

Effects of End Sill and Step Slope on Stepped Spillway Energy Dissipation

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ABSTRACT

In this study, experimental procedure and laboratory works have been conducted to investigate the energy loss rate on stepped spillway, using inclined steps together with end sill. To have a more elucidated investigation inclined steps with different slopes (Horizontal, 7, 10, and 12 degrees with respect to the horizon) and end sill with different thicknesses (5 and 10 mm) and heights (6, 8, 10, and 15 mm) were used to determine the impact of these parameters on the relative energy loss. Results show that using inclined steps together with end sill has a considerable effect on the energy loss of both nappe (30 liter/sec) and skimming (90 liter/sec) flows; however, energy dissipation in nappe flows is greater than that in skimming flows. Energy loss resulted from end sills with smaller thicknesses is higher than that of end sills with greater thicknesses. Comparison of the results of the current survey with similar studies reveals that the approach used in the current investigation is more efficient than previous ones.

KEYWORDS

End sill step slope, Stepped spillway, Energy dissipation, Nappe flow, Skimming Flow

1. Introduction

The remnants of ancient structures show that Stepped Spillways have been used for 3500 years. As a matter of fact, not only these Spillways have been applied as a dissipater, but also they have had a wide variety of applications. As a case in point, between the 16th and 18th centuries, they were served for decorative and aesthetic applications (Chanson 2002). In the early twentieth, these Spillways became practically obsolete, due to their long construction time, high maintenance cost, and low hydraulic efficiency and other options were replaced. In recent years, by

means of technology and use of Roller Compacted Concrete (R.C.C) technique, construction time of Spillway and its maintenance cost has extremely been reduced and their hydraulic efficiency has considerably been promoted. Owing to foregoing reasons, the tendency to reuse the Spillways has intriguingly increased. By employing this type of spillways, the energy of the flow is substantially dissipated. As a consequence, the size of downstream stilling basin is remarkably reduced. In Stepped Spillways, the flow pattern does not remain constant as the discharge is changed. For instance, nappe flow,

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skimming flow, and transition flow are observed in Low-rate flow, high-rate flow, and between these two flow regimes, respectively. One of the most important parameters in energy dissipation is drop number which is indicated by q^2/gHT^3 ; where q is flow discharge per channel width, g is gravity acceleration, and HT is total drop height. Investigations (Peyras, Royet et al. 1992, Israngkura and Chinnarasri 1994) show that by increasing the drop number, the relative energy loss ratio decreases.

Many researchers have worked on flow condition, aeration, and energy loss in stepped spillways with horizontal steps: Andre (André 2004), Bina et al. considered energy loss in nappe flow regime (Musavi-Jahromi, Bina et al. 2008), Boes and Hager, Cheng et al., Estrella et al. considered velocity and air concentration in air-water flow (Boes and Hager 2003, Cheng and Chen 2013, Estrella Toral, Sánchez Juny et al. 2013). Felder et al. experimentally studied air-water flow properties and energy dissipation (Felder, Guenther et al. 2012), Gonzalez studied free surface aeration (Gonzalez 2005), Horner, Hunt, Kositgittiwong et al., Ohtsu and Yasuda considered characteristics of flow conditions on stepped channels (Horner 1969, Ohtsu and Yasuda 1997, Hunt, Temple et al. 2012, Kositgittiwong, Chinnarasri et al. 2013), Rice and Kadavi study was about RCC stepped spillways (Rice and Kadavy 1996), Sorensen worked on hydraulic model investigations (Sorensen 1985), Tabbara et al. simulated flow over stepped chutes (Tabbara, Chatila et al. 2005), Toombes studied air-water flow properties on low gradient stepped chutes

(Toombes 2002), Yasuda and Ohtsu studied skimming flow (Yasuda and Ohtsu 1999), Zare and Doering worked on inception point of air entrainment and energy dissipation in the case of stepped spillway equipped with baffles and sills (Zare and Doering 2012, Zare and Doering 2012). Some others worked on flow conditions and energy dissipation in stepped spillways equipped with inclined steps or end sill: Hamedi et al. compared energy losses obtained from vertical end sills and curved end sills (Hamedi, Malekmohammadi et al. 2012). Mansoori and Pedram studied the effect of thickness, height and upper angle of the end sills on the loss of energy (Mansoori and Pedram 2008), Sedaghat Nezhad investigated the influence of the height of the end sills and slope of the chute on the energy loss and according to the loss of energy and the force imposed to the end sills; she indicated the optimal shape of the end sill (Sedaghat Nezhad 2009). Sohrabi pour is one of the researchers who tried to increase the amount of the energy loss by adding the end sills with different thicknesses at the edge of the steps (Sohrabi pour 2003).

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

2. Nappe flow regime

Among the proposed equations, the equations by Chanson (Chanson 1994), Chamani and Rajaratnam (Chamani and Rajaratnam 1994) and Fratino (Fratino, Piccinni et al. 2000) are considered as the best relations for nappe flow. The following equation was proposed by Chanson

(Chanson 1994), in order to determine the dissipation energy rate in nappe flow along with hydraulic jump, in stepped spillways:

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

Where H_{max} is total energy ($H_{dam} + 3/2 h_c$); ΔH is dissipated energy along the chute; d_c is flow critical depth (m); H_{dam} is dam height and h is step height (m).

Moreover, the equation proposed by Fratino and Colleagues (Fratino, Piccinni et al. 2000) for nappe flow is as follows:

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

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

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

Chamani and Rajaratnam (Chamani and Rajaratnam 1994) also presented the subsequent equation to obtain the dissipation energy rate in all nappe flow regimes in stepped spillways:

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

Where α is energy loss coefficient of each step and N is 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 is horizontal step length (m).

Among all the investigations conducted on spillways, the research performed by Chaturabul can be singled out. In his research, the height of the employed end sills has been considered as 5, 10, and 15 mm on various step slopes and this has led to presenting a relation between relative energy loss and drop number. The result of his investigation demonstrated that relative energy loss experienced an increment of 8%, due to the existence of an end sill (Chaturabul 2002).

Chinnarasri and Wongwises examined the inclination of step brink to determine the energy loss increase. They also mentioned that the energy dissipation rate in the form of step with end sill is greater than that in the form of horizontal or inclined step. Chaturabul's investigation showed that energy loss in step equipped with end sill is 8% more than that in a horizontal step (Chinnarasri and Wongwises 2004, Chinnarasri and Wongwises 2006).

3. Skimming flow regime

Chanson presented an equation in order to estimate dissipation energy rate in skimming flow in stepped spillways (Chanson 2002):

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

Where f can be obtained as follows:

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

Where D_H is hydraulic depth of the flow. Foregoing equation is applicable for mild slope chutes.
 $\theta \leq 20^\circ$

Another equation which can be used to determine the dissipation energy rate in the skimming flow regime is the utilization of Chanson's equation for calculation of the remaining energy at end of the chute (Chanson 2002).

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

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

The following equation is used to calculate y :

$$\frac{y}{h_c} = \sqrt[2]{\frac{f}{8 \sin \theta}} \quad (11)$$

While f is calculated using Eq. (9).

The following equation has been also offered by Chamani and Rajaratnam, in order to estimate the remaining energy at the end of the chute (Chamani and Rajaratnam 1999).

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

Where y_m is mixed depth (air and water), u_m is mixed flow velocity, and z is height from the baseline.

4. Dimensional Analysis

Buckingham's method, as one of the most appropriate methods in dimensional analysis, has been used.

Chinnarasry and Wongwises (Chinnarasri and Wongwises 2006) considered effective parameters for energy dissipation in high slope stepped spillways including discharge per unit width, flow head, step height, step length, slope height, and gravity acceleration. In this research, other factors such as spillway slope and water density were also considered as follows.

Moreover, in order to determine the effect of number of the steps on energy loss in steps without threshold and slope, number of steps was also regarded as another effective parameter.

Effective factors for energy dissipation in threshold stepped spillway include:

q : Discharge in unit width of the spillway

s : spillway slope

E_0 : flow head

h : Step height

ρ_w : water density

l : Step length

N : number of steps

m : height of slope plus End sill height

t : Thickness of End sill

g : Gravity acceleration

N : number of steps

ρ_w : water density

$$E_L = E_L(q, E_0, h, l, m, t, g, s, \rho_w, N) \quad (13)$$

Dimensionless parameters obtained from Buckingham's theories:

$$f = f(E_L, q, E_0, h, l, m, t, g, s, \rho_w, N) \quad (14)$$

Number of variables is $n=11$.

$\rho[ML^{-3}], g[LT^{-2}], h[L]m = 3 \rightarrow$ basic dimensions

$$\pi = n - m = 11 - 3 = 8$$

$$f\left(E_L, E_0 h^{-1}, q \sqrt{\frac{1}{gh^3}}, lh^{-1}, wh^{-1}, th^{-1}, s, N\right) = 0 \quad (15)$$

$$(16)$$

$$\varphi\left(\frac{E_0}{h}, q \sqrt{\frac{1}{gh^3}}, \frac{l}{h}, \frac{m}{h}, \frac{t}{h}, f, s, \frac{\mu}{\rho \sqrt{gh^3}}, N\right) = 0 = E_L$$

The performed dimensional analysis is simultaneous for sill and sloped stepped spillway. Most of these dimensionless parameters are not used in the present paper, while they can be used in other papers with different subjects and regarding the same field.

In the present paper, only m/h dimensionless parameter is used and the effect of sill thickness is studied on energy dissipation rate.

5. Experimental Setup

Current research has been conducted at the Institute of Water Research on a stepped spillway with the scale of 1:15. Steps and walls were made of Plexiglas and have been mounted on the steel structure. Wall thickness was 10 mm. The used chute spillway was a broad-crested weir and number of the steps was 60. At stepped spillways, especially in skimming flow regime and high discharges, developed flow is formed in the middle of the chute. Afterward, the hydraulic conditions become stable. Therefore, in the present investigation, only four steps were inclined and had sill; all were placed after the middle of the chute (steps 39-42). Horizontal Length of the steps was 14 cm; step height was 4.66 cm and chute width was 1.33 m.

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 two different discharges of 30 liters per second for nappe flow regime and 90 liters per second for skimming flow regime.

Water depth and flow velocity have been measured by using a liminimeter (precision of 1 mm) and a pitot-tube, respectively. To measure the water level in the reservoir, stage discharge relationship has been used. Flow discharge has been measured by sharp crested weir at the end of downstream chute. The flow passed over the spillway has been calculated and compared with the discharge. Pegram et al. conducted some experiments on the stepped spillways with scales of 1:10 and 1:20 and concluded that models with scale of 1:20 and higher can present the actual spillway behavior by Froude number similitude (Pegram, Officer et al. 1999). Considering this fact, the results of recent study are applicable for models 15 to 20 times this spillway. Characteristics of the used end sills are presented in Fig. 1 and Table 1.

Three different slopes of 7°, 10°, and 12° relative to the horizon were used.

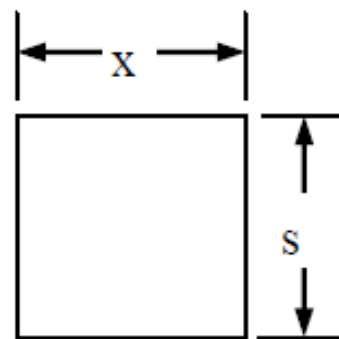


Fig. 1. Schematic representation of the rectangular end sills

Table 1. Specifications of the rectangular end sills

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

Depth along spillway width was measured by 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 from the water flow. Due to the insufficient liminimeter accuracy and the possibility of outlook error, spillway imaging was performed through the experiment. The depths were determined accurately and compared with liminimeter values in Arc GIS software. Finally, average of the three depths across each line of piezometer was used as the step width.

Aforementioned procedure is used for determination of the flow depth in nappe flow. On the other hand, in skimming flow regime, nappe flow jets do not exist due to greater depth of the flow. Similarly, flow depth was measured by liminimeter and was compared with images. Average of the depths (at right-side, left-side, and middle of the step) was used as the average step depth.

To measure the velocity, the pitot-tube was used. This measurement was difficult since the flow was two-phase and bleeding had to be performed regularly. In nappe flow regime, flow depth was not high enough to measure velocity in different depths; the velocity was only measured in step side and in 0.6 m depth. On the other hand, the velocity was measured in depths of 0.2 and 0.8 m in skimming flow. The average of these values was set as the

velocity of that section. Finally, averages of left, right, and middle sections were averaged and set as the total average of that step.

It should be noted that due to the oscillating nature of the flow on the stepped spillways, the employed method contains error.

Pitot-tube was employed to determine the velocity. Generally, the height difference between two hoses exited from the pitot-tube, h , was used to determine the velocity: $v = \sqrt{2gh}$. In this formula, h is in meters to yield the velocity in meter/second.

Piezometer was used to measure oscillation of the pressure, statically and dynamically. These data are used in another paper to study pressure on stepped spillways. In this chute, only four steps (39-42) were inclined and had sill. Depth and velocity values were measured on these steps and on 38th step. To determine the energy loss, data on 38th and 42th steps are sufficient. Velocity and depth values were recorded on other steps for future investigations.

The liminimeter has an accuracy of 1 millimeter.

Since the employed apparatuses are not advanced, the measured velocity by the pitot-tube contains error. However, this error is in absolute value measurement. Since the error value is constant, error of the relative velocity measurement lies in an acceptable range.

Water enters the chute from the reservoir. The reservoir is very large and able to provide the required water for stepped chutes of the upper and lower Siahbishe. The water enters transferring pipes from the pumps and falls into the

reservoir. When the reservoir is completely filled, the vent is opened and water falls into the chute.

The employed pump has a pumping capacity of 220 liters of water in a second and swing check valves were used to open and close the pipes. Bleeding was performed by a small pump and the water entered the channel, before turning the main pump on. In order to determine the energy level in upstream and downstream of the amended steps, the following equations have been used:

$$H_1 = y_1 + \frac{v_1^2}{2g} + z \quad (17)$$

$$H_2 = y_2 + \frac{v_2^2}{2g} + z \quad (18)$$

Where H is flow energy, y is flow depth, v is flow velocity in proper sections, g is gravity acceleration and z is height from baseline (Bottom of the last modified step has been assumed as the baseline and z=0).

6. Result and Discussion

6.1. Analyzing the energy dissipation in Nappe flow regime

The tests were conducted on the horizontal steps, before applying the changes to the steps, to calculate the effects of the changes on the dissipation energy rate. Values obtained for the dissipation energy rate from the test were 0.5128 and 0.5112, derived from Chamani and Rajaratnam correlation (Chamani and Rajaratnam 1994), which shows a suitable agreement.

Then, the changes (inclination of steps and end sill) were applied to the steps and dissipation energy was measured for

different slopes and end sills. The results are presented in Table 2.

The obtained results show that the height of the steps, thickness of the end sills, and the height of the inclined steps are effective on dissipation energy rate.

In this section, parameter $m=(p+w)$ is used, where p is height of the end sill and w is height of the step inclination (Fig. 2).

In Fig. 3, m/h is a dimensionless parameter and was defined in dimensional analysis and in Fig. 2, $\Delta H/H_{max}$ is energy loss for maximum energy.

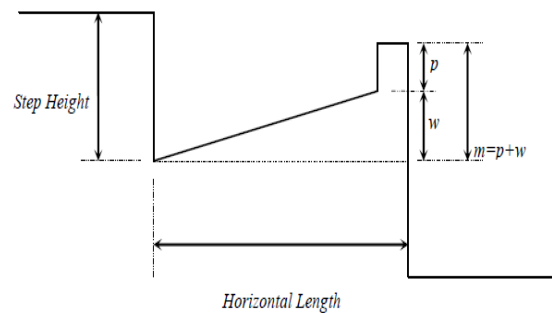


Fig. 2. Schematic view of the step

An overall conclusion of the data for all slopes has been presented. Additionally, the fitted curve between different points has been presented. As it can be seen, the curve is a quadratic one. It is obvious that if the ratio of m/h increases up to 0.7, the dissipation energy rate is first increased and after that is decreased. This graph suggests that the best ratio for m/h is about 0.7 and excessive increase has a negative impact on dissipation energy rate. For the optimum practical design, in order to achieve the acceptable energy loss, m values more than 0.7 should be eliminated.

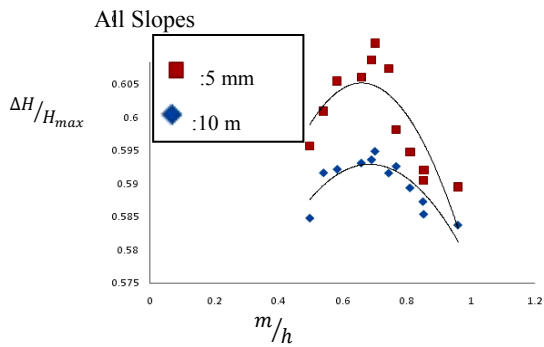


Fig. 3. Dissipation energy loss per meter for all tested slopes

When m/h ratio is greater than 0.7, flow is jumped from one or more steps and the amount of energy loss is decreased. This step practically plays no significant role in energy dissipation. As a consequence, the energy dissipation rate is decreased.



Fig. 4. Step with slope of 7° , end sill height of 6 mm and thickness of 5 mm



Fig. 5. Step with slope of 12° , end sill height of 15 mm and thickness of 5 mm

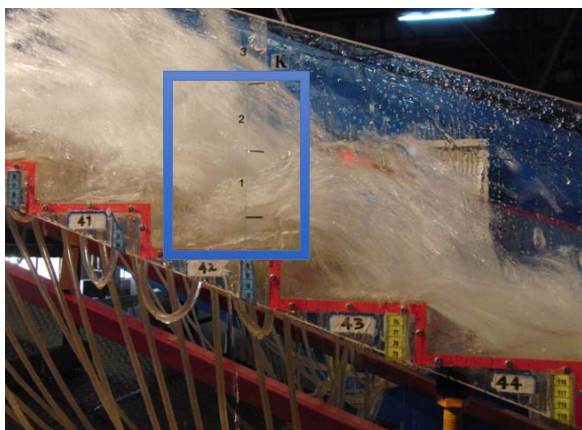


Fig. 6. Step with slope of 10° , end sill height of 10 mm and thickness of 5 mm

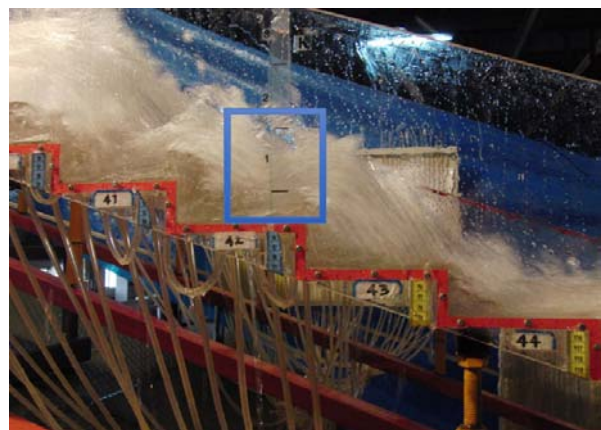


Fig. 7. Step with slope of 10° , end sill height of 10 mm and thickness of 10 mm

Table 2. Comparison of energies derived from the test

Run number	Energy loss values (test)	Thickness (mm)	m/h	Inclined step angle θ (degrees)	Height of the end sill (mm)
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

In table 2, energy loss values obtained from experiments in the range that caused the increase of dissipation energy rate (effective end sill) are presented.

Figures 4 and 5 show that the flow jumps over the steps by an increase in “m” parameter, while discharge is constant. It can be inferred from the results that energy loss in end sill with 5 mm thickness is more than end sill with 10 mm thickness. It can be due to the following major points; first: in lower thicknesses when available amount of space for hydraulic jump is more and due to this fact a better hydraulic jump is occurred; as a result, more energy loss is obtained. The jet falls at an average distance of 4.25 cm from the step side, in the case with 5 mm width sill. We set this point as the start point for the jump and the jump length has the same value. However, when the sill width is 10 mm (due to a 5 mm

smaller space), 12% of the hydraulic jump length is decreased, which is a significant reduction.

Second: actually, effective length of the step is more in low thicknesses of the end sill and this is shown in Figs. 8 to 12:



Fig. 8. Step with slope of 10°, end sill height of 10 mm and thickness of 5 mm



Fig. 9. Step with slope of 10°, end sill height of 10 mm and thickness of 10 mm

For the Spillway of this research:

Height of each step was 4.66 cm and length of each step was 14 cm. For horizontal steps, slope was:

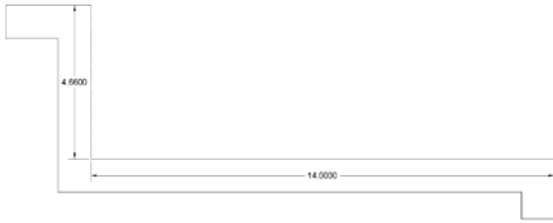


Fig. 10. Schematic view of the horizontal step

$$S_h = \frac{h}{L} = \frac{4.66}{14} = 0.33 \cong 18.41^0 \quad (19)$$

If end sill with 5 mm thickness is applied, effective length would be 14-0.5=13.5 cm and the slope is:

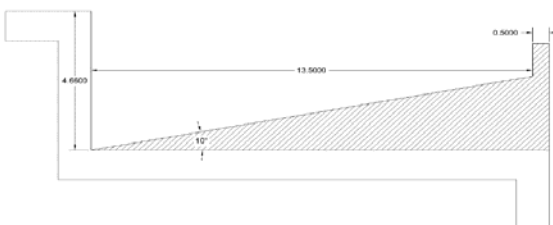


Fig. 11. Schematic view of Step with slope of 10°, end sill height of 10mm and thickness of 5 mm

$$S_{t=5 \text{ mm}} = \frac{h}{L} = \frac{4.66}{13.5} = 0.345 \cong 19.04^0 \quad (20)$$

If end sill with 10 mm thickness is applied, effective length would be 14-1=13cm and the slope is:

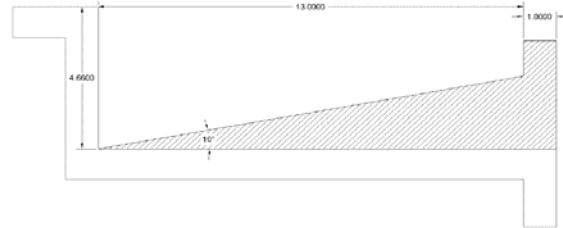


Fig. 12. Schematic view of Step with slope of 10°, end sill height of 10mm and thickness of 10 mm

$$S_{t=10 \text{ mm}} = \frac{h}{L''} = \frac{4.66}{13} = 0.358 \cong 19.72^0 \quad (21)$$

The results show that decreasing the effective length will lead to an increase in slope and lower the energy loss obtained from higher slopes.

6.2. Analyzing the energy dissipation in Skimming flow regime

Like nappe flow regime, dissipation energy rate is obtained in horizontal steps. Value obtained for the dissipation energy rate from test was 0.3514 and dissipation energy rate derived from Chanson correlation (Chanson 2002) was 0.3508. The good agreement between results of test and Chanson correlation is obvious. Then, the changes have been imposed on the steps and dissipation energy rate has been measured for different slopes and end sills. The results are presented in Table 3. The results show that the height, thickness and upward angle of the end sills and also the height of the inclination of the step have a negligible effect on the dissipation energy rate. In this section, the effect of m/h ratio on dissipation energy is examined, in skimming flow.

A comparison shows that 10 mm thickness has a slightly better performance in the energy loss.

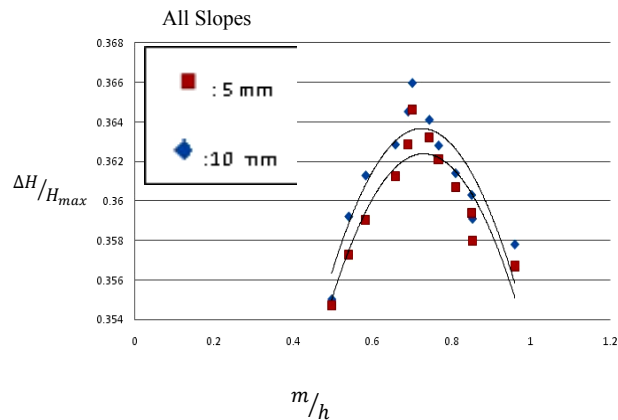


Fig. 13. Energy loss per m for all tested slopes

In figure 13, m/h is dimensionless parameter and has been defined in dimensional analysis and Fig. 2, and $\Delta H/H_{max}$ is energy loss divided by the maximum energy. Similar to the nappe flow, increase in the dissipation energy rate continues up to 0.7 and after that it is decreased. Once again, it verifies the fact that excessive increase in m/h ratio has a negative impact on dissipation energy rate.



Fig. 14. Step with slope of 7°, end sill height of 6mm and thickness of 5mm

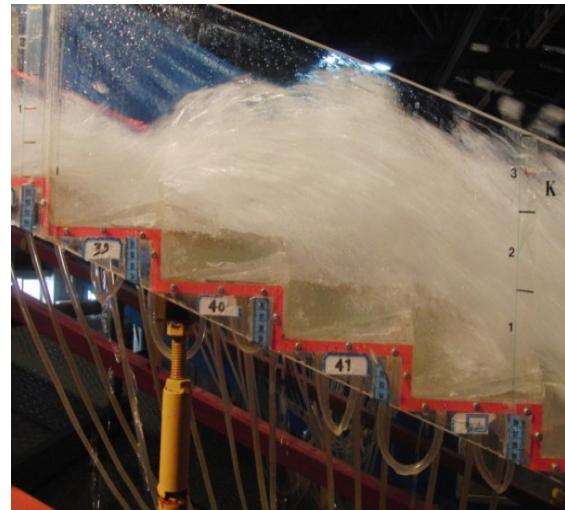


Fig. 15. Step with slope of 12°, end sill height of 15mm and thickness of 5mm

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

In table 3 energy loss values obtained from experiments in the range that caused the increase of dissipation energy rate (effective end sill) are presented.

As can be seen from Fig. 16, in the case of end sill height of 6 mm and slope of 7 degree, when the flow reaches the end sill, it jumps from 2 steps completely and returns to the chute on 4th modified step. But it does not mean that the second and third steps are totally useless, because a part of water remains on the steps (red box in the figure) and some part of energy is dissipated. Also, spray is another reason that the energy loss occurs.

Table 3. Comparison of energies derived from the test

Run number	Energy Loss values (test)	Thickness (mm)	m/h	Inclined step angle \square (degrees)	Height of the endsill (mm)
1	0.355022	5	0.4972	7	6
2	0.359207	5	0.5401	7	8
3	0.361285	5	0.5829	7	10
4	0.362848	5	0.6580	10	6
5	0.364517	5	0.6901	7	15
6	0.365962	5	0.7008	10	8
7	0.354725	10	0.4972	7	6
8	0.357268	10	0.5401	7	8
9	0.359039	10	0.5829	7	10
10	0.361264	10	0.6580	10	6
11	0.362863	10	0.6901	7	15
12	0.364622	10	0.7008	10	8

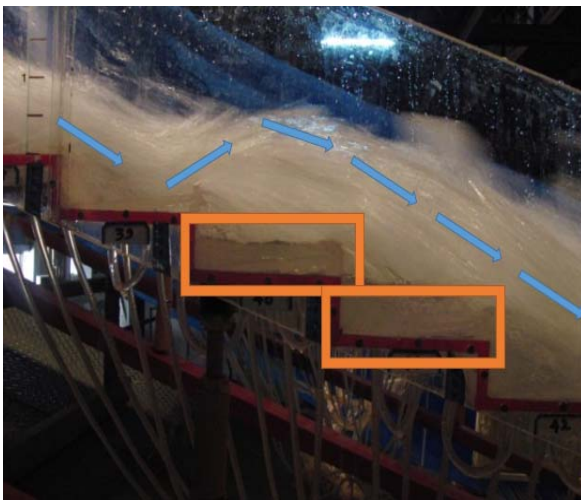


Fig. 16. Step with slope of 7°, end sill height of 6mm and thickness of 5mm

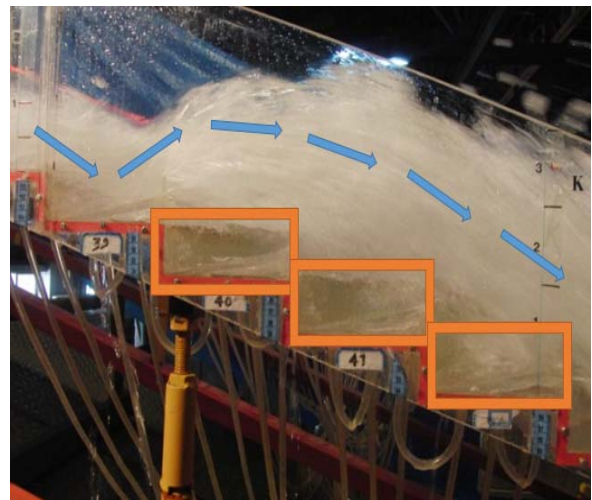


Fig. 17. Step with slope of 12°, end sill height of 15mm and thickness of 5mm

As can be seen from Fig. 17, in the case of end sill height of 15mm and slope of 12 degree, when the flow reaches the end sill, it jumps from 3 steps completely and returns to the chute after modified steps. But it does not mean that these steps are totally useless, because a part of water remains on the steps (red box in the figure) and some part of energy is dissipated. Also, spray is another reason that the energy loss occurs. Effect of the spray in this case is more than the previous case. This investigation is the first one in the field of studying the simultaneous effects of inclination and sill in stepped spillways. Hence, there is not any possibility for comparison with similar results. However, a comparison which is made between single states (i. e. horizontal step, inclined step, or step with sill) is presented.

8. Conclusion

To have a review, this fact should be highlighted that the energy loss is associated with the geometry of the steps. The results show that inclination of steps and use of end sill has significant influence on the energy loss. In both nappe and skimming flows with m/h ratios lower or equal to 0.7, an incremental trend of energy loss can be seen; but for greater values, it decreases due to jumping of the flow over several steps. Furthermore, in both flow regimes, thickness of end sill has considerable effect on the increase of energy dissipation rate. Reduction of the thickness will increase the energy loss. Generally, the influence of these parameters on nappe flow regime is greater than that in skimming flow regime.

This research demonstrated that using inclined steps together with vertical end sill

will increase the dissipation energy rate approximately 15% in average (for various vertical end sills) for nappe flow and 2% in average for skimming flow and shows better performance compared to the use of end sill in nappe flow. In skimming flow, it can be stated that the changes imposed on steps have no significant effect on the energy loss.

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