The effect of step number and the slope of the Gabion-Stepped Spillway on Energy dissipation

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Abstract

Gabion stepped spillways (GSS) have been widely used to dissipate excess kinetic energy in hydraulic systems, particularly in erodible channels, due to their ease of construction, material availability, durability, and cost-effectiveness. GSS are primarily employed along rivers to protect streambeds and erosion-prone waterways. These spillways have gained significant attention among designers due to their energy dissipation efficiency, structural stability, and environmental compatibility, accommodating both overflow and underflow conditions. This study investigates the effects of slope and number of steps on flow characteristics, energy dissipation, and hydraulic jump properties at the downstream of GSS. For this purpose, 21 alternatives of GSS with three different steps (4, 6, 8), three different slopes (21.8°, 26.6°, 33.7°) were constructed and each alternative has conducted under five different flow discharge (30, 35, 40, 45, and 50 L/s). Total of 105 experiments were conducted, and the results indicate that GSS increases the energy dissipation by up to 81.5%. showing 9–20% higher dissipation than similar conventional stepped spillways (CSS) and 55–74.3% higher dissipation than the no step chute models. Additionally, reducing the number of steps and slope (provided that tumbling flow is maintained) enhances relative energy loss. On average, the reduction in the hydraulic jump length downstream of GSS was estimated at 44.1% for gabion models and 28.8% for CSS.

Introduction

Controlling the kinetic energy in high-velocity flows streams is a significant challenge in hydraulic structure design. Therefore, reduction of the kinetic energy before the flow is conveyed to the downstream stream is one way to prevent damage to the downstream environment (Hager, 1992). GSS is a commonly energy dissipater which is used in the open watercourses to dissipate kinetic energy and reduce its erosive power, thereby reducing flow energy and trapping some of the suspended sediment upstream (Stephenson, 1979).

Furthermore, due to the presence of underflow, gabion stepped spillways can pass a higher discharge with a lower water depth over the crest, which can be crucial in the case

of flood. Additionally, due to the stepp which increases the flow turbulence, the amount of oxygen entering the water increases, which is of environmental concern in many cases (Alabas et al., 2023).

Gabion structures have numerous applications in the hydraulic construction and are currently used in many countries for the construction of small dams and various types of spillways (Al-Fawzy et al., 2020). The construction of GSS is simple and convenient, and they are resistant and stable against loads from water pressure (Daneshfaraz et al., 2021). The energy dissipation of the flow over such a structure is also high, thus reducing the construction costs of stilling basins. In addition to their use in dams and spillways, they can be used in watershed management for erosion control in waterways or riverbank protection near intakes or bends (Hussain et al., 2022).

In this case, in addition to preserving and contributing to soil stability, in areas with abundant rock, the construction cost is significantly lower than that of a similar concrete or rock cemented structures. An important characteristic of this type of structure is the underflow through the porous body of the spillway, which creates complexity in the flow behavior (Daneshfaraz et al., 2024). Most of the research conducted so far has been related to stepped spillways of large concrete dams or rigid stepped spillways without porosity (Chanson, 1994; Chamani and Rajaratnam, 1999; Gonzalez et al., 2008; Hussein & Shamkhi, 2023; Mero & Mitchell, 2017; Sharifi, 2025), and in comparison, studies on gabion stepped spillways (with porosity) have been limited. Using physical models can provide a reasonable estimate of energy dissipation and the behavior of the structure against changes in effective parameters. The energy dissipation of gabion stepped spillways is a function of the upstream and downstream slopes of the spillway, the number of steps, porosity, and the Froude number. Changing the porosity changes the ratio of underflow to overflow, and consequently, the percentage of energy dissipation decreases (Elghandour et al., 2023; Simões et al., 2024).

Christodoulou (1993) and Sorensen (1985) presented their model testing results on stepped spillways, stating that the effect of the number of steps on energy dissipation is evident. For a given ratio of (critical flow depth) to (step height), the energy dissipation increases with an increasing number of stepp, and the effect of the number of steps is greater at higher discharges. Their experiments also showed that the energy dissipation decreases when the flow transitions from nappe flow to skimming flow.

Chinnarasri et al (2008) also investigated the hydraulic characteristics of flow in GSS and compared their energy dissipation with that of non-GSS. Their results showed that the energy dissipation ratio in GSS, compared to the non-gabion type, with 20 steps and spillway slopes of 30, 45, and 60 degrees, was 7, 10, and 14 percent higher, respectively, resulting in lower outlet velocities. This research also indicated that the shape and size of the aggregates have a very small effect on energy dissipation.

Felder and Chanson (2022) conducted experiments on a physical model of a CSS with a height of one meter and a slope of 26.6 degrees. They considered five different step configurations and measured the residual energy downstream of the spillway. Although the results showed that the number of steps did not have a significant effect on the residual energy downstream, a spillway with 10 steps, each 10 centimeters high, had lower residual energy downstream, indicating greater energy dissipation in this spillway.

Chafi et al. (2010) studied the flow and energy dissipation in CSS under both nappe and skimming flow regimes. In this research, a spillway with 6 steps and a slope of 32 degrees was constructed. The experimental results showed that nappe flow has higher energy dissipation than skimming flow, and the energy dissipation in this flow depends on the number of steps and also the flow discharge.

Wuthrich and Chanson (2014) investigated the hydraulic characteristics of CSS by comparing two types: impervious stepped spillways and gabion stepped spillways. They concluded that the interactions between seepage flow and overflow are a function of discharge, gabion

shape, and flow regime. They also found that the percentage of energy dissipation in gabion stepped spillways in skimming flow is less than that in impervious stepped spillways.

Vashisth (2017) conducted experiments to study the effects of energy dissipation in GSS using various parameters such as flow depth, flow velocity, and discharge characteristics. In this study, four four-stepp GSS models with a height and width of 20 and 24.5 cm, respectively, and with an average aggregate size of 12.75 mm placed in the central core of the step, were constructed. The results indicate that due to the impact of water flow on the porous space of the aggregates, oscillating waves are formed downstream of the spillway, which increases the energy dissipation of the structure to a maximum of 87 percent. The relative energy loss in this structure is approximately 75 percent.

Pallavi and Harshith (2018) conducted experiments to investigate the overflow and underflow in GSS and then compared the hydraulic characteristics of this type of spillway with a CSS. In this model, the spillway is integrated. The results show that energy dissipation in the GSS is greater than that in the CSS due to the division of flow into overflow and underflow. For the same discharge, the water depth over the gabion spillway is less than that over the solid spillway, and this depth decreases with increasing aggregate size. Finally, the flow velocity decreases as it passes through the gabion, indicating that the GSS is much more effective on sloping surfaces.

Al-Fawzy et al. (2020) conducted a study with a total of 25 laboratory experiments and 175 operational tests to investigate the energy dissipation of a three-step GSS and gravel with five different diameters. The results showed a direct effect of energy dissipation with flow discharge and an inverse effect with the ratio of the third step length to the total dam length, the diameter of the sand and gravel sample, and density.

Chanson (2022), in a review article, examined the hydraulic characteristics of flow over CSS, including the complex two-phase flow dynamics of water and air and the amount of energy dissipation on the steps, and presented a summary of three decades of active hydraulic research, sometimes during major floods.

According to the above, the objective of the present study is to investigate the effect of the number of steps and the slope of GSS on the energy dissipation of the structure and the hydraulic characteristics of the flow. The energy dissipating structure, unlike gabion stepped spillways where the entire spillway body is made of gabion and is stepped, is constructed from a combination of a rigid stepped spillway on which gabion packages are placed. Therefore, the energy dissipation of the structure and its effect on hydraulic jump characteristics, including hydraulic jump length, conjugate depths of the jump, and roller length, are investigated in this type of spillway, and finally, the best model in terms of energy dissipation is introduced.

Materials and Methods

Effective Parameters

To achieve the objectives of this research, the various parameters affecting the hydraulic condition in GSS were first identified, and a general relationship including dimensionless parameters was derived through dimensional analysis. The effective parameters in these experiments are presented in Equation (1):

$$F\left(\Delta E.E_0.V.y_c.y_1.y_2.H.L_G.L_S.h.L_j.L_r.N.s.\mu.\sigma.\rho.g\right)=0 \quad (1)$$

In the above equations, ΔE is the energy dissipation of the structure, E_0 is the initial energy upstream of the structure, and V represents the velocity at any point. Yc represents the critical flow depth, y_1 and y_2 are the initial and secondary depths of the downstream hydraulic jump, respectively. Lj and Lr are the jump length, and the roller length respectively, L_G represents the length of the gabion baskets, which, for overlapping, is 1.5 times the step length of the stepped spillway (Ls). h represents the step height of both the stepped and gabion spillways, which has three values: 7.5, 10, and 15 cm for 8, 6, and 4 step,

respectively. N is the number of steps, s represents the steps slope, and H represents the total height of the spillway. μ and ρ are the dynamic viscosity and the density of water respectively, g represents the acceleration of gravity, and σ is the surface tension. Through dimensional analysis using the Buckingham π theorem, and selecting the V, Y and ρ as the repeated variables, the following general dimensionless relationship is obtained:

$$F\left(\frac{\Delta E}{E_0}.Fr.Re.We.\frac{q^2}{gH^3}.\frac{L_j}{y_2}.\frac{L_r}{y_2}.\frac{y_2}{y_1}.N.s\right)=0 \quad (2)$$

In which, Re = the Reynolds number ($Re = (\frac{\rho v y}{\mu})$), Fr= the Froude number ($Fr = (\frac{q}{\sqrt{gy^3}})$), We =the Weber number, and the ($\frac{q^2}{gH^3}$) = drop number. Given that the Reynolds number in the range of these experiments is greater than 2000 (Table 1), the flow is turbulent, and the Reynolds number can be neglected (Chow, 1973). It is worth mentioning that since the minimum water depth over the crest of the spillway in these experiments is 6.2 cm, the effects of the Weber number (We) can also be neglected. As a result, because the discharge number is a combination of the Froude number and the structure's geometry, it represents a better dimensionless number than the Froude number and is used in calculations alongside the number of steps and slope, which simplifies to:

$$\frac{\Delta E}{E_0}.\frac{L_j}{y_2}.\frac{L_r}{y_2}.\frac{y_2}{y_1}=F(\frac{q^2}{gH^3}.N.s) \quad (3)$$

The experiments were conducted in the Hydraulics Laboratory of the Faculty of Water and Environmental Engineering at Shahid Chamran University of Ahvaz. The laboratory has a main underground water reservoir from which water was pumped to a stilling basin at the beginning of the flume. A valve installed at the entrance pipe to control the inlet discharge. The channel has a rectangular cross-section and is made of Plexiglas. It is 750 cm long, 56 cm wide, and 60 cm high. A tailgate at the end of the channel is installed to control the flow depth within the flume to have the desire tailwater depth to get the location of the hydraulic jump (Figure 1). The water flowing in the channel is transferred to a tank at the end, where the discharge can be measured using a v-notch weir installed on the concrete wall of the tank, for which a calibration curve has been previously prepared. Two parallel rails are installed on the top of the flume's wall body to move a point gauge with an accuracy of 1 mm for measuring the downstream water depth (y_2). In this research, two models of CSS and GSS were constructed to investigate their relative energy dissipation and hydraulic characteristics, as well as a simple chute as a control model with a smooth glass surface with three slopes of 21.8, 26.6, and 33.7 degrees. The width of the constructed physical models of the GSS was 56 cm, and the number of steppes was 4, 6, and 8 with heights of 15, 10, and 7.5 cm, respectively. The porosity of the gabion baskets was 40 percent. To determine the porosity percentage, the volume of the aggregates was measured by pouring them into a graduated glass cube and measuring the rise in the water level in the cube, and then subtracting it from the total volume of the gabion basket. The porosity is obtained from the remaining number divided by the total volume of the gabion box according to Equation (4):

$$e=\frac{V_{void}}{V_{total}} \quad (4)$$

In Equation (4), V_{void} is the void volume in cubic centimeters and V_{total} is the total volume of the gabion unit. The size of the rock aggregates was determined using sieves between diameters of 12.7 to 16 mm with D_{50}= 14 mm and a porosity of 40 percent. Figure (2) shows a view of the flume and how the gabion baskets are placed on the stepped spillways. The total height (H) was constant and equal to 60 cm.

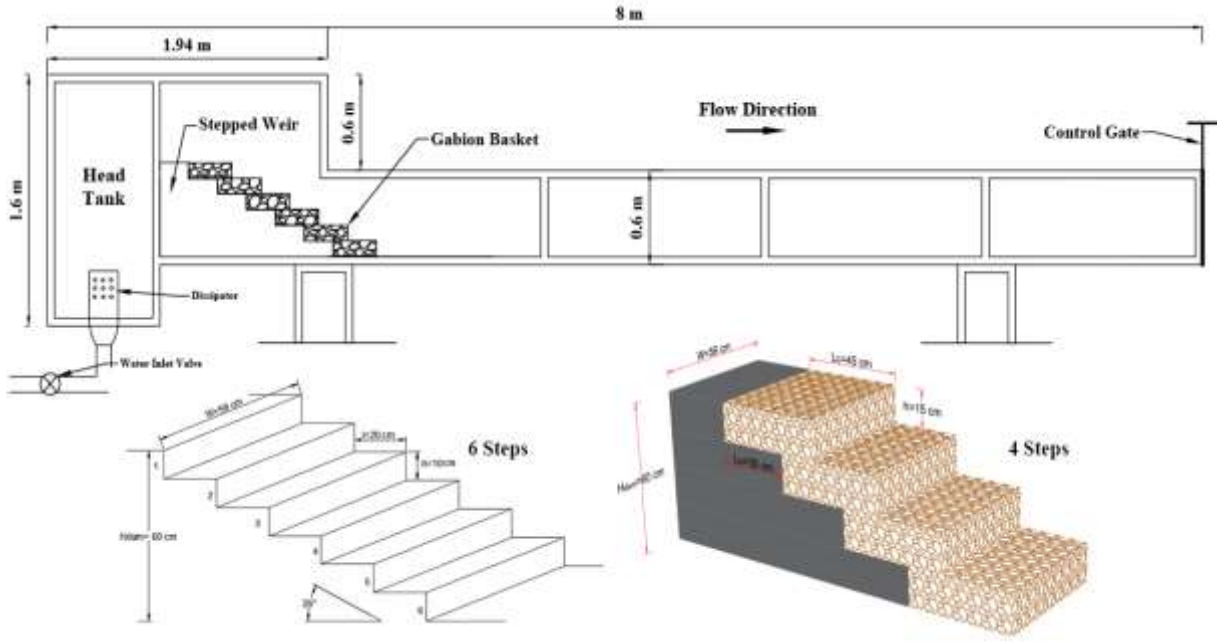


Fig. 1- Plan view of the experimental flume and the geometric and hydraulic dimensions of the gabion-stepped spillway with 4 and 6 steps



Fig. 2- A view of the experimental flume with a rigid stepped spillway and the arrangement of gabion baskets on the stepped spillway

The upstream energy of the spillway is calculated as follows:

$$E_0 = (H + y) + \frac{q^2}{2g(H + y)^2} \qquad (5)$$

Given that the second term in Equation (5) is negligible due to the low approaching flow velocity in the stilling basin, and since the flow over the spillway forms a critical depth, the equation can be simplified as:

$$E_0 = H + y = H + \frac{3}{2}y_c \qquad (6)$$

In the above equation, H represents the total height of the spillway, y is the flow depth above the crest, and y_c is the critical flow depth.

For each series of experiments, after setting up the model and establishing steady-state conditions, different flow discharge were applied to each model. Various parameters,

including the flow depths upstream and downstream of the spillway, as well as the flow depth downstream of the jump; roller length and jump length were measured. The flow was controlled using the downstream gate to ensure that the hydraulic jump occurred at the toe of the spillway. The Sequent depth upstream of the hydraulic jump, y_1 (point 1 at the end of the slope and before the hydraulic jump), could not be measured directly due to high turbulence, aeration, and chaotic flow conditions at the toe of the spillway. Therefore, y_1 was calculated using the Belanger equation (Equation 7) and the downstream flow depth y_2 (Chow, 1973).

$$\frac{y_1}{y_2} = \frac{1}{2}(\sqrt{(1 + 8Fr_2^2} - 1) \quad (7)$$

The relative energy dissipation is defined as:

$$\frac{\Delta E}{E_0} = \frac{E_0 - E_1}{E_0} = 1 - \frac{E_1}{E_0} \quad (8)$$

Tables (1) and (2) present the range of parameter variations and the naming convention for the models used in this study, respectively. In the hydraulic jumps observed during the experiments, the roller length was measured as the distance from the start of the jump to the last rolling wave. The jump length was defined as the distance from the start of the jump to a point on the water surface immediately after the last rolling wave, where the height of this point is approximately equal to the tailwater elevation.

Table 1- Range of Parameter Variations in This Study

Range of Variations	Q (Lit/s)	$\frac{y_2}{y_1}$	s	N	Fr_1	v_1	Re	$\frac{L_r}{y_2}$	$\frac{L_j}{y_2}$
Min	30	2.68	21.8	4	2.10	1.323	67314	1.22	3.73
Max	50	5.26	35	8	7.81	3.603	110944	2.90	5.85

Table 2- Naming Convention for the Models Constructed in This Study

Description	Model	Description	Model	Description	Model
8 steps	N_3	6 steps	N_2	4 steps	N_1
Slope of 33.7 degrees	s_3	Slope of 26.6 degrees	s_2	Slope of 21.8 degrees	s_1
Stepped Spillway Models (S)					
8-step stepped spillway with a slope of 21.8 degrees	Ss_1N_3	6-step stepped spillway with a slope of 21.8 degrees	Ss_1N_2	4-step stepped spillway with a slope of 21.8 degrees	Ss_1N_1
8-step stepped spillway with a slope of 26.6 degrees	Ss_2N_3	6-step stepped spillway with a slope of 26.6 degrees	Ss_2N_2	4-step stepped spillway with a slope of 26.6 degrees	Ss_2N_1
8-step stepped spillway with a slope of 33.7 degrees	Ss_3N_3	6-step stepped spillway with a slope of 33.7 degrees	Ss_3N_2	4-step stepped spillway with a slope of 33.7 degrees	Ss_3N_1
Gabion-Stepped Spillway Models (G)					
8-step gabion-stepped spillway with a slope of 21.8 degrees	Gs_1N_3	6-step gabion-stepped spillway with a slope of 21.8 degrees	Gs_1N_2	4-step gabion-stepped spillway with a slope of 21.8 degrees	Gs_1N_1
8-step gabion-stepped spillway with a slope of 26.6 degrees	Gs_2N_3	6-step gabion-stepped spillway with a slope of 26.6 degrees	Gs_2N_2	4-step gabion-stepped spillway with a slope of 26.6 degrees	Gs_2N_1
8-step gabion-stepped spillway with a slope of 33.7 degrees	Gs_3N_3	6-step gabion-stepped spillway with a slope of 33.7 degrees	Gs_3N_2	4-step gabion-stepped spillway with a slope of 33.7 degrees	Gs_3N_1
Chute Models (C)					
Chute with a slope of 33.7 degrees	Cs_3	Chute with a slope of 26.6 degrees	Cs_2	Chute with a slope of 21.8 degrees	Cs_1

Results and Discussion

Observations – Flow Regime Transition

At the beginning of each experiment, it was observed that at low flow rates and high step heights on the stepped spillway, the flow formed a nappe flow regime. In this regime, the water cascaded over the edge of each step, falling freely onto the lower step. Energy dissipation occurred through the mixing of water and air, and incomplete hydraulic jumps were occasionally observed on the steps. In the nappe flow regime, the total height of the spillway was divided into several vertical waterfalls, and at low slopes, the flow sometimes leaped over specific steps, rendering them ineffective (Figure 3). As the flow rate increased, the flow depth over the steps also increased, and the steps partially lost their role, acting more like roughness elements as the flow transitioned to a skimming flow regime. When gabion blocks were placed on the steps, the flow was divided into two parts: overtopping and infiltrating. The flow became highly turbulent upon colliding with the aggregates inside the gabions.

Although the amount of air entrainment was not measured in this study, if the number of air bubbles is considered as an indicator of turbulence, observations showed that compared to control experiments on the stepped spillway and simple chute, the number of air bubbles within the flow was higher and increased significantly with a decrease in slope and the number of steps. Based on the observations and results obtained, it was found that in spillways where flow regime transitions (from nappe to transitional or transitional to skimming) occur, the difference in energy dissipation is more pronounced. Table (3) presents the flow regime transitions for models with different slopes and step numbers, showing the regime change using the parameter yc/h (where yc is the critical depth, representing the flow rate, and h is the step height). For example, in a gabion-stepped spillway with 4 steps and a slope of 33.7 degrees, the flow remained nappe up to yc/h=0.54 (flow rate of 40 liters per second). As the flow rate increased, the flow transitioned from nappe to transitional, and at yc/h=0.62 (flow rate of 50 liters per second), it transitioned from transitional to skimming. The parameter yc/h was selected for comparison with other researchers who have studied this field (Table 4).



Fig. 3- Interaction of water with steps on the stepped spillway and the formation of an incomplete hydraulic jump.

Table 3- Flow Regime Transition in Stepped and Gabion-Stepped Spillways

Slope (degree)	Weir	Number of Steps	Height of Steps (cm)	y_c/h			
				$NA. to TRA.$	Discharge of changing	$TRA. to SK.$	Discharge of changing
33.7	Stepped	4	15	TRA	-	0.62	Q=50 lit/s
		6	10	TRA	-	0.87	Q=45 lit/s
		8	7.5	TRA	-	1.07	Q=40 lit/s
	Gabion-Stepped	4	15	0.54	Q=40 lit/s	0.62	Q=50 lit/s
		6	10	TRA	-	0.93	Q=50 lit/s
		8	7.5	TRA	-	1.16	Q=45 lit/s
26.6	Stepped	4	15	0.49	Q=35 lit/s	TRA	-
		6	10	0.74	Q=35 lit/s	TRA	-
		8	7.5	TRA	-	1.24	Q=50 lit/s
	Gabion-Stepped	4	15	0.54	Q=40 lit/s	0.62	Q=50 lit/s
		6	10	0.80	Q=40 lit/s	TRA	-
		8	7.5	TRA	-	TRA	-
21.8	Stepped	4	15	0.62	Q=50 lit/s	TRA	-
		6	10	0.74	Q=35 lit/s	TRA	-
		8	7.5	TRA	-	TRA	-
	Gabion-Stepped	4	15	NA	-	NA	-
		6	10	0.80	Q=40 lit/s	TRA	-
		8	7.5	TRA	-	TRA	-

NA : Nappe Flow * TRA : Transition Flow * SK : Skimming Flow

Table 4-Flow Regime Transition in Previous Studies

Researcher	Slope (degrees)	Number of Steps	Step Height (cm)	Model	y_c/h	
					$NA. to TRA.$	$TRA. to SK.$
Wuthrich & Chanson (2014)	26.6	10	10	Stepped Spillway	0.50	0.90
				Gabion-Stepped Spillway	0.60	0.90
Gonzalez et al. (2008)	21.8	10	10	Stepped Spillway	0.64	0.97
				Rough-Bed Spillway	0.64	0.97

In Figure (4), a gabion-stepped spillway with 6 steps and a slope of 33.7 degrees is compared at flow rates of 30 and 50 liters per second. As observed in Figure 4-a, at the minimum flow rate (30 liters per second), the nappe flow regime is dominant. In this regime,

the flow not only passes through the porous gabion but also forms an incomplete hydraulic jump on the final step, which contributes to increased energy dissipation. With an increase in flow rate (Figure 4-b), the flow regime first tends toward a transitional regime and then transitions to a skimming flow regime. In this regime, the gabion steps act like large roughness elements along the flow path, resulting in a significant reduction in energy dissipation compared to the nappe flow regime.

One of the most important benefits of gabions is their ability to control flow energy at high velocities and prevent cavitation due to the infiltrating flow passing through them. In Figure (5-a) 4-step stepped spillway with the same slope and flow rate is shown in two conditions: without gabions (Figure 5-a) and with gabions (Figure 5-b). The effect of gabions on controlling flow energy is clearly evident.



(a) **(b)**

Fig. 4- Flow regime transition at two flow rates of 30 (a) and 50 liters per second (b) in a 6-step gabion-stepped spillway with a slope of 33.7 degrees.



(a) **(b)**

Fig. 5- The effect of gabions on energy dissipation with infiltrating flow in a 4-step spillway model with a slope of 33.7 degrees and a flow rate of 30 liters per second. (a) Stepped spillway, (b) Gabion-stepped spillway.

Energy Dissipation

1. Effect of Slope on Energy Dissipation

In stepped spillways, as the flow rate increases, the role of steps in energy dissipation decreases. With a constant number of steps, a reduction in slope and the consequent increase in step length causes the flow to tend toward a nappe flow regime. At low flow rates, a complete or sometimes incomplete hydraulic jump form on each step. However, in gabion-stepped spillways, energy dissipation is significantly higher compared to both stepped spillways and simple chutes. This is due to the presence of gabion baskets on the steps. Although in nappe flow regimes, gabions prevent the formation of an air cushion at the lower edge of the step (which is a factor in the formation of jumps on the step), they allow the flow to pass through the porous aggregate within the gabions, thereby dissipating energy. In Figures (6-a) and (6-b), two gabion-stepped spillway models with the same flow rate and number of steps but different slopes (33.7° and 21.8°, respectively) are shown to investigate the effect of slope. As seen in Figure 5-a, the skimming flow regime dominates, transitioning to a transitional regime at the end, and the steps largely lose their role as energy dissipaters. In contrast, in Figure (6-b) with a slope of 21.8°, the flow regime transitions from skimming to transitional and then to nappe, playing a much greater role in energy dissipation. As evident from the images, reducing the slope and increasing the step length enhances energy dissipation.

The effect of slope on relative energy dissipation ($\Delta E/E0$) for stepped and gabion-stepped spillways, averaged over the number of steps, and for the chute model, is plotted against the dimensionless parameter q^2/gH^3 (drop number) in Figure (7). As shown in the graph, with a constant spillway height, increasing the flow rate per unit width (q) reduces the relative energy loss. In fact, as the depth increases, the effects of the laminar sublayer on the velocity profile diminish, and the shear stress on the flow decreases.

Looking at the lower part of the graph, which examines energy dissipation percentages for the chute model, the maximum energy dissipation occurs at the mildest slope (21.8°) and the minimum flow rate, amounting to 34.8%. Observations suggest that the primary factor influencing energy dissipation in the chute model is the flow path length, which is why the slope has the most significant impact on energy loss. In all models, reducing the slope increases energy dissipation.

The highest energy dissipation occurs in the gabion-stepped spillway with a slope of 21.8° and at the minimum flow rate, averaging 79.5%. Compared to the maximum energy dissipation in the stepped spillway and chute model at the same slope, this is 9.4% and 44.7% higher, respectively, highlighting the impact of gabion baskets on flow turbulence and aeration. The average percentage of energy dissipation, the ratio of jump length to secondary flow depth, and the conjugate depth ratio for different step numbers and slopes are summarized in Table (5) for comparison. According to the table, the highest average energy dissipation occurs in the gabion-stepped spillway with a slope of 21.8°, which also has the lowest ratio of jump length to secondary flow depth and the lowest conjugate depth ratio. Therefore, reducing the slope increases energy dissipation because it increases the step length and, in the case of gabion-stepped spillways, the length of the shared section. This brings the flow closer to the nappe regime, causing incomplete or complete jumps on the steps and enhancing mixing.

The graphs in Figure (8) plot the relative energy loss against slope for an 8-step spillway at different flow rates. The analysis reveals that reducing the slope increases the relative energy loss. Additionally, the relationship between slope and relative energy loss follows a similar trend across all flow rates. Comparing the two models (stepped and gabion-stepped spillways), it is evident that the increase in energy loss follows a parallel trend, with the gabion-stepped spillway exhibiting higher energy dissipation in all cases.



(a) **(b)**

Fig. 6- Gabion-Stepped Spillway with 6 Steps. (a) Slope of 33.7° at a flow rate of 50 liters per second. (b) Slope of 21.8° at a flow rate of 50 liters per second.

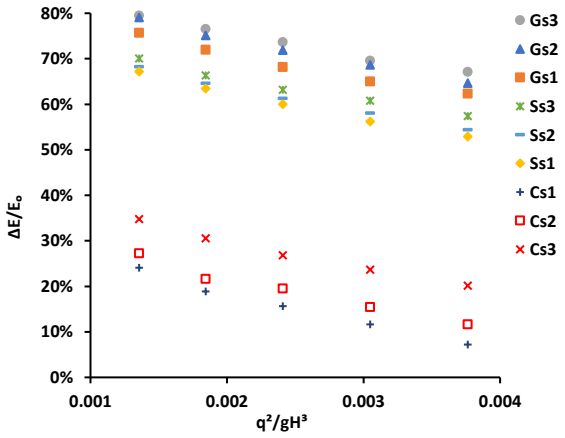
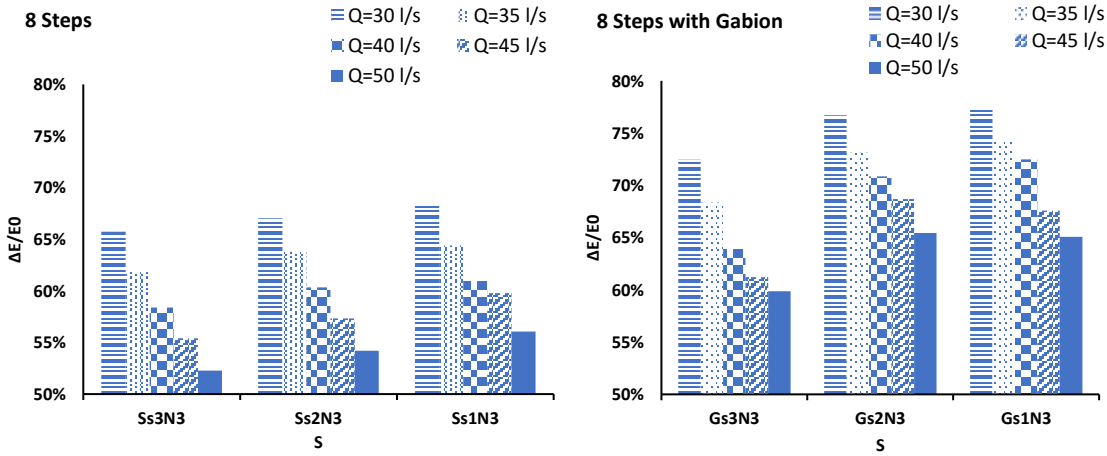


Fig.7- Effect of Slope on Energy Dissipation (Averaged Over Step Numbers)



(a) **(b)**

Fig. 8- Variation of Relative Energy Loss with Slope, (a) Stepped Spillway, (b) Gabion-Stepped Spillway

Table 5- Average Results of Energy Dissipation, Jump Length to Secondary Flow Depth Ratio, and Conjugate Depth Ratio for Different Stepp Numbers and Slopes

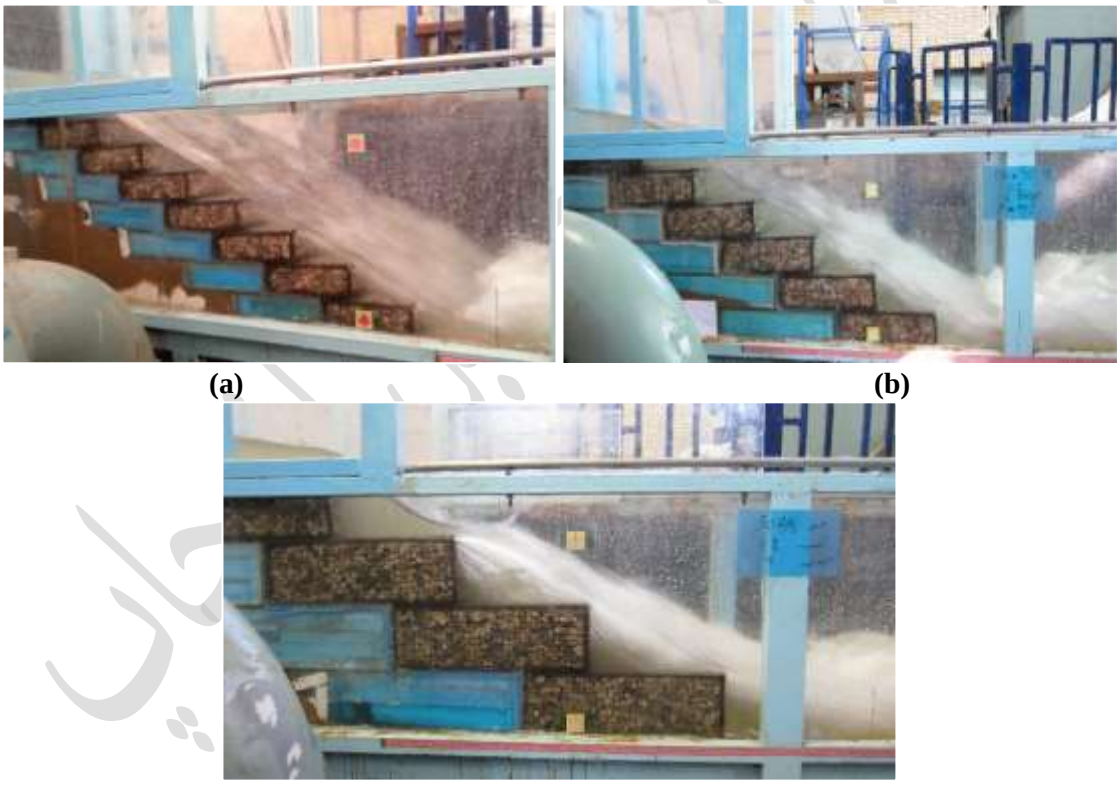
Model	Slope (degree)	Q (Lit/s)	$\Delta E/E_0$	L_j/y_2	y_2/y_1
Rigid Stepps	33.7	50	52.9%	5.828	5.406
		45	56.3%	5.737	5.322
		40	60.1%	5.703	5.186
		35	63.5%	5.672	5.108
		30	67.2%	5.541	4.996
	26.6	50	54.4%	5.744	5.240
		45	58.1%	5.679	5.107
		40	61.3%	5.566	5.033
		35	64.6%	5.312	4.959
		30	68.2%	5.010	4.853
	21.8	50	57.4%	5.363	4.898
		45	60.8%	5.307	4.798
		40	63.2%	5.229	4.733
		35	66.4%	5.157	4.668
		30	70.1%	5.006	4.562
Gabion-stepped	33.7	50	62.4%	5.463	4.336
		45	65.0%	5.380	4.215
		40	68.2%	5.235	4.067
		35	72.0%	5.103	3.849
		30	75.7%	4.759	3.608
	26.6	50	64.7%	5.225	4.019
		45	68.7%	5.109	3.744
		40	71.9%	4.946	3.546
		35	75.2%	4.429	3.350
		30	79.1%	4.050	2.989
	21.8	50	67.2%	4.846	3.694
		45	69.6%	4.688	3.612
		40	73.7%	4.582	3.304
		35	76.5%	4.215	3.104
		30	79.5%	3.907	2.908
Chute	33.7	50	7.2%	6.066	9.85
		45	11.7%	6.053	9.91
		40	15.7%	5.991	10.07
		35	18.9%	5.969	10.37
		30	24.1%	5.955	10.55
	26.6	50	11.6%	6.073	9.632
		45	15.5%	6.044	9.632
		40	19.5%	5.981	9.603
		35	21.7%	5.928	9.718
		30	27.3%	5.917	9.713
	21.8	50	20.2%	6.009	8.68
		45	23.7%	5.963	8.77
		40	26.8%	5.862	8.94
		35	30.6%	5.829	9.11
		30	34.8%	5.765	9.30

2. Effect of Number of stepp on Energy Dissipation

In stepped spillways, the total height of the spillway is divided into a series of steps, making the number of steps a critical factor in energy dissipation. In nappe flow regimes, the total height consists of several vertical waterfalls, and the flow can form complete or incomplete hydraulic jumps (depending on the horizontal length of the steps) as it impacts successive steps. In non-nappe flow regimes, the steps act like large roughness elements, and the flow passes over them coherently and parallel to the spillway slope. Additionally, a vortex region is often observed at the edge of each step.

In Figure (9), three different models of GSS with 8, 6, and 4 steps, a slope of 26.6°, and a flow rate of 50 liters per second are compared. Due to the constant total height of the spillway (H), the 8-step spillway has shorter step heights (h), reducing the effectiveness of each step on energy dissipation. As shown in Figure 9-a, the flow is predominantly skimming.

In Figure (9-b), the 6-step spillway initially exhibits skimming flow, transitioning to a transitional regime at the end, demonstrating the effect of fewer steps and increased step height. However, in the 4-step spillway (Figure 9-c), the flow tends toward a nappe regime, cascading over the gabion baskets and forming incomplete hydraulic jumps. The more intense impact with the aggregates results in greater flow dispersion and energy dissipation.



(a) **(b)**

(c)

Fig. 9- Comparison of gabion-stepped spillways with 8 steps (a), 6 steps (b), and 4 steps (c) at a slope of 26.6° and a flow rate of 50 liters per second.

The average results of energy dissipation percentage, the ratio of jump length to secondary flow depth, and the ratio of conjugate depths for various slopes for each number of steps are presented in Table (6). According to the table, the highest average percentage of energy dissipation is associated with the 4-step gabion stepped spillway model with a flow rate of 30 liters per second, where the lowest ratio of jump length to secondary flow depth also occurs in this model.

In Figure (10), the effect of different numbers of steps on the energy dissipation of stepped and gabion stepped spillways is examined by averaging across all three slopes. As observed in the graph, as the number of steps increases and the step height decreases, energy dissipation decreases. In other words, an increase in flow rate leads to the formation of skimming flow, which reduces the effect of step roughness on energy dissipation. Alternatively, as the number of steps increases (with a decrease in step height) and the flow transitions from nappe to skimming flow, the turbulence and the impact of steps on flow resistance diminish, resulting in reduced energy dissipation.

Table 6- Average Results of Energy Dissipation, Jump Length to Secondary Flow Depth Ratio, and Conjugate Depth Ratio for Different Slopes and Step Numbers

Model	Number of Steps	Q (Lit/s)	$\Delta E/E_0$	L_j/y_2	y_2/y_1
Rigid Steps	4	50	55.8%	5.496	5.083
		45	59.8%	5.375	4.893
		40	63.4%	5.298	4.751
		35	66.7%	5.146	4.662
		30	70.2%	4.959	4.534
	6	50	54.8%	5.691	5.196
		45	57.8%	5.614	5.136
		40	61.2%	5.547	5.042
		35	64.5%	5.455	4.969
		30	68.4%	5.218	4.836
	8	50	54.2%	5.749	5.266
		45	57.5%	5.733	5.198
		40	59.9%	5.653	5.159
		35	63.3%	5.539	5.105
		30	67.0%	5.379	5.041
Gabion-Stepped	4	50	68.4%	4.989	3.536
		45	71.2%	4.854	3.382
		40	74.4%	4.660	3.172
		35	77.7%	4.197	2.900
		30	80.6%	3.842	2.699
	6	50	62.4%	5.265	4.306
		45	66.2%	5.137	4.077
		40	70.3%	5.035	3.790
		35	74.0%	4.708	3.536
		30	78.3%	4.315	3.141
	8	50	63.5%	5.279	4.208
		45	65.8%	5.185	4.112
		40	69.1%	5.068	3.955
		35	72.0%	4.842	3.866
		30	75.5%	4.558	3.664
Chute		50	13.0%	6.049	9.386
		45	17.0%	6.020	9.437
		40	20.7%	5.944	9.538
		35	23.7%	5.909	9.732
		30	28.7%	5.879	9.855

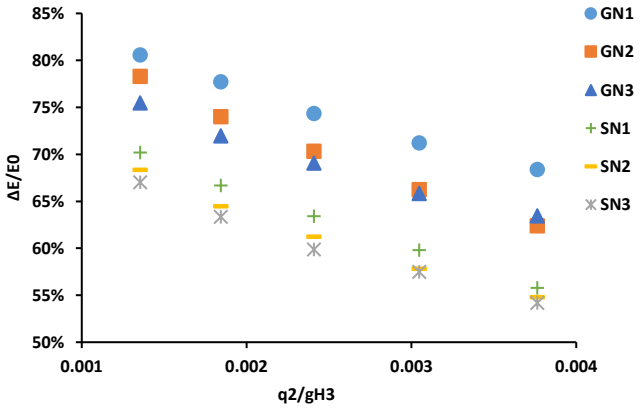
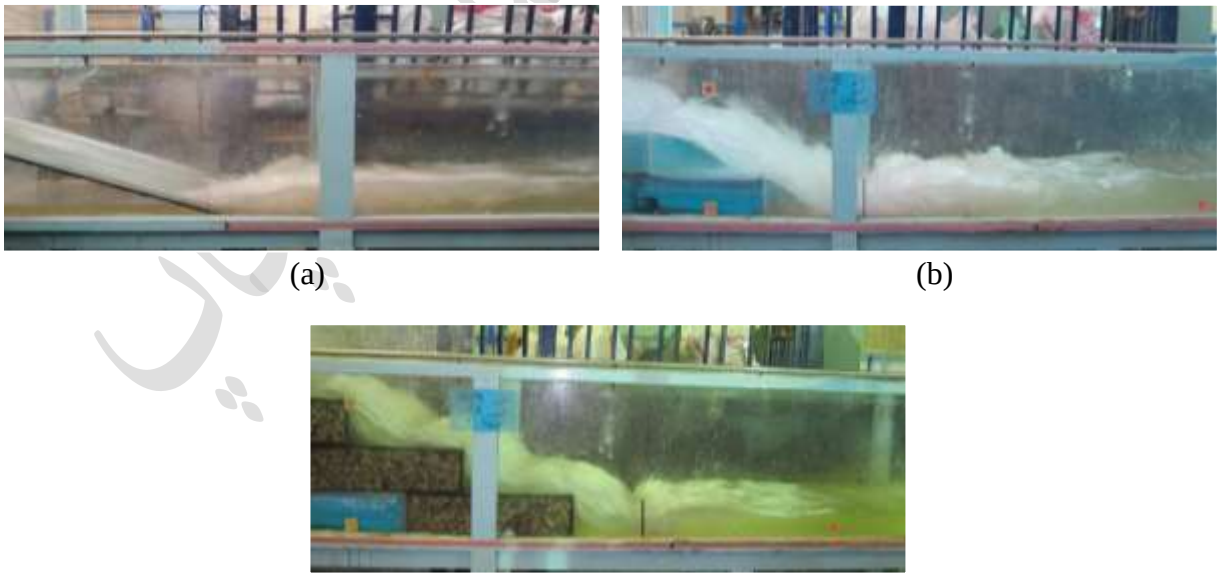


Fig. 10- Effect of step number on energy dissipation in stepped and gabion-stepped spillways, averaged over slopes.

Characteristics of Hydraulic Jump Downstream

In this section, the characteristics of the hydraulic jump downstream of the spillway, including sequent depth and hydraulic jump length, are examined. Then, the effects of slope and the number of steps on these parameters are analyzed. As shown in Figure (11), the jump length and roller length in the case of the GSS (Figure 11-c) are significantly shorter than those of the stepped spillway (Figure 11-b) and the chute (Figure 11-a). The reason for this is the greater turbulence and lower flow velocity in gabion stepped spillways, as well as the resistance provided by the gabion aggregates, which disperses the flow and causes energy dissipation before reaching the base of the slope. In general, gabion stepped spillways, due to the presence of gabions, have a greater ability to control the water flow, which results in a reduction in hydraulic jump length and roller length.



(a) (b)

(c)

Fig. 11- A view of the hydraulic jump downstream of the chute (a), the 4-step stepped spillway (b), and the 4-step gabion stepped spillway (c) at a slope of 21.8 degrees and a flow rate of 30 liters per second.

1. Effect of Slope

The relative values of conjugate depths versus the Froude number for both stepped and gabion stepped spillways at different slopes, averaged over the number of steps, are plotted in Figure (12). This graph indicates that the relative conjugate depths in both stepped and gabion stepped spillways increase with an increase in flow rate. Additionally, as shown in Figure (12-a), the relative conjugate depth ratio increases with an increase in the slope of both the gabion structure and the stepped spillway. A decrease in slope in the gabion spillway, due to high turbulence, leads to an increase in the initial depth and a decrease in the secondary depth of the jump, which is fully justified by the energy diagram in hydraulic discussions. Furthermore, the ratio of conjugate depths in the stepped spillway, due to its low initial depth and high secondary jump depth, is greater than that in gabion spillways. In contrast, this ratio in the chute model is approximately 2 to 4 times higher than in stepped and gabion stepped spillways, with an average value of 9.6. The range of percentage reduction in conjugate jump depth at different flow rates varies from 20.1% in the 8-step stepped spillway with a 21.8-degree slope to 35.8% in the 4-step gabion stepped spillway with the same slope.

In Figure (12-b), the variations in the ratio of jump length to secondary depth versus the Froude number for stepped and gabion stepped spillways are plotted to examine the effect of slope on the reduction of jump length, averaged over the number of steps. As observed, this ratio is lower in gabion stepped spillways because the placement of gabion baskets on the spillway divides the flow into overpass and through-pass sections, increasing flow turbulence as the water collides with these baskets. With increased turbulence and reduced velocity, the initial depth of the jump increases, leading to a decrease in the Froude number. This results in greater energy dissipation and a reduction in the hydraulic jump length. Overall, the conditions indicate that, based on the above points, a decrease in slope, especially at low flow rates, is a contributing factor to the reduction in hydraulic jump length.

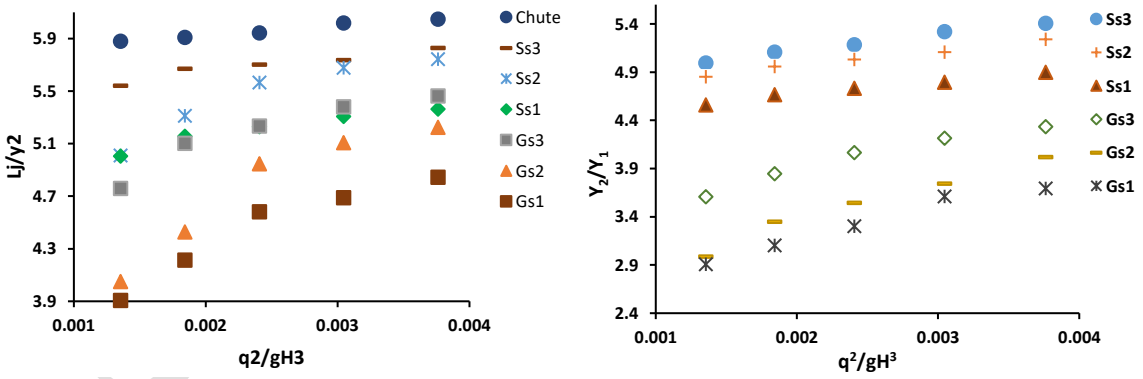


Fig. 12- Variations in the relative values of conjugate depths (a) and the ratio of jump length to secondary depth (b) of the hydraulic jump versus the Froude number, averaged over the number of steps.

2. Effect of the Number of Steps

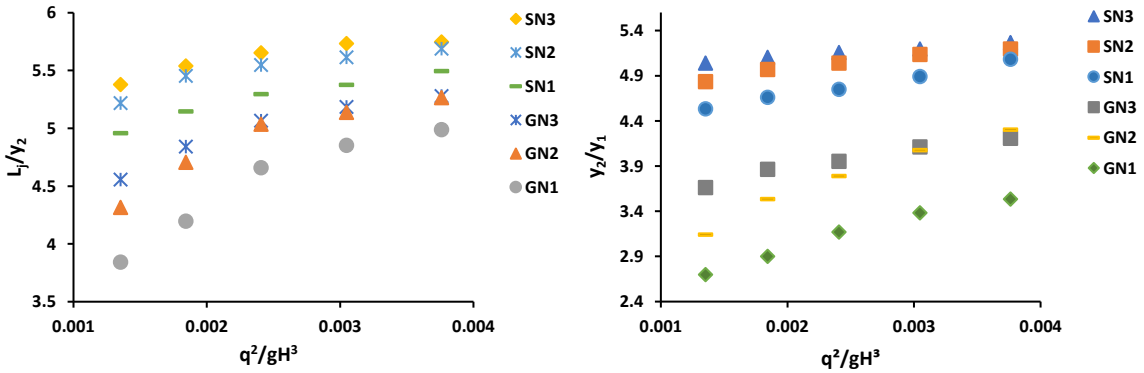
The relative values of conjugate depths versus the Froude number for both stepped and gabion stepped spillways, with different numbers of steps and an average slope, are plotted in Figure (13-a). According to the graph, as the flow rate per unit width increases, the ratio of conjugate depths also increases. Additionally, as the number of steps increases, the flow depth over the spillway increases (forming skimming flow), the initial flow depth decreases, and the secondary depth of the jump increases.

In Figure (13-b), the variations in the ratio of jump length to secondary depth versus the Froude number for stepped and gabion stepped spillways are plotted to examine the effect of the number of steps on the reduction of jump length, averaged over the slope. According to the graph, the 4-step spillway shows a significant difference compared to the 6-step and 8-step spillways in terms of reducing jump length. This is due to the larger step dimensions, the formation of nappe flow, and ultimately, greater energy dissipation in this spillway compared to the other two models.

To demonstrate the difference in conjugate depths between stepped and gabion stepped spillways compared to the average chute model, the depth reduction parameter is defined as follows:

$$D^* = \frac{y_2{}^* - y_2}{y_2{}^*} \qquad (9)$$

In this equation, $y_2{}^*$ represents the secondary depth of the jump in the chute model, and y_2 represents the secondary depth of the jump in the stepped and gabion stepped spillway models. The results of conjugate depth reduction for different models are presented in Table (7). As shown in the table, the highest percentage of depth reduction generally corresponds to the 4-step spillway, which has larger step dimensions.



(a) (b)

Fig.13- Variations in relative conjugate depths (a) and the ratio of jump length to secondary depth (b) of the hydraulic jump versus the Froude number for different numbers of steps, averaged over the slope.

Table 7- Average percentage reduction in conjugate jump depth for stepped and gabion stepped spillway models compared to the chute.

Average Discharge	Averaged Slope	Weir Model	Number of Steps	D^*
Q	S	Stepped	4	23.1
			6	21.6
			8	20.9
		Gabion-Stepped	4	35.2
			6	30.3
			8	28.8

To calculate the percentage reduction in hydraulic jump length, Equation (10) can be used. In this equation, Lj^* represents the average jump length downstream of the chute model, and Lj represents the jump length in the stepped and gabion stepped spillway models.

$$T^* = \frac{L_j{}^* - L_j}{L_j{}^*} \qquad (10)$$

The shortest jump length across all models corresponds to the 4-step gabion stepped spillway with a slope of 21.8 degrees and a flow rate of 30 liters per second, which is equal to 36 cm. The average percentage reduction in jump length for different models is provided in Table (8).

Figure (14) compares the results of the present study with those of Peyras et al. (1992), Chinnarasri et al. (2008), and Wuthrich & Chanson (2014). In this figure, for better comparison with other researchers, the gabion stepped spillway with a slope of 26.6 degrees—the slope used by most researchers—was selected for different numbers of steps.

Given that the experiments conducted by Chinnarasri et al. and Wuthrich & Chanson (2014) were performed with a larger number of steps, the formation of skimming flow reduced the effect of steps on flow resistance, resulting in decreased energy dissipation. Table (9) shows the range of variables in the compared studies.

Table 8- Average percentage reduction in jump length for stepped and gabion stepped spillway models compared to the chute.

Average Discharge	Averaged Slope	Weir Model	Number of Steps	T^*
Q	S	Stepped	4	31.6
			6	27.8
			8	27
		Gabion-Stepped	4	50.3
			6	41.5
			8	40.4

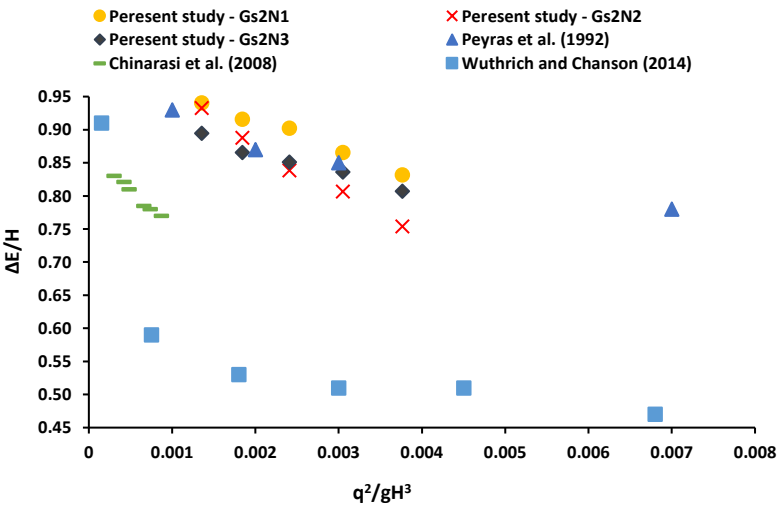


Fig. 14- Comparison of relative energy dissipation in this study with other research studies

Table 9- Comparison of the range of variables in this study with those of other researchers.

Researcher	Q (lit/s)	D_{50} (mm)	Slope (degree)	Number of Steps	Width of flume (cm)	Height of Steps (cm)
Present Research	30-50	14	26.6	4-6-8	56	15-10-7.5
Wuthrich & Chanson (2014)	5-114	14	26.6	10	52	10
Chinnarasri et al. (2008)	4-68	50-70	30	20	40	7.5
Peyras et al. (1992)	50-200	30-45	26.6	4	80	100

Given that these experiments were conducted under different laboratory conditions and ranges of parameters, and considering the trend in this figure, it can be concluded that the use of stepped spillways with gabion baskets can be an effective method for energy dissipation compared to other conventional energy dissipation methods.

The analysis of the planned experiments in this study demonstrates that the presence of steps, particularly gabion-type steps with overpass and through-pass flows, has a significant impact on the energy dissipation of the structure (in some cases, more than 80% of the initial energy is dissipated). This energy dissipation greatly affects the dimensions of the downstream stilling basin and may even eliminate the need for a stilling basin under standard conditions. Such structures, especially gabion stepped spillways, are highly suitable for natural sloped soil channels and drainage paths designed for flood discharge. In addition to preventing channel erosion, they offer significant cost savings by eliminating the need for protective structures and energy dissipators such as stilling basins.

Conclusion

The main objective of this study was to investigate the effect of the number of steps in gabion stepped spillways on flow conditions and hydraulic characteristics. To achieve this goal, two models of gabion stepped spillways, one model of a stepped spillway, and one simple chute model (as a control) were constructed for comparison. By placing gabion bundles on the stepped spillway, the relative energy dissipation increased across all slopes. Additionally, in all slopes and step numbers, the relative energy dissipation of the gabion stepped spillway was higher than that of the control models (stepped spillway and simple chute).

With an increase in the Froude number in all models, the formation of non-nappe flow and the reduced effect of step roughness led to a decrease in relative energy dissipation. This decrease was more pronounced in the 4-step model, while the 6-step and 8-step models showed nearly similar values. Furthermore, with an increase in the Froude number (flow rate) across different slopes, the relative energy dissipation values for different step numbers converged.

For the same number of steps, the relative energy dissipation was highest at a slope of 21.8 degrees and lowest at a slope of 35 degrees. In general, it can be concluded that energy dissipation in gabion stepped spillways increased by up to 81.5% compared to the upstream energy, which is 9.8% and 46.7% higher than the maximum energy dissipation in the stepped spillway and chute models, respectively, at the same slope. Additionally, in gabion stepped spillways, the overall energy dissipation increased by 9% to 20% compared to stepped spillways and by 55% to 74.3% compared to the chute model.

The ratio of conjugate jump depths decreased with a reduction in spillway slope (from 35 degrees to 26.6 degrees or from 26.6 degrees to 21.8 degrees) and a decrease in the number of steps. This ratio decreased by 26.2% to 35.8% in gabion stepped spillways and by 20.1% to 23.3% in stepped spillways compared to the chute model.

The jump length showed the highest percentage reduction in hydraulic jump length compared to the chute model in the gabion stepped spillway at a slope of 21.8 degrees, 4 steps, and a flow rate of 30 liters per second (minimum flow rate), with a reduction of

63.3%. The lowest reduction occurred at a slope of 35 degrees, 8 steps, and a flow rate of 50 liters per second (maximum flow rate), with a reduction of 31.1%. On average, the reduction was 44.1% for all gabion models and 28.8% for stepped spillway models.

A comparison of the results of this study with other energy dissipation methods indicates that this method can be considered an effective approach for energy dissipation.

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Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article. Confirmation.

Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contribution

First Author: Afshin Mahjoubi (33.3%),
Second Author: Seyed Mahmood Kashefipour (33.3%),
Third Author: Niloofar Kianersi(33.3%).

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