years, stepped cascades have been used in hydraulic structures to dissipate energy (Chanson 2000). The design of hydraulic structures must ensure that water is discharged in a safe manner to prevent any damage to the structure and surrounding locations (Chanson 2001: Felder 2013). Carosi and Chanson (2008) state that the stepped spillway design has many good points, such as increasing the energy dissipation rate in the chute and reducing the size of the stilling basin downstream.

Many researchers have studied the impact of geometry on energy dissipation. According to Sorensen (1985), the energy dissipation in spillways depends on four functions: (a) discharge, (b) slope of spillway, (c) geometry of steps, (d) the steps number. Chinnarasri and Wongwises (2006) examined the characteristics of flow and the energy dissipation factors by studying the impact of changes in the geometry for steps. A comparison of the ratio of the energy losses was created based on step geometry (horizontal steps, inclined steps, and steps with end sills). The results illustrate the link between the ratios of energy dissipation and the relative critical depth of flow in the three types of steps. High efficiency in terms of energy dissipation ratio was found in spillways containing steps with end sills. Moreover, the results explain the impact of the number of steps, such that an increase in the number of steps will lead to an increase in the ratio of energy dissipation. New proposed correlations were done for practical applications to show the relationship between the ratio of energy dissipation and the relative critical depth of flow. The number of steps affects energy dissipation at the higher values of the ratio, and the ratio of the smaller values was very effective in the stepped surface.

Hunt et al. (2009) point out that when the height of the step increases there is an increase in energy dissipation. The loss of energy may be defined as the remaining head at the toe of the spillway and is known as (Hr), or the heads difference between the upstream and downstream of the spillway. This is also known as (ΔH); (ΔH) is probably more widely used. Tabari and Tavakoli (2016) study several parameters, such as the number of steps, the height of the step, the length of the step, and unit discharge, to ascertain the influence of these parameters on the dissipation of energy in the simple stepped spillway. The Flow-3D model was applied, and the relationship between the dissipation of energy and flow critical depth was studied in the stepped spillway. In addition, the finite volume method was utilised to find the results of the equations, and the $K - \varepsilon$ model was applied to study the turbulence of the flow. The outcomes show that when the discharge increases, this leads to decreases in the dissipation of energy, and when the number of steps increases and their height decreases, this leads to decreases in the dissipation of energy.

According to Hamedi et al. (2011), this experimental method has been used in the study to increase the energy loss on spillways with the stepped slopes in a nappe flow regime. Various models for stepped spillway have been studied, including a reverse slope with variable angles and different end sills installed on the edges of the steps. They focused on the variables of height, thickness and the upper angle of the end sills. The results show that the energy dissipation increases in a hybrid model and that this means that the hybrid model is a better model than others in terms of the dissipation of energy. In addition, the results indicate that energy dissipation is better with both inclined steps and end sills models than with inclined steps only or with the models utilised in previous studies. In general, the combination of inclined steps and end sills, or inclined steps only, gives better performance in energy loss when compared with a horizontal step. The aim of this study is to improve the hydraulic performance for stepped spillways, to increase energy losses by changing the shape of the traditional sill to a quarter circle sill, and compare this with the normally stepped spillway.

2. FLOW REGIMES

On stepped spillways, there are three types of flow regimes. These are nappe flow for low discharges, skimming flow for high discharges, and transition flow. The nappe flow regime is considered the most efficient by researchers in the hydraulic field (Pegram et al. 1999). According to Chanson and Toombes (2004) the flow in stepped spillways can become a skimming flow with large volumes of discharge, and as a consequence of free-falling nappe with low-volume discharges. On the other hand, there is a range of transition flows occurring between nappe flow and skimming flow which have different properties, such as the troubled flow motion related to strong splashing. The regimes display significantly different flow characteristics. The regimes depend on discharge rate and step geometry (height, slope and length) (Toombes 2002).

Nappe flow regime: Nappe flow occurs when the fluid passes from one step to another, for example, free-falling down the steps with air pockets underneath. The free-falling nappe is affected by the step, with or without a complete hydraulic jump. With relatively low discharge rates, the regime of flow is nappe flow. It is made by a flat slope with large step heights, which are usually unwieldy (Rajaratnam 1990). Nappe flows over stepped spillways dissipate more energy than the two other regimes. Energy dissipation comes from three causes (i) jet break up in air, (ii) the impact of the jet on the step, and (iii) formation of a hydraulic jump (completely or partially) (Chanson 1994).

Skimming flow regime: Skimming flow regimes happen at a large flow rate. The flow depth is large when compared with step height in the steep slope of the stepped spillway. The flow characteristics are good in energy dissipation and aeration, and the water moves down the spillway without touching the steps. The flow in the triangular space between the steps and the main flow is filled with aerated water. Vortex energy is generated when the water collides with the edges of the steps and is directed back up. At the vortex, and afterward, the water returns to the main flow. This process is not constant, i.e. it is not steady or uniform. The process happens irregularly and changes in places where the overflow is returned to the major flow. In contrast, nappe flow is an alternative to skimming flow. It occurs in flow from upper to lower steps, generating a series of free nappes on cascades down the spillway. The phenomenon can be noted in a wide range of flows on stepped spillways with flatter slopes, and in small values of flow on steep stepped spillways, especially at the crest (Pegram et al. 1999).

The transition between nappe and skimming flow**:** this flow regime has common hydraulic characteristics on some steps with the nappe flow, while it may appear as skimming flow on the rest of the steps (André & Schleiss 2004).

Chanson (2001) re-evaluated a large number of data and suggested formulae to forecast the nappe flow and skimming flow upper and lower limits. The other range is transition flow, where:

$$\frac{y_c}{h} = 0.89 - 0.4\left(\frac{h}{l}\right) \quad \text{Lower limit of transition flow} \qquad (1a)$$

$$\frac{y_c}{h} = 1.2 - 0.325\left(\frac{h}{l}\right) \quad \text{Upper limit of transition flow} \qquad (1b)$$

Where:

y_c = critical depth;

h = step height and;

l = length of the step.

The limitations for the equations (1) are applied for horizontal and flat steps, and the gradient of the channels is between 3.4º - 60º. It is unsure whether the equation is valid outside that range of gradients. There are significant differences in characteristics of flow between nappe and skimming flow regimes. The unstable flow conditions are in a transition flow regime that may lead to fluctuating hydrodynamic load causing vibration in the hydraulic structure (Chanson 2000).

3. EXPERIMENTAL METHODOLOGY

3.1. Instrumentation

In the current study at Deakin University, the flume dimensions are 500cm long, 25cm depth, and 7.5cm width. The maximum flow rate range is 150(l/min), as shown in figure (1). In the flume end at the downstream, there is a sluice gate to control and regulate the tail water level and the hydraulic jump downstream of the weir. The source of the water is a tank with (250 l) capacity. The water is pumped by a pump with a flow rate range between (10 l/min to 150 l/min). Water depths are measured using point gauges located 20 cm upstream of the weir, at the weir crest, and 10 cm and 300 cm downstream of the weir. The location of the weir is 80 cm from the inlet point. Staff gauges on the glass of the flume walls are used for verification of point gauges. Water flow rates are measured by utilising a digital flow meter located in the flume intake pipeline.

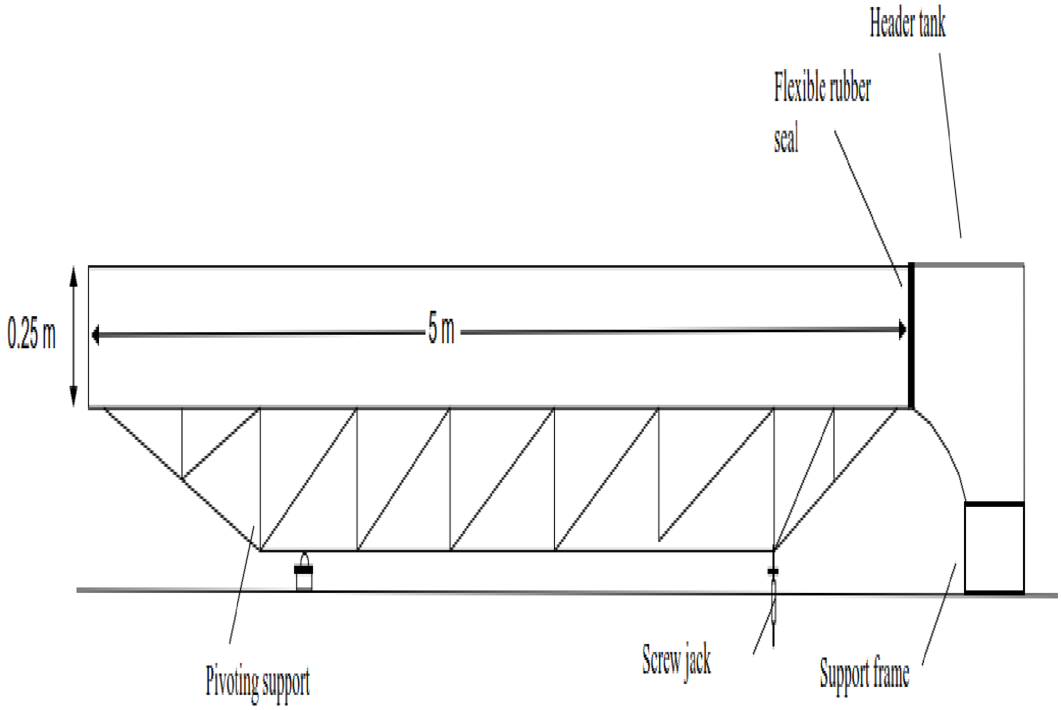


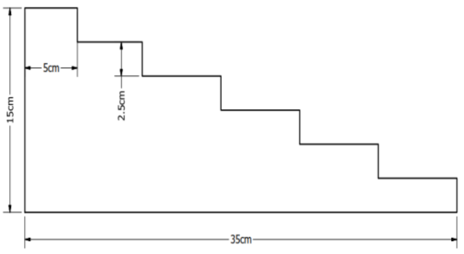
Figure 1A Flume sketch

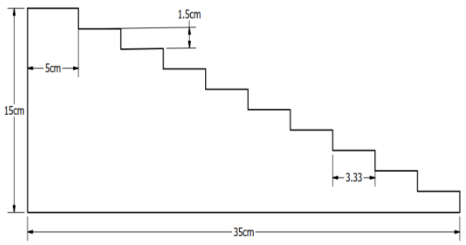
Figure 1B Flume used in experimental work

3.2. Model Description

In this part of the study, there are three models in experimental work to cover all areas of investigation. The description of these models is as follows:

All models have the same height, width, and board crest (height: 15cm, width: 7.5cm, and board crest: 5cm). For all models, the downstream slope is (26.6°). The surface of the downstream slope has four configurations as shown in figures (2) and (3). These shapes were studied to make a compression between the traditional and modified shapes.





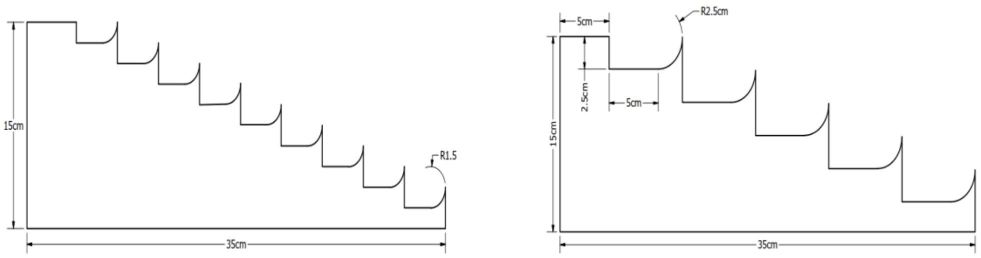


Figure 2 Configurations of model (Θ =26.6°)

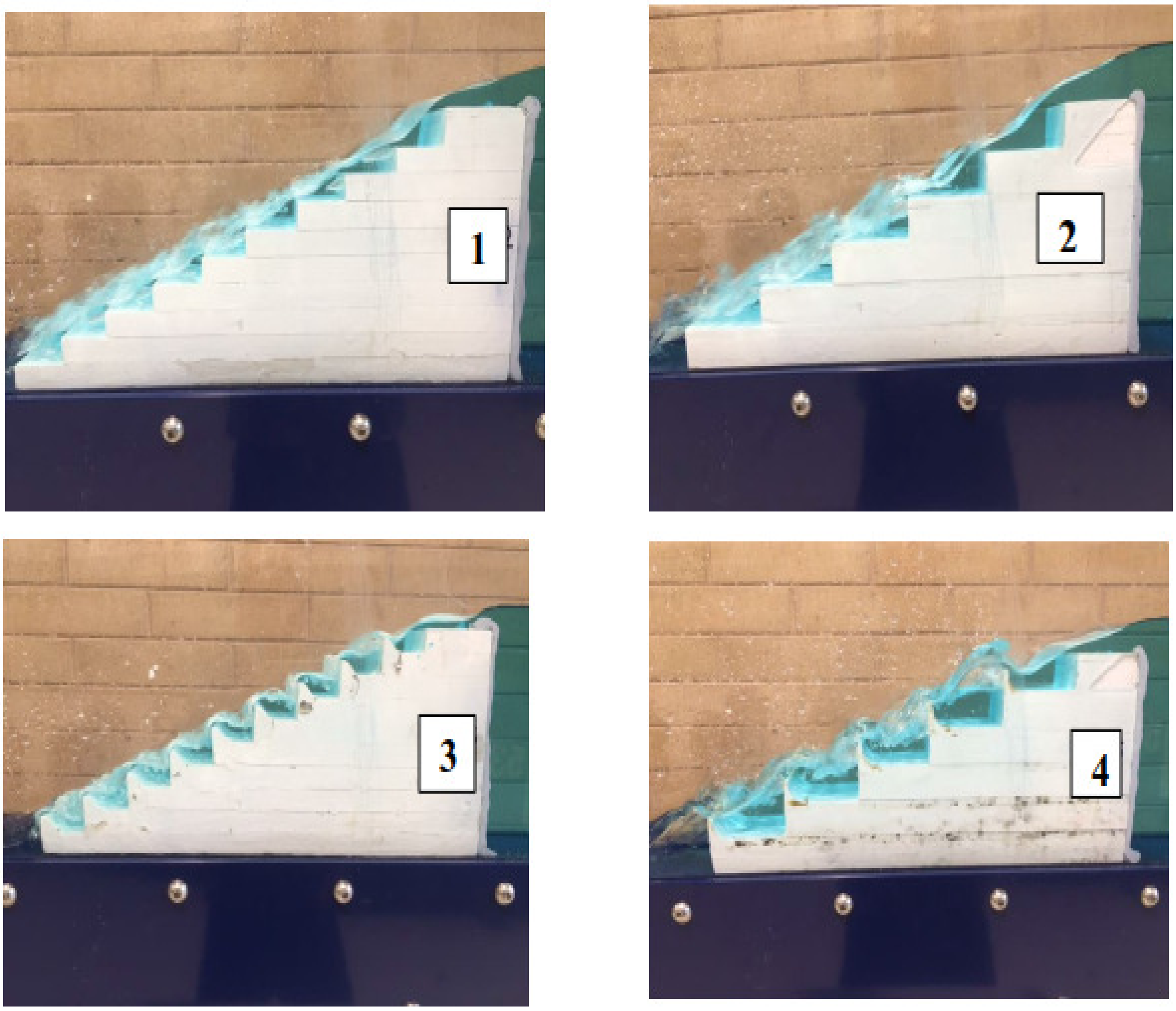


Figure 3 Physical models (Θ =26.6°)

3.3. Dimensional Analysis for Weirs

Previous studies on stepped spillways have illustrated that the significant and effective parameters are as follows:

1. The fluid properties: mass density (ρ), dynamic viscosity (μ), and acceleration of gravity (g), surface tension (σ).
2. Flow characteristics by flow depth (y) and flow velocity (V).
3. The shape properties for spillway: the height of spillway (Hd), spillway width (W), the length of step (ls), the height of step (hs), number of steps (Ns), and radius of step (Rs).

The Buckingham theory for dimensional analysis is used to create the dimensional analysis of the weir. It is a function of the parameters of f (Hd, W, Ns, hs, ls, Rs, V, y, g, ρ, μ, σ) =0. The repetitive parameters are yc, ρ, and V because they are available in most of the parameters. The outcome of dimensional analysis is:

$$\frac{\Delta H}{H_0} = f(\frac{H_d}{y_c}, \frac{L}{y_c}, \frac{W}{y_c}, \frac{h_s}{y_c}, \frac{l_s}{y_c}, \frac{R_s}{y_c}, N_s, W_e, R_e, F_r) \qquad (2)$$

Dimensionless parameters are important to investigate the energy dissipation and aeration in weirs.

3.4. Methodology

The present work will use quantitative methodology to study the energy dissipation process. The equipment and information (such as flume, physical model material, experimental design, data collecting, analysis and evaluation) are consistent with these principles.

One of the main goals of the current research is to determine the efficiency of energy dissipation for each stepped spillway. The energy (*Eo*) upstream of the weir is calculated by:

$$E_o = Z_o + E_c = Z_o + \sqrt[3]{\frac{q_w^2}{g}} \qquad (3)$$

Ec is the critical energy over the crest, *Zo* is the elevation of the crest and equal to spillway height considering the invert of the flume as a datum, *g* is the acceleration of gravity and equal to 9.81 m/s^2. The energy, *Ed*, at the downstream end, before the hydraulic jump, is expressed by the following formula,

$$E_d = Z_o + \frac{p}{\gamma} + \alpha \frac{V^2}{2g} \qquad (4)$$

Zo is the invert elevation of the flume and is equal to zero, α is the kinetic energy correction coefficient.

Boes and Hager (2003) observe that α =1.1. The velocity head is calculated from the discharge and water depth at the downstream end of the spillway. The depth of this section, or clear water depth, is back calculated from the sequent depth of the hydraulic jump at the downstream end of the spillway. This method is widely used by many researchers (Peyras et al. 1992). The principle behind it is to measure the sequent depth of the hydraulic jump at the toe of spillway, where there is a clear, non-aerated, water depth, then calculate the upstream initial depth entering the jump by the hydraulic jump formula (Chow 1959):

$$y_1 = \frac{y_2}{2} \left(\sqrt{1 + 8\left(\frac{q_w^2}{8\, y_2^3}\right)} - 1 \right) \qquad (5)$$

This method avoids the need to measure the clear water depth at the spillway toe, as the flow at this section is characterised by a two-phase flow nature.

It is necessary that the hydraulic jump is located such that y1 of the jump represents the clear water depth at the toe of the spillway. If measurements are precisely made, the energy at the toe of the stepped spillway could be very accurate; for instance, Pegram et al. (1999) discovered a 2% error in their range of reported flows.

André & Schleiss (2004) carried out a sensitivity analysis to study the effect of the jump position on the computation of residual energy at the toe. They discovered that the residual energy will be overestimated if the jump submerges the last steps (by about 13% for the last two drowned steps), and will be underestimated by about 3% if the jump is far from the base of the last step. They concluded that the optimum position is when the front of the hydraulic jump is located at the point where the plunging flow reaches the basin bottom. Depth y_2 is measured using a point gauge installed (0.5 m) downstream of the end of the spillway.

The energy dissipation efficiency is calculated using the following formula:

$$\% \frac{\Delta E}{E_0} = \left(\frac{E_o - E_d}{E_o}\right) \qquad (6)$$

ΔE is the difference in the energy between upstream and downstream of the stepped spillway.

4. RESULTS AND ANALYSIS

The method of computing energy dissipation was explained in section (3). The percentage of energy dissipation efficiency is defined as ΔE/Eo. In figure (4) the percentage of energy dissipation, equation 5, is shown versus the dimensionless parameter yc/hs for various discharges. In model 1, the percentage of energy dissipation efficiency varies from 76% in the first run for lower discharge to 63% in the last run at higher discharge. In the modified model (model 2) the percentage of efficiency varied from 88% to 75%; this efficiency is higher than the typical case in all flow regimes. While the efficiency of energy dissipation for Sorensen is higher than all in the nappe flow regime, it has about the same values for the transition flow regime. This derives from the number of steps in the Sorensen model (13 steps). In the skimming flow regime, the efficiency is higher than the typical case. The lower effectiveness in large discharges may be because the nappe over-shoots disappeared.

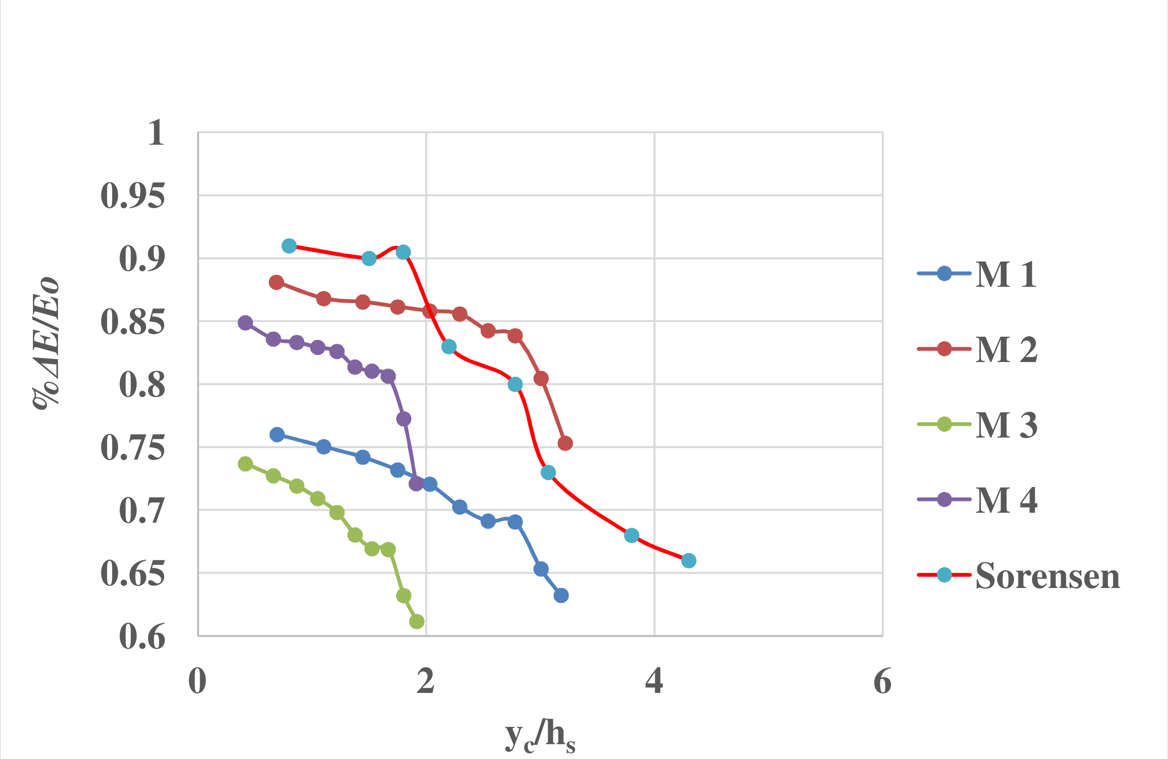


Figure 4 Variation of Relative Energy Loss with y_c/h_s

Figure (5) presents the relationship between the energy dissipation rate and yc/Nhs for the same discharge and same downstream slope for the weir, with a different step height and number for models 2 and 4. When the number of steps increases, the energy loss ratio increases various the relative critical flow depth yc /Nhs. It is clear that step height and number of steps, Nhs, impact on energy loss rate because when the number of steps increases, the flow path is longer.

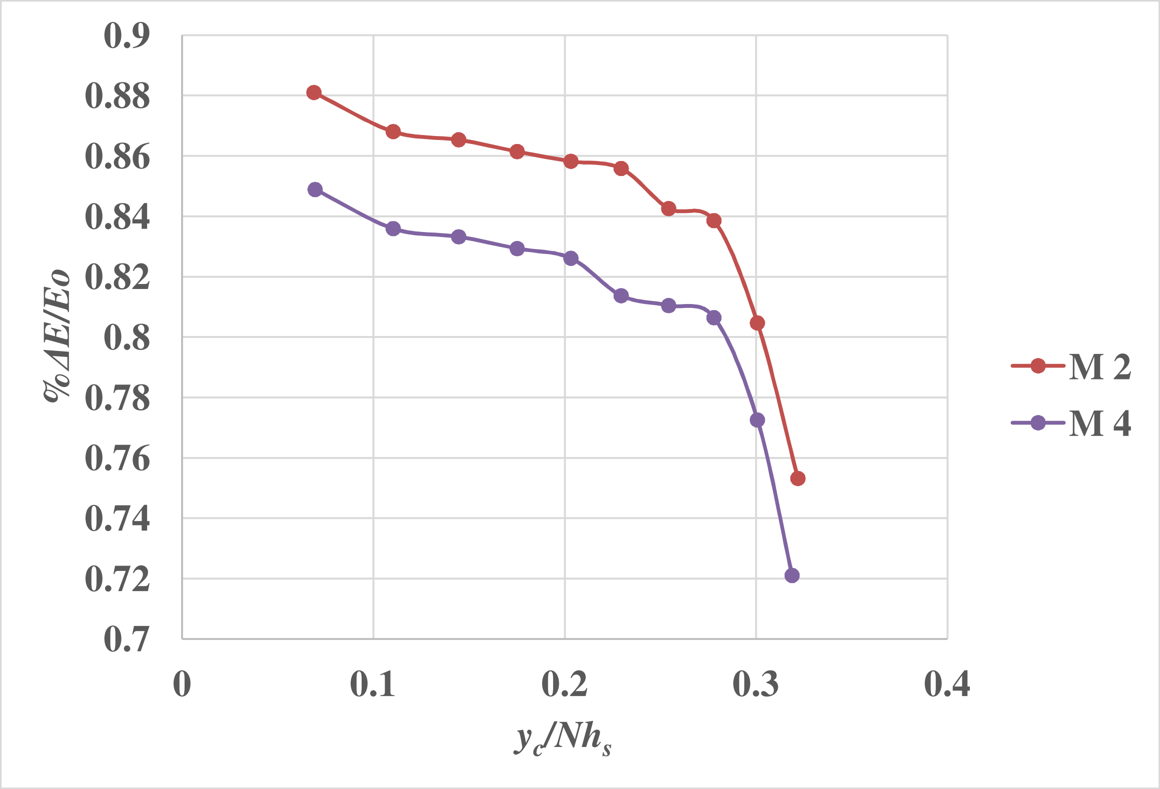


Figure 5 Variation of Relative Energy Loss with y_c/Nh_s

5. CONCLUSIONS

The conclusions obtained from the data are:

1. Typical case observations show the same behaviour mentioned by other researchers, such as the trend of energy dissipation efficiency, and boundaries between flow regimes. Nappe flow shows higher efficiency than both transition and skimming flows.
2. The results for model 2 show improved energy dissipation, especially for a nappe flow regime. The new changes in step shape in models 2 and 4 lead to positive impacts for stepped weirs, compared with other models.
3. Models with 10 steps of 1.5 cm height give better performance than models with 6 steps of 2.5 cm height at the nappe flow range, while, they have convergent results at other flow regimes. In other words, step number has a greater effect than step height for low discharges.

ACKNOWLEDGEMENTS

The authors would like to express them sincere thanks to the govement and Ministry of higher education and Scientific Research in Iraq for providing the financial cover for the study (scholarship for PhD student Udai Adnain Jahad). They acknowledge the technical assistance of civil lab staff in school of Engineering and Built Environment (Deakin University).

REFERENCES

[1] André, S & Schleiss, A, High velocity aerated flows on stepped chutes with macro-roughness elements, (No. LCH-BOOK-2008-020), EPFL-LCH, 2004.

[2] Boes, R & Hager, W. Hydraulic design of stepped spillways, *Journal of Hydraulic Engineering*, 129(9), 2003, pp. 671-679.

[3] Carosi, G, & Chanson, H. Turbulence characteristics in skimming flows on stepped spillways, *Canadian Journal of Civil Engineering*, 35(9), 2008, pp. 865-880.

[4] Chanson, H. Comparison of energy dissipation between nappe and skimming flow regimes on stepped chutes, *Journal of hydraulic research,* 32 (2), 1994, pp. 213–218.

[5] Chanson, H. Hydraulics of Stepped Spillways: Current Status, *Journal of Hydraulic Engineering,* 126(9), 2000, pp. 636-637.

[6] Chanson, H. Hydraulic design of stepped spillways and downstream energy dissipators, *Dam Engineering,* 11(4), 2001, pp. 205–242.

[7] Chanson, H & Toombes, L. Hydraulics of stepped chutes: The transition flow', *Journal of Hydraulic Research*, 42(1), 2004, pp.43-54.

[8] Chinnarasri, C, & Wongwises, S. Flow patterns and energy dissipation over various stepped chutes, *Journal of irrigation and drainage engineering*, 132(1), 2006, pp. 70–76.

[9] Chow, V. *Open-Channel Hydraulics*, New York: McGraw- Hil, 1959.

[10] Felder, S. Air-water flow properties on stepped spillways for embankment dams: Aeration, energy dissipation and turbulence on uniform, non-uniform and pooled stepped chutes, PhD thesis, Queensland University 2013.

[11] Hamedi, A, Mansoori, A, Malekmohamadi, I & Roshanaei, H. Estimating energy dissipation in stepped spillways with reverse inclined steps and end sill, In *World Environmental and Water Resources Congress. Bearing Knowl Sustain. ASCE*, 2011.

[12] Hunt, S, & Kadavy, K. The effect of step height on energy dissipation in stepped spillways', In *World Environmental and Water Resources Congress 2009: Great Rivers* (pp. 3061-3071). ASCE.

[13] Pegram, G, Officer, A & Mottram, S. Hydraulics of skimming flow on modeled stepped spillways, *Journal of hydraulic engineering*, 125(5), 1999, pp. 500-510.

[14] Peyras, L, Royet, P & Degoutte, G. Flow and energy dissipation over stepped gabion weirs, *Journal of Hydraulic Engineering*, 118(5), 1992 pp.707-717.

[15] Rajaratnam, N. Skimming flow in stepped spillways, *Journal of Hydraulic Engineering*, 116, (4), 1990, pp. 587–591.

[16] Sorensen, R Stepped spillway hydraulic model investigation, *Journal of Hydraulic Engineering*, 111(12), 1985, pp.1461–1472.

[17] Tabari, M & Tavakoli, S. Effects of Stepped Spillway Geometry on Flow Pattern and Energy Dissipation', *Arabian Journal for Science and Engineering*, 41(4), 2016, pp. 1215-1224.

[18] Najm Obaid Salim Alghazali and Salam M. Jasim, Location of Air Inception Point for Different Configurations of Stepped Spillways. *International Journal of Civil Engineering and Technology*, 5(4), 2014, pp.82–90.

[19] Mohammed M. Salman and Prof. Dr. Abdulaziz, Abdulrassol Aziz, The Effect of Improvement Surrounding Soil on Bored Pile, Friction Capacity, International Journal of Civil Engineering and Technology, 7(1), 2016, pp. 260-273.

[20] Toombes, L. Experimental study of air-water flow properties on low-gradient stepped cascades, PhD thesis, Queensland University 2002.