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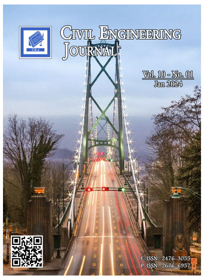
Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 01, January, 2024



Effect of the Stepped Spillway Geometry on the Flow Energy Dissipation

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Received 16 July 2023; Revised 29 November 2023; Accepted 11 December 2023; Published 01 January 2024

Abstract

In this research, flume experiments were conducted on stepped weirs to investigate the effect of step shape on the energy dissipation of flow. Four configurations with a constant number of steps were considered, namely, horizontal steps, inclined steps, horizontal steps with rounded sills, and inclined steps with rounded sills. The slopes of inclined steps were 13% and 23%, and the diameters of the rounded sills of the step ends were 10 and 15 cm. The majority of previous studies focused on energy dissipation in stepped weirs in horizontal and inclined steps. In this research, new step geometries were used, such as horizontal steps with rounded sills and inclined steps with rounded sills. Dimensional analysis was applied to correlate the different variables affecting the flow hydraulics. Flow rates in the range of 0.61-9.12 lit/sec were used with each step shape. Results showed that the inclined steps with rounded sills had the highest flow energy dissipation in comparison to the other types. Rounded sills at the end of steps had more effective energy dissipation than did the horizontal step. However, the 23% inclination slope with rounded sills of a 7.5 cm radius was the most effective in dissipating flow energy.

Keywords: Inclined Step; Stepped Weirs; Hydraulic; Rounded Sill; Energy Dissipation; Flow.

1. Introduction

Spillways are structures widely used to evacuate excess flow from dam reservoirs. High flow velocity is one of the most important hydraulic problems in spillways, as it leads to cavitation and scouring downstream of the channel. Hence, flow energy dissipation is the main issue with spillways. Stepped spillways are widely used in hydraulic engineering as water energy dissipation facilities and show great potential for achieving better rates of water energy dissipation with the release of excess floodwater [1–3]. They can reduce the size of the stilling basin, the number of downstream protection works, and the extent of river erosion downstream, thereby obtaining excellent economic and technical performance indicators [4, 5].

Many studies have been conducted to improve these properties and thus enhance the effects of water energy dissipation and the hydraulic properties of spillways. Christodoulou (1993) [6] carried out an economical study of three options, including a stilling basin, a flip bucket, and a stepped spillway, for the design of energy dissipation in large dams. He found that using a stepped spillway is an economic decision. Frizell et al. (2012) [7] found that the benefit of the stepped spillway compared with other energy dissipation structures reduces the possibility of cavitation on the spillway. Guenther et al. (2013) [8] performed a measure of energy dissipation on stepped chutes with a 26.6° slope. The results showed that among the studied configurations (i.e., pooled stepped spillway and two-stepped spillway with in-line and staggered configurations of flat and pooled steps), flat steps had the lowest residual energy.

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http://dx.doi.org/10.28991/CEJ-2024-010-01-09

Chinnarasri et al. (2006) [9] found that the energy dissipation of the flat stepped chute is comparatively lower than that in stepped chutes with an end sill slope of 45°. Barani et al. (2005) [10] investigated the dissipation of flow energy over spillways of different step shapes. Results showed that the dissipation of flow energy on the end sill and inclined stepped spillways is greater than that on the plain shape because it increases with the increase in height of the end sill or the adverse slope shape. Chaturabul (2002) [11] conducted a laboratory study of the energy loss and measurement of the outlet velocity on stepped channels with end sills. Different channel slopes and sill end heights (i.e., 5, 10, and 15 mm) were used. A relationship was found between relative energy loss and the number of drops. Moreover, the presence of an end sill increased the relative energy loss by 8%.

Chinnarasri et al. (2004) [12] investigated the flow regimes and energy loss on chutes with inclined steps. They presented that the slope of the inclined steps increased the relative energy loss and reduced the outlet velocity by 10%. Chamani et al. (1999) [13] and Chanson et al. (2002) [14] conducted experiments on the skimming flow regime and developed empirical formulas to determine the rate of energy loss in this system. Gandhi et al. (2016) [15] presented a review of stepped spillways and the effect of baffle blocks on energy dissipation and concluded that the use of baffles can reduce the length of the stilling basin. Rezapour Tabari et al. (2016) [16] numerically investigated three types of geometric models with 10, 15, and 20 steps and step heights of 0.1, 0.06, and 0.05 m, respectively, where the total heights of all spillways were adjusted to 1 m. A 45-degree slope was considered for all the models as well. Each model featuring the above geometric types was tested at three levels of water discharge (i.e., 0.025, 0.039, and 0.057 cubic meters per unit width). The results revealed that as the flow discharge increases, energy dissipation decreases, and as the number of steps increases and their height decreases, energy dissipation decreases. The obtained findings were compared with those of other researchers and empirical and mathematical studies, and an acceptable coincidence was finally obtained.

Using the concept of weir flow formula to characterize flow energy dissipation in a small weir equipped with steppes of different geometries, Dust & Wohl (2012) [17] investigated the flow characteristics of overstepped broad crested weirs. The results indicated that the C coefficient of the weir increases with the upstream head. Moreover, the shallow flow over the steps using the concepts of broad crested weirs is valid for such flows over stepped weirs. Hamedi et al. (2014) [18] experimentally investigated the effect of step slope with end sill height on flow energy dissipation. Their results showed average increases of 15% in the dissipation energy rate (for various vertical end sills) for nappe flow and 2% for skimming flow. Mero et al. (2016) [19] investigated energy dissipation and flow regimes over the stepped spillways of several step configurations, including horizontal, inclined, and horizontal with curved steps. The energy losses highlighted those inclined and horizontally curved steps dissipated significantly more energy compared to horizontal steps. Abdel Aal et al. (2018) [20] investigated the impact of breakers on energy dissipation in two types of stepped spillways. The results showed that the stepped spillway with breakers dissipated more energy than the traditional stepped spillway. Hekmatzadeh et al. (2017) [21] numerically investigated the energy dissipation of flow over stepped spillways with different configurations, such as flat steps and inclined slopes of 26.6° and 8.9°. They observed that the flat spillway has the highest rate of energy dissipation in comparison to the inclined slopes.

Salmasi et al. (2022) [22] investigated the effect of step slopes (15°, 25°, and 45°) and step numbers (5–50) on the energy dissipation of flow. They found that for a constant flow rate passing over a stepped spillway, an increase in energy dissipation occurs as the spillway slope and number of steps increase. In a numerical investigation, Ma et al. (2022) [5] found that the energy dissipation performance of the interval-pooled stepped spillway was generally better than that of the pooled stepped spillways and the horizontal stepped spillway. Peng et al. (2019) [23] numerically investigated energy dissipation in stepped spillways with different inclined slopes in skimming flow regions and found that the energy dissipation rate increases with an increase in horizontal face angles. Azmeri et al. (2021) [24] investigated a number of stepped weir models to evaluate the energy dissipation and hydraulic jumps downstream the stepped weirs. The results showed that energy dissipation increases during hydraulic jumps formed downstream of the weir as the Froude number and length of hydraulic jumps rise. Meanwhile, energy dissipation declines when the flow depth ratio in the hydraulic jump rises.

Ghaderi et al. (2021) [25] experimentally and numerically investigated the effect of roughness elements on the steps and their impact on energy dissipation. The results showed that the presence of appendage elements on the steps increased the turbulent kinetic energy (TKE) values and Darcy-Weisbach friction, resulting in a significant increase in energy dissipation. Reducing the height of the elements can significantly increase energy dissipation and the TKE value. Ghaderi et al. (2021) [26] numerically investigated the effect of the geometric characteristics of pooled steps on energy dissipation performance. Three different step geometries were considered: flat steps, pooled steps, and notched pooled steps. The numerical findings showed that the flat step configuration has the best energy dissipation performance among the three configurations. Meanwhile, the pooled steps enhanced energy dissipation by 5.84% in comparison to the simple pooled steps.

Most of the previous studies focused on energy dissipation in stepped weirs with horizontal and inclined steps. In the present research, new step geometries were used, such as horizontal with rounded sill steps and inclined steps with rounded sills. The present study is an experimental work that uses four configurations, namely, horizontal steps, inclined steps, flat steps with rounded sills, and inclined steps with rounded sills, to examine their effect on flow energy dissipation. The results indicated an increase in relative energy losses at a high rate of 90.85%.

2. Theoretical Approach

To provide a better explanation of the flow and energy characteristics between the inlet section of the approach channel and any interesting step section in the spillway, the following sections discuss these aspects in detail.

2.1. Computation Domain of the Stepped Spillway

Flow energy dissipation between the inlet section of the spillway, E_o, and any section of the spillway outlet, E_i, is estimated as shown in Figure 1.

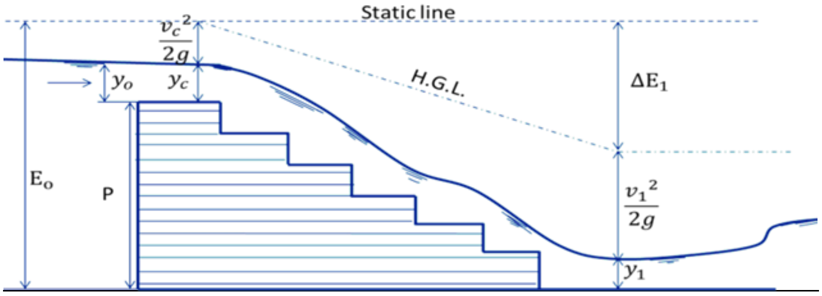


Figure 1. Parameters of energy dissipation

The total energy E_o consists of dam height, P, critical depth, y_c and velocity head, $\frac{v_o^2}{2g}$:

$$E_o = P + y_c + \frac{v_c^2}{2g} \tag{1}$$

where v_c is the velocity of the flow at the critical section, and g is the acceleration of gravity. The critical depth, y_c is expressed as follows:

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

The velocity head is written as follows:

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

Substituting q^2 from Equation 2 into Equation 3, results in the following

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

Then Equation 1 becomes as follows:

$$E_o = P + y_c + \frac{y_c}{2} = P + \frac{3}{2}y_c \tag{5}$$

Energy loss, ΔE_1, is the difference between the energy at the upstream of the spillway and that at the section of interesting step 1, E_1 , as follows:

$$\Delta E_1 = E_o - E_1 \tag{6}$$

Equation 6 used to calculate the value of the energy loss through the stepped spillway. Energy dissipation, $\frac{\Delta E_1}{E_o}$, is one of the dimensionless parameters widely used to study the energy dissipation property [27]. Flow discharge calculated using the formula derived by Rehbock [28-30]. This discharge value is verified through the measured value reading obtained from the gauge attached to the inlet pipe. Weir discharge equation is as follows:

$$Q = \frac{2}{3}\, C_d \sqrt{2g}\, B\, H^{\frac{3}{2}} \tag{7}$$

B is the crested width of the spillway, and H is the head over the crest of the weir. International standard ISO 1438 [30, 31] adopted the 1929 Rehbock formula for the flow calculation, in which the discharge coefficient C_d is obtained as follows:

$$C_d = 0.602 + 0.083\frac{H}{P} \tag{8}$$

2.2. Dimensional Analysis

In this research, dimensional analysis was applied to correlate the different physical quantities that affect the phenomenon to determine a number of variables. The variables affecting flow energy dissipation, ΔE_1 , and obtaining simple mathematical relationships are total energy loss, E_o, discharge per unit width, q, step height, h_s increment height above the horizontal step at the adverse slope, h_v, and the acceleration of gravity, g. These parameters are written as follows:

$$\Delta E_1 = f(E_o, q, h_s, h_v, g) \tag{9}$$

Using Buckingham $\pi - theorem$ [32], the parameters in Equation 9 can be expressed in dimensionless form, as follows:

$$\frac{\Delta E_1}{E_o} = F\left(\frac{q^2}{E_o^3 g}, \frac{h_s}{E_o}, \frac{h_v}{E_o}\right) \tag{10}$$

The critical depth, $y_c^3 = \frac{q^2}{g}$, with the term $\frac{q^2}{E_o^3 g}$ may be written as $\frac{y_c}{h_s}$. Therefore, Equation (10) can be written as follows:

$$\frac{\Delta E_1}{E_o} = F\left(\frac{y_c}{E_o}, \frac{h_s}{E_o}, \frac{h_v}{E_o}\right) \tag{11}$$

The dimensionless term $\frac{\Delta E_1}{E_o}$ is widely used in previous studies and refers to relative energy loss characteristics. In addition, the term $\frac{y_c}{E_o}$ is called the critical flow depth relative to the total energy loss. Rajaratnam (1990) [33] and Chanson (1994) [2] suggested that the term $\frac{y_c}{E_o}$ is an important parameter in the occurrence of skimming flow. All dimensionless terms described in Equation 11 are used as parameters in the present study.

3. Experimental Setup

The experiments were conducted in a laboratory channel in the Hydraulic Laboratory of the Water Resources Engineering Department, University of Mustansiriyah, Iraq. The experiments were carried out in a hydraulic channel 3.5 m long and 0.3 m wide. The stepped channel was made of plastic with a thickness of 0.05 m and sidewalls with a height of 0.45 m. The dimensions of each step were 23×39.5 cm, and the step height was 9 cm. A broad-crested weir followed by five steps was considered for the test. The overall slope of the step spillway was 23% with five steps. The experiments were conducted for a range of flow rates (0.61–9.12 L/s). resulted in a Froude number ranging from 1.2 to 9.4. Figure 2 shows the schematic of the experimental apparatus device. Water pumped from the reservoir to the upstream tank flowed over the stepped weir. The water level over the spillway was measured using a point gauge with an accuracy of 1 mm (Figure 2). A schematic of the step configurations is shown in Figure 3.

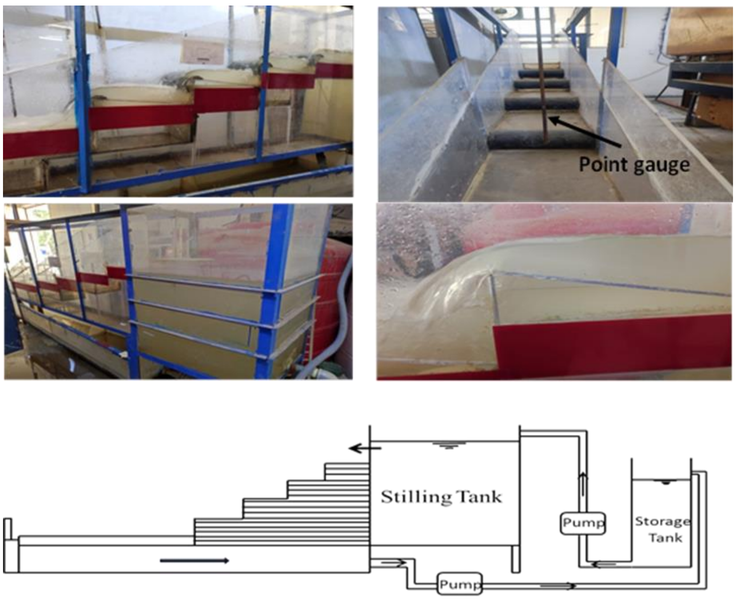


Figure 2. Schematic of experimental device

Four types of steps were used: horizontal, horizontal with rounded sill, inclined, and inclined with rounded sill steps using two slopes of 13% and 23%. Two bending radii were used for the rounded sill types of 10 and 15 cm. The experimental data are listed in Tables 1 to 5. These Tables include measurements of the height above crest of spillway H, calculation of the factor C_d from Equation 8, measurement of various discharges and Froude number calculations. The tables also show the change of $\frac{\Delta E_1}{E_o}$ with different values of flow, and the significant effect of the circular part on dissipating energy is evident. The two dimensionless terms of h_s/E_o, and h_v/E_orepresent the effect of the step shape on the loss of flow energy through the stepped spillway.

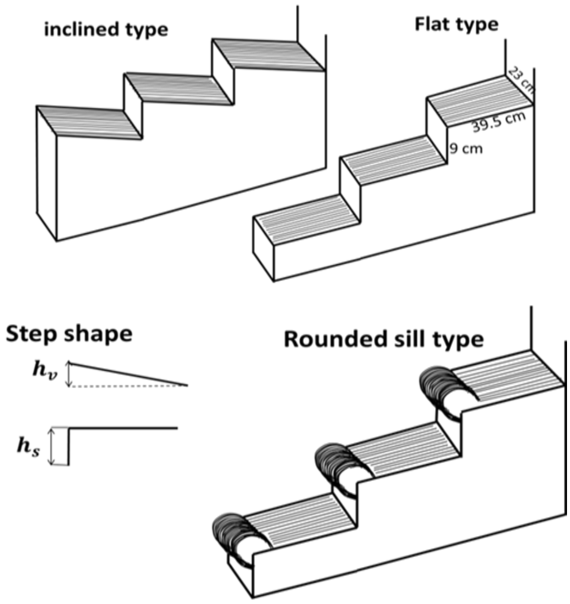


Figure 3. Types of steps used in experimental work

Table 1. Experimental data for horizontal step type

H, cm	C_d	Q, L/s	y_c, cm	F_r	$\Delta E_1/E_o$
7.5	0.615	8.591	5.22	2.828	0.753
6.8	0.614	7.401	4.726	2.679	0.784
6.0	0.613	6.120	4.163	2.621	0.810
5.4	0.612	5.216	3.743	2.249	0.848
5.0	0.611	4.641	3.462	1.935	0.872
4.5	0.610	3.957	3.113	1.871	0.886
4.0	0.609	3.311	2.764	1.935	0.896
3.6	0.608	2.824	2.486	2.031	0.903
3.3	0.608	2.476	2.277	2.031	0.910
2.7	0.607	1.829	1.861	2.539	0.912

Table 2. Experimental data for horizontal step with rounded sill of R = 5 cm

H, cm	C_d	Q, L/s	y_c , cm	F_r	$\Delta E_1/E_o$
7.9	0.616	9.298	5.503	2.006	0.804
7.0	0.614	7.735	4.867	2.066	0.820
6.6	0.614	7.073	4.585	2.096	0.828
6.0	0.613	6.120	4.163	2.098	0.841
5.5	0.612	5.363	3.813	2.206	0.848
5.0	0.611	4.641	3.462	1.988	0.870
4.5	0.610	3.957	3.113	2.097	0.878
4.0	0.609	3.311	2.764	2.188	0.887
3.5	0.608	2.706	2.416	2.045	0.905
2.3	0.606	1.436	1.584	1.462	0.946

Table 3. Experimental data for inclined type of S = 13%

H, cm	C_d	Q, L/s	y_c, cm	F_r	$\Delta E_1/E_o$
7.8	0.616	9.120	5.432	2.563	0.766
7.2	0.615	8.073	5.008	2.526	0.785
6.8	0.614	7.401	4.726	2.451	0.800
6.5	0.614	6.911	4.515	2.502	0.805
5.7	0.612	5.661	3.953	2.408	0.832
5.4	0.612	5.216	3.742	2.743	0.820
5.0	0.611	4.641	3.462	3.068	0.814
4.6	0.610	4.091	3.183	4.163	0.761
4.3	0.609	3.694	2.974	3.343	0.823
4.0	0.609	3.311	2.764	3.984	0.800
3.6	0.608	2.824	2.486	4.233	0.806
3.4	0.608	2.590	2.347	4.211	0.817
3.2	0.607	2.363	2.208	4.418	0.817
2.7	0.607	1.829	1.861	5.463	0.800
2.4	0.606	1.531	1.653	6.013	0.799
2.0	0.605	1.164	1.377	5.177	0.859
1.8	0.605	0.993	1.238	5.659	0.858
1.5	0.604	0.755	1.031	8.38	0.806
1.3	0.604	0.608	0.894	9.443	0.803

Table 4. Experimental data for inclined type of S = 23% with rounded sill of R=7.5 cm

H, cm	C_d	Q, L/s	y_c, cm	F_r	$\Delta E_1/E_o$
8.3	0.617	10.025	5.786	1.508	0.825
7.2	0.615	8.073	5.008	1.350	0.851
6.8	0.614	7.401	4.726	1.334	0.859
6.0	0.613	6.120	4.163	1.244	0.875
5.5	0.612	5.363	3.813	1.271	0.884
5.0	0.611	4.641	3.462	1.147	0.896
4.6	0.610	4.091	3.183	1.121	0.904
4.4	0.610	3.825	3.043	1.210	0.906
3.8	0.609	3.064	2.625	1.277	0.917
3.5	0.608	2.706	2.416	1.167	0.925
3.2	0.607	2.363	2.208	1.304	0.929
2.6	0.606	1.728	1.792	1.306	0.942
2.3	0.606	1.436	1.584	1.345	0.948
2.0	0.605	1.164	1.377	1.400	0.954
1.6	0.605	0.832	1.100	1.154	0.964
1.3	0.604	0.608	0.894	2.389	0.958

Table 5. Experimental data for the inclined type of S = 23% with rounded sill of R=5 cm

H, cm	C_d	Q, L/s	y_c, cm	F_r	$\Delta E_1/E_o$
7.7	0.616	8.942	5.361	1.669	0.828
7.4	0.615	8.417	5.149	1.784	0.828
6.8	0.614	7.401	4.726	1.639	0.847
6.3	0.613	6.590	4.374	1.668	0.856
5.7	0.612	5.661	3.953	1.454	0.876
5.3	0.611	5.070	3.672	1.510	0.882
4.8	0.610	4.363	3.323	1.445	0.894
4.3	0.609	3.694	2.974	1.209	0.908
3.7	0.608	2.943	2.556	1.106	0.921
3.0	0.607	2.144	2.069	1.308	0.933
2.6	0.606	1.728	1.792	1.581	0.938
2.1	0.605	1.252	1.446	1.356	0.952
1.6	0.605	0.832	1.100	1.473	0.962
1.4	0.604	0.680	0.962	1.514	0.966

The size of the hydraulic channel used is of the small type, with a length of 3.5 meters and a small width of 30 cm to demonstrate the longitudinal effect of the flow. It gave reasonable results and was easy to control and work on. The larger the hydraulic channel, the better the results.

The flowchart of the research methodology that was used to achieve the study's aims is shown in Figure 4.

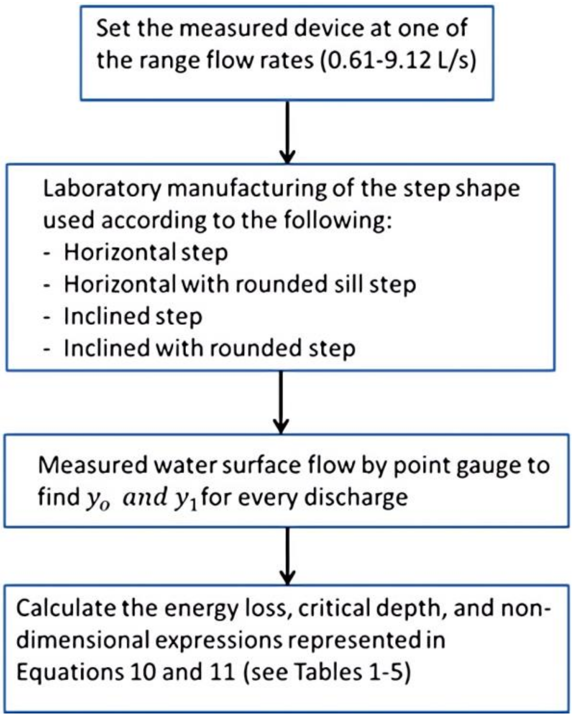


Figure 4. Flowchart of experimental work

4. Results and Discussions

In this section, the effect of step configuration on flow energy loss is discussed in detail.

4.1. Effect of Step Configuration on Energy Loss

Experiments were carried out for a wide range of discharge (0.61-9.12 L/s) for horizontal flat steps, inclined steps, and steps with rounded ends. This section describes the effect of step geometry on energy loss in terms of relative energy loss, $\Delta E_1/E_o$, versus relative critical flow, y_c/E_o (see Figure 5). Figure 5-a presents the relative energy loss of steps with rounded ends of 5 cm radius which has a value of 86.27% in comparison to 85.75% for horizontal flat steps. The presence of the rounded sill (curvature radius is 5 cm) formed a vertical sill height of 2.5 cm. This condition impeded the movement of the flow and raised it in the direction of rotation without free fall thereby increasing the loss of flow energy. Figure 5-b shows that the inclined step type of the 23% slope has a greater average relative energy loss of 89.1% than that of the flat step with a rounded sill of R=5 cm. These findings indicate that the inclined step type of 23% provides greater energy loss than the flat type with a rounded sill over y_c/E_o values ranging within 0.04-0.1.

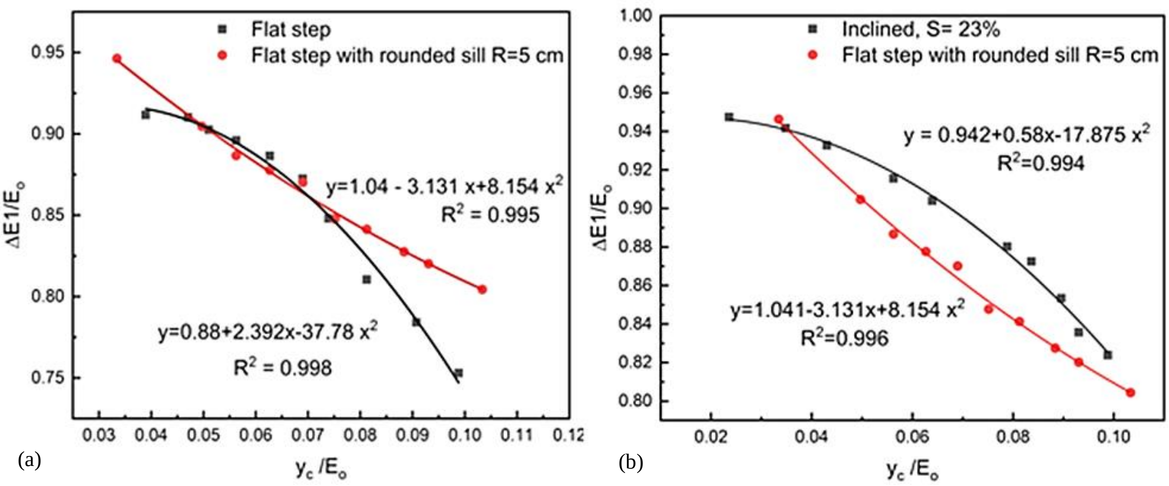


Figure 5. Effect of the step shape on the energy loss of flow for term $\frac{y_c}{E_o}$

4.2. Effect of Step Slope on Energy Loss

Two inclined steps (13% and 23%) were examined and compared to horizontal flat steps. The results showed that the 23% inclined steps had the highest values of dissipating flow energy in comparison to the other types (inclined slope of 13% and horizontal flat steps). This finding coincides with those of many previous studies, e.g., Hamedi et al. (2014) [18], Mero et al. (2016) [19], Peng et al. (2019) [23], and Salmasi et al. (2022) [22]. Figure 6 shows the effect of the inclined steps (13% and 23%) on flow energy dissipation in comparison to horizontal flat steps. The 23° inclined step dissipates 89.07% more relative energy losses than that of the horizontal step, which posted an 85.75% relative energy loss (see Figure 6-a). Figure 6-b indicates that the 23% step slope shows smooth curve behavior. Energy dissipation for the 23% step slope is higher than that of the 13% step slope, and the points of the last curve are randomly distributed. However, the use of the rounded sill at the end of the step avoided the random distribution of curve points, as shown in Figure 6-c.

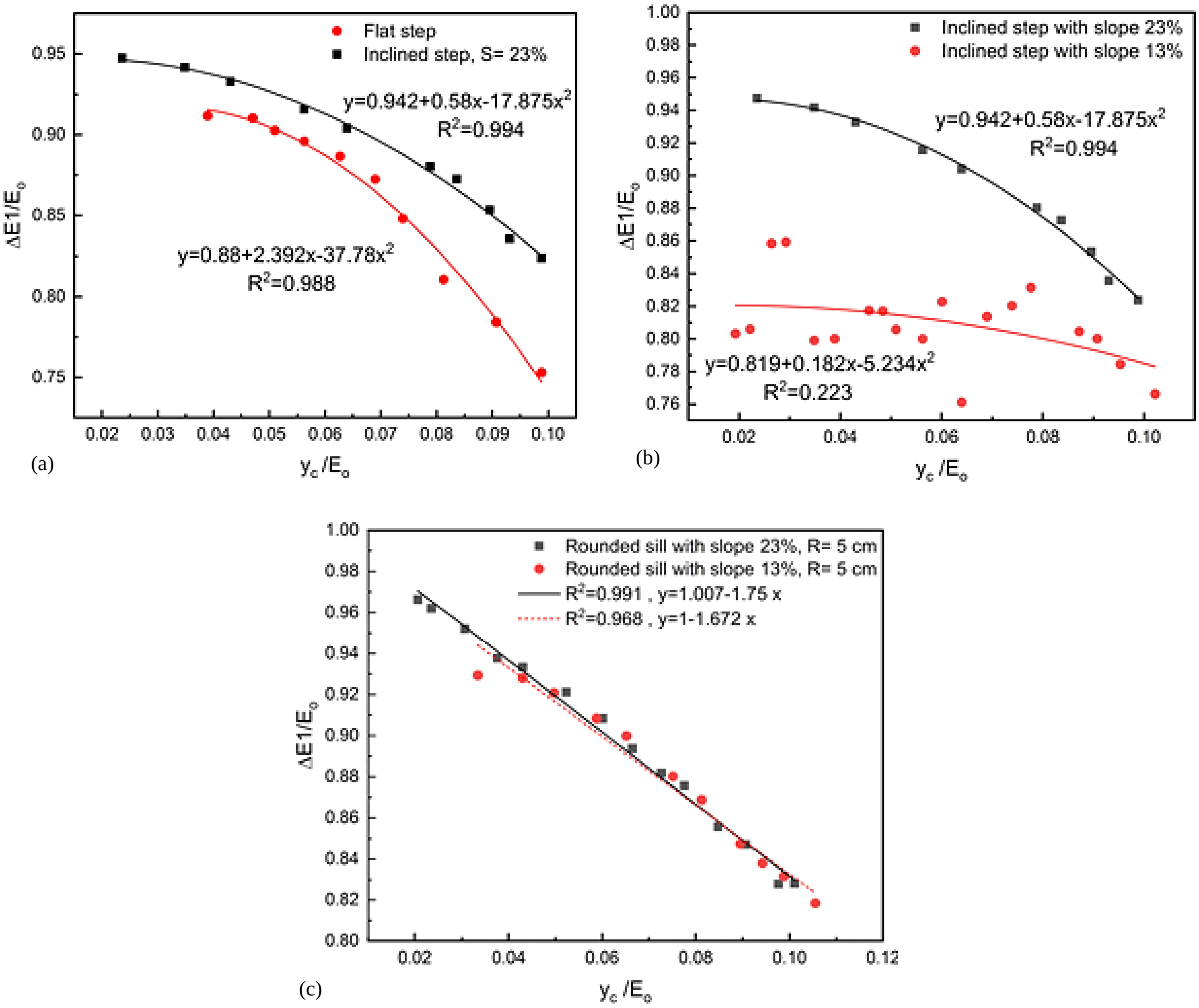


Figure 6. Effect of step slope on the energy loss of flow

In Figure 6-c, despite the use of two different slopes, no effect of the slope on the stepped spillway was observed due to the presence of the rounded sill placed at the end of the step. Accordingly, the effect of the rounded sill on the energy dissipation of flow was found.

4.3. Effect of Rounded Sill Type on Energy Loss

Figure 6 shows that a rounded sill increases the dissipation of flow energy. In addition, it reduces the momentum force of flow due to the dissipation of flow energy thus controlling the expected damage at the downstream of the spillway. Figure 7 presents the relationship between relative energy loss and relative critical depth for different flow rates and end sill geometries. The presence of the rounded sill at the end of the step results in linear relationships between relative energy loss and relative critical depth with a correlation coefficient R^2 greater than 95%. Figure 7-a shows the comparison between relative energy loss and relative critical depth for two models of the rounded sills (5 and 7.5 cm) with an upward inclined step of 23%. The figure shows that the inclined type with a slope of 23% and rounded sill radius of 7.5 cm has a 90.85% average relative energy loss, which is larger than that of the same slope with 5 cm radius and an average relative energy loss of 89.93%. This outcome is due to the occurrence of the vertical sill with 7.5 cm radius.

Figure 7-b shows the comparison between relative energy loss and relative critical depth for an inclined step of 23% without a rounded sill and with a rounded sill of 5 cm radius at the end of the steps. Results showed an average relative energy loss of 89.93% for the rounded sills and 89.07% for the inclined steps. This finding indicates that the slight increase in flow energy loss is due to the increase in vertical sills resulting from the presence of rounded ends. Similar to Figures. 7-a and 7-b, Figure 7-c presents the comparison for different step inclinations (23% and 13%) with a constant rounded end sill of 5 cm radius. The results showed that the step model with a 23% slope had an average relative energy loss of 87.91%. For a constant step inclination of 23% without rounded sills and with a rounded end sill of 7.5 cm radius, a comparison was made between relative energy loss and relative critical depth (see Figure 7-d). The results revealed that the rounded sill with a radius of 7.5 cm and a step inclination of 23% has a 90.85% average relative energy loss, which is greater than that of the same step inclination, which reached 89.1% relative energy loss. The following equations indicate the relations between relative energy loss and relative critical depth for high values through the stepped spillway (see Figure 7):

$$\frac{\Delta E_1}{E_o} = 1 - 1.644\frac{y_c}{E_o}, \qquad R^2 = 0.951\text{ , for inclined type S} = 23\% \tag{12}$$

$$\frac{\Delta E_1}{E_o} = 0.999 - 1.544\frac{y_c}{E_o}, \qquad R^2 = 0.992\text{ , for inclined S} = 23\%\text{ with rounded sill R} = 7.5\text{ cm} \tag{13}$$

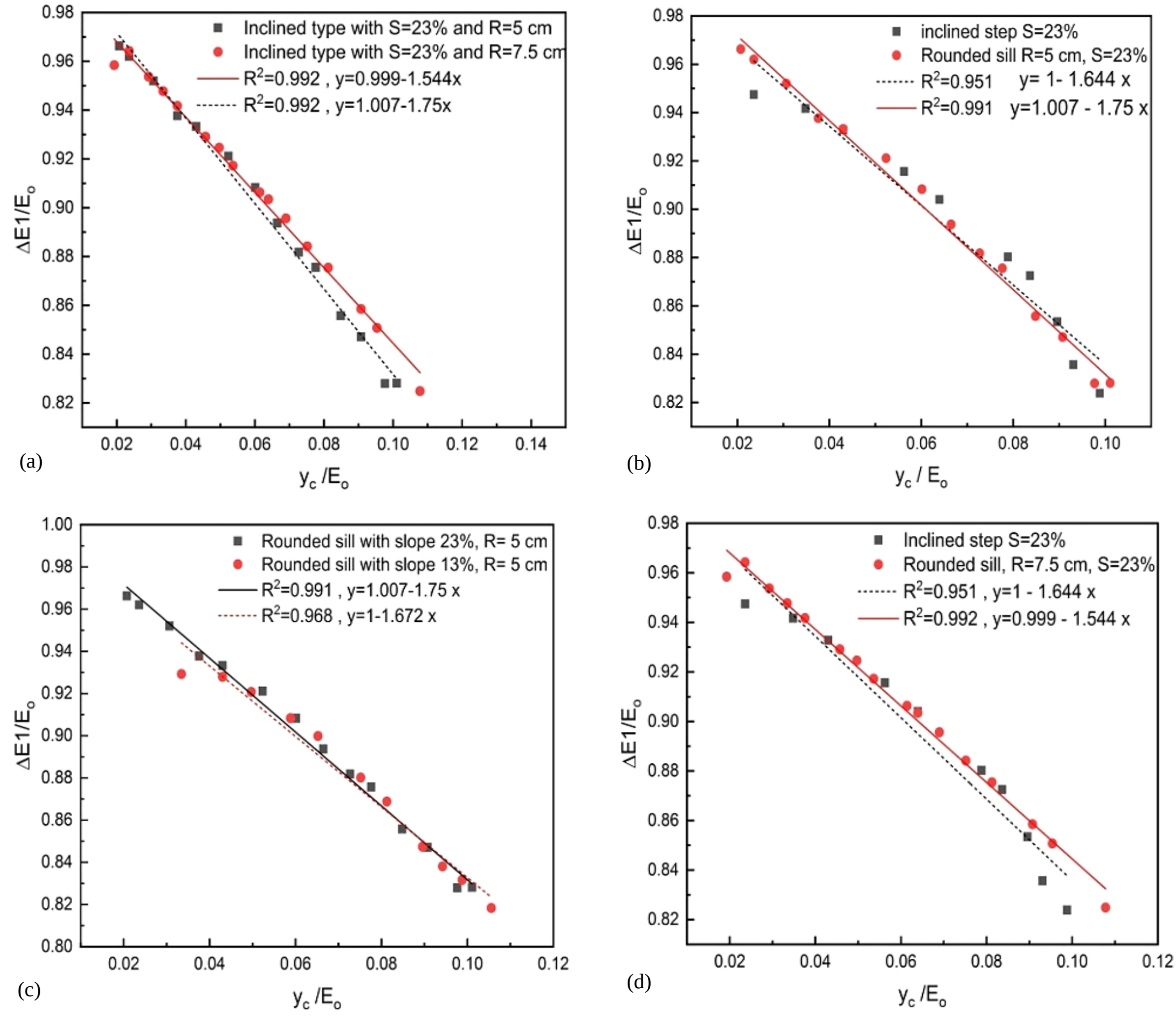


Figure 7. Effect of the rounded sill on the loss of energy flow

Table 6 summarizes the values of loss ratios for the types of step forms used in the experiments.

Table 6. Values of the average relative energy loss for different types of steps

Type of step	Average relative energy loss
Flat	85.75%
Inclined S= 23%	89.1%
Inclined S= 23% with rounded sill R= 5 cm	89.93%
Inclined S= 23% with rounded sill R= 7.5 cm	90.85%
Inclined S= 13%	80.9%
Inclined S= 13% with rounded sill R= 5 cm	87.91%
Flat with rounded sill R= 5 cm	86.27%

Table 6 summarizes that the highest flow energy dissipation through the stepped weir is 90.85% for the inclined type with an inclination of 23% and a rounded sill with a radius of 7.5 cm. The lowest value of flow energy dissipation is 80.9% for the inclined type, with a slope of 13%. Table 6 also shows the effect of step roundness on flow energy dissipation for the horizontal steps. The results of the present study are compared to the previous studies [34, 35]. Accordingly, the roundness of steps or the use of rounded step edges and rounded sills produces more energy dissipation in comparison to the traditional stepped weirs.

4.4. Effect of Step Height on Energy Loss for the Horizontal Type

In this section, the effect of step height on energy dissipation was studied. The flow state at the inclined slope of 23% increases flow energy dissipation more than that when the step is horizontal, as shown in Figure 8-a. However, the energy loss points become randomly distributed (see Figure 8-b) when the step slope changes from 23% to 13% and is compared with the flow for the horizontal step. This finding indicates that the effect of changing the step slope on energy loss is the same as that shown in Figure 6-b, which resulted in the random distribution of the points. The random distribution of points in Figure 8-b was changed by placing a rounded sill with a radius of 5 cm on the 13% step slope and comparing it with the flow on the horizontal slope. Figure 8-c shows this change and indicates an increase in flow energy dissipation. Figure 8-d provides another illustration of the importance and effectiveness of a rounded sill in dissipating flow energy. It compares two cases with a horizontal step, one of which has a rounded sill. The results show that the step shape with a rounded sill causes more flow energy dissipation than the other type of horizontal shape.

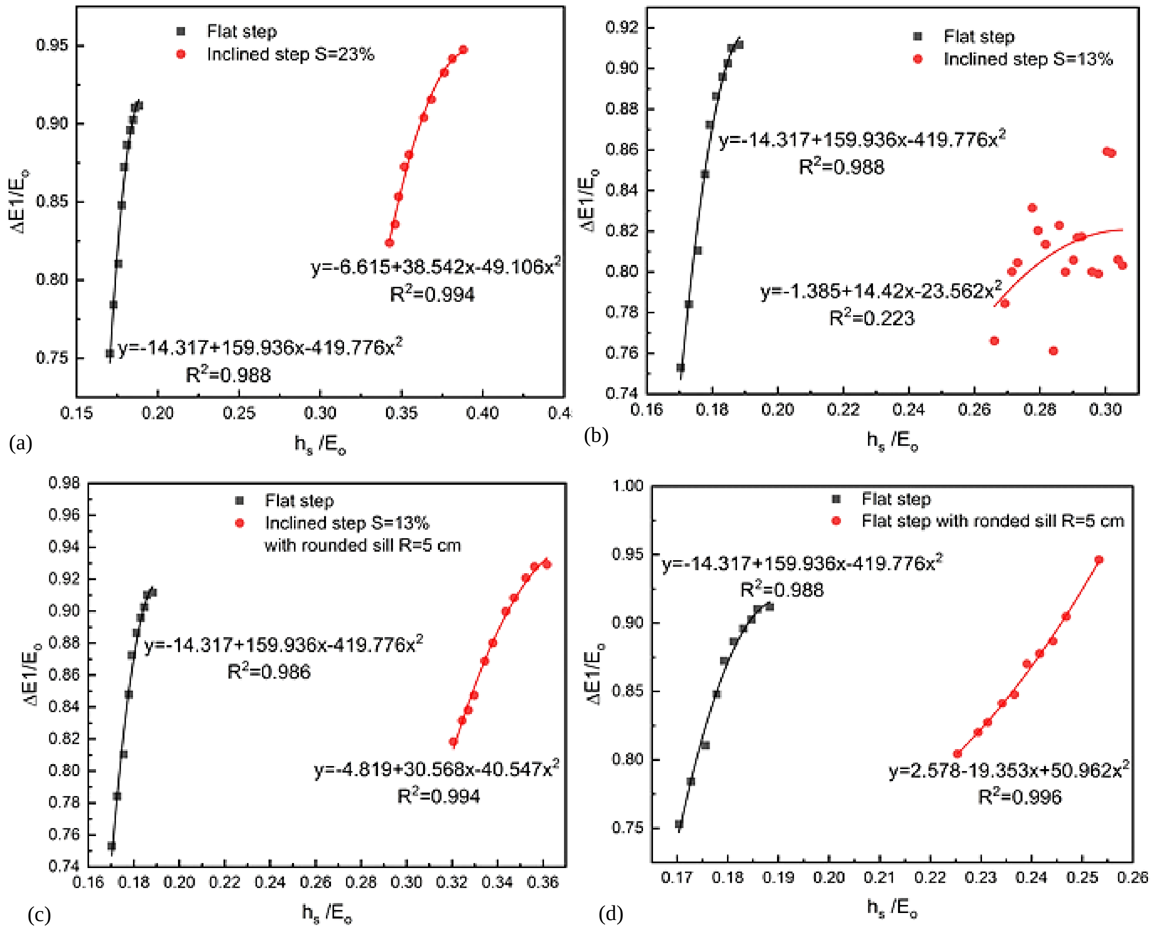
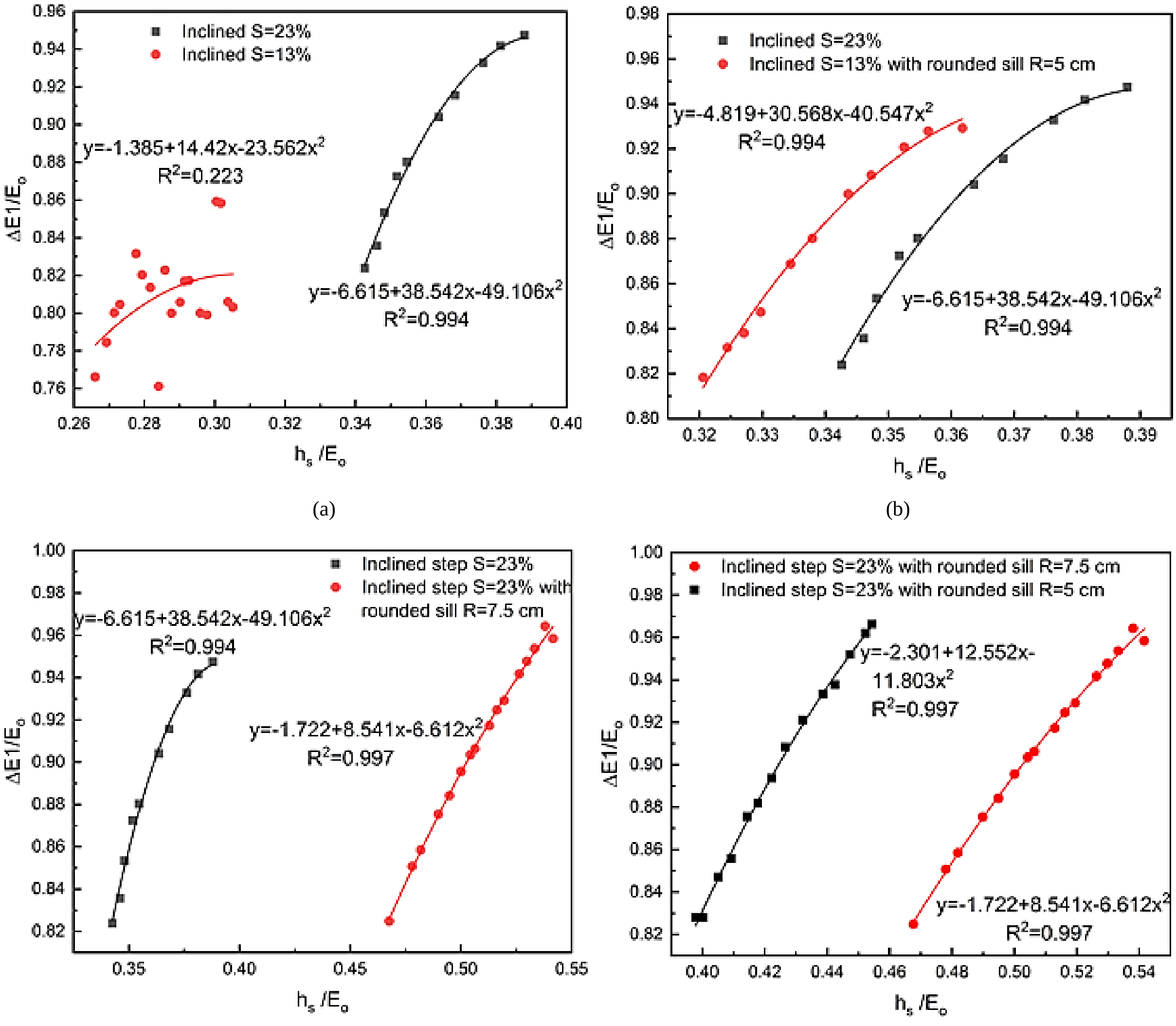


Figure 8. Effect of step height on the loss of energy flow

4.5. Effect of Step Height with Rounded Sill on Energy Loss

Figure 9 presents the relationship between relative step height h_s/E_o and relative energy loss, $\Delta E_1/E_o$. The value of $\Delta E_1/E_o$ increases as the value of h_s/E_o increased. Thus, all the curves on the right of the figure have higher values of step height ratio, with the highest relative energy losses. The figure also shows the effect of the rounded sill on the dissipation of flow energy at the relative step height. The dissipation of flow energy at the inclined step slope of 23% is much greater than that of the inclined step slope of 13% (see Figure 9-a). The results of the comparison between the two cases indicate that the steps with rounded sill provide more flow energy dissipation, as shown in Figure 9-b. In addition, if the diameter of the rounded sills were changed by 7.5 cm and the step slope was 23%, the rounded sills would attract more flow energy dissipations than just the inclined sills (see Figure 9-c). Figure 9-d indicates that the dissipation of flow energy of the inclined step slope of 23% with a rounded sill of 7.5 cm radius is greater than that of the same inclined slope with a rounded sill of 5 cm. This result indicates that the value of h_s/E_o for the rounded sill R= 7.5 cm is greater than that for the rounded sill R = 5.0 cm.



(c) (d)

Figure 9. Effect of rounded sill on energy loss of flow for term $\frac{h_s}{E_o}$

4.6. Effect of Increment Height above the Horizontal Step on Energy Loss

The effect of the third dimensionless term h_v/E_o represents the relative increment height above the horizontal step, as shown in Figure 10. The figure shows changes in flow energy dissipation similar to those in Figure 9. Therefore, the effect of increment height is the same as the effect of step height. Generally, the flow energy dissipation is effective when using a rounded sill at the end of the step with inclination.

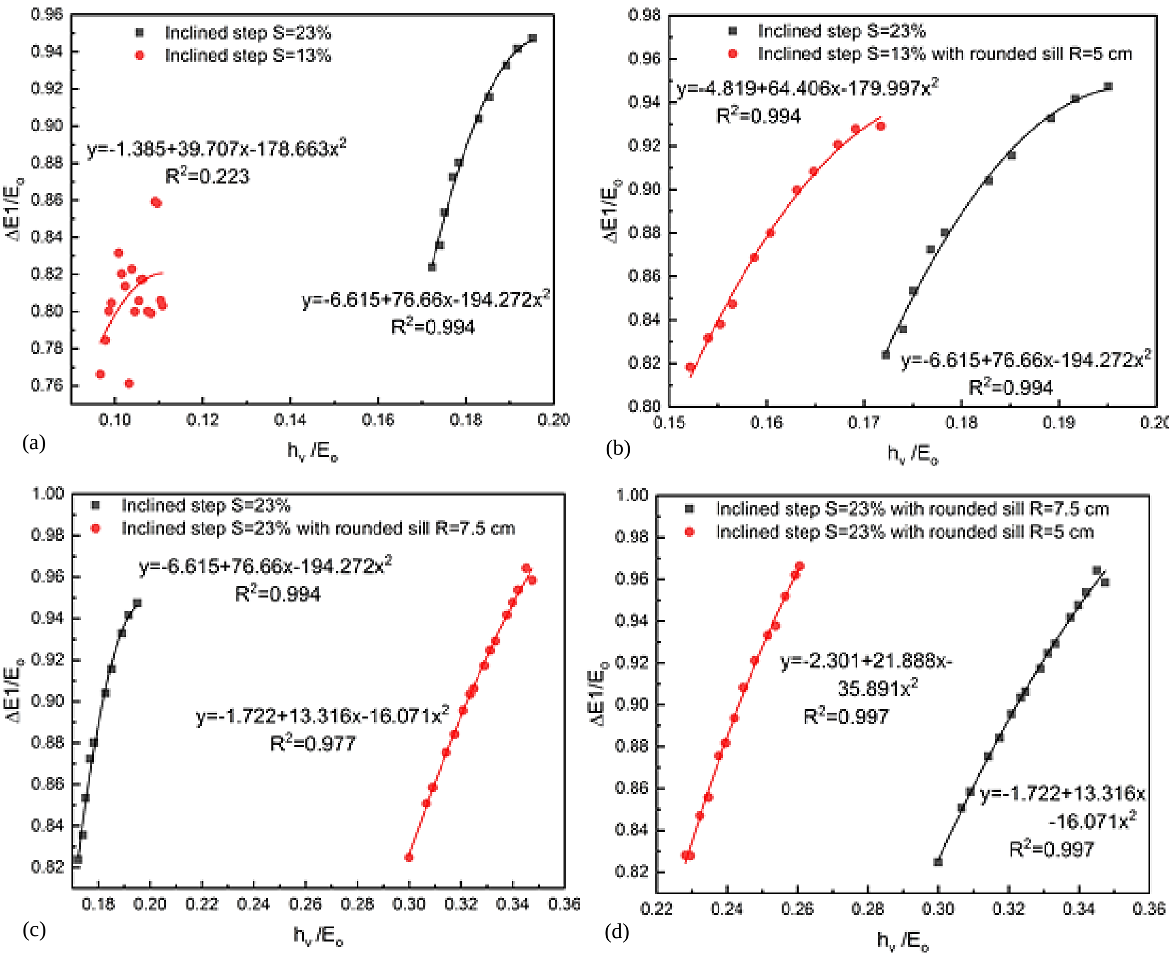


Figure 10. Effect of rounded sill on the energy loss of flow for the term $\frac{h_v}{E_o}$

5. Conclusions

In this study, the relationship between stepped weir configurations and energy dissipation is presented. The effect of stepped weir configurations on flow energy dissipation was experimentally examined for four types of step shapes, namely horizontal, horizontal with a rounded sill, inclined, and inclined with a rounded sill of 5 and 7.5 cm radii. In the inclined type, the two slopes were 13% and 23%. The conclusions drawn from the present study are as follows:

- The use of rounded sills produces more energy dissipation than that of traditional stepped weirs.
- Flow energy dissipation was greater than that of flat stepped weirs as follows:
  - 0.6% in horizontal stepped weirs with rounded sills (R=5cm) on the step edges.
  - 2.5% in inclined steps slopes of 13% with rounded sills (R=5 cm) on the step edges.
  - 4.9% in inclined steps slopes of 23% with rounded sills (R=5 cm) on the step edges.
  - 6.0% in inclined steps slopes of 23% with rounded sills (R=7.5 cm) on the step edges.
- The presence of the rounded sill at the end of the step results in linear relationships between relative energy loss and the relative critical depth.
- The relationship between $\Delta E_1/E_o$ and y_c/E_o showed a homogeneous distribution of points for the rounded sill configuration in comparison to the inclined type of 13% slope.
- The two dimensionless terms of relative step height h_s/E_o and relative increment height h_v/E_o have a similar effect on energy loss on the stepped weirs.

From a structural viewpoint, it is considered difficult to create the rounded part at the end of the step, but from a hydraulic standpoint, it results in an increase in the dissipation of flow energy when using the rounded part in the stepped spillway. Therefore, the risk of flow falling behind the spillway is reduced due to the dissipation of excess flow energy.

Our research findings encourage us to continue carrying out laboratory work with a wide channel with varying spillway steps in length and height for a range of flow rates to pass over the rounded sill geometry.

6. Declarations

6.1. Author Contributions

Conceptualization, K.R.G., S.M., Z.A.H., and A.Q.R.; methodology, K.R.G.; formal analysis, K.R.G.; investigation, K.R.G., S.M., Z.A.H., and A.Q.R.; writing—original draft preparation, K.R.G.; writing—review and editing, K.R.G., S.M., Z.A.H., and A.Q.R.; visualization, S.M., Z.A.H., and A.Q.R. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding & Acknowledgements

The researchers thank the hydraulics laboratory staff in the Water Resources Engineering Department, especially the laboratory supervisor. We also extend our thanks to Mustansiriyah University for their support and facilitation of this research.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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