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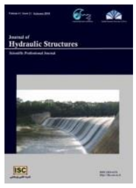

Dimensionless Equations for Hydraulic Jump Stilling Basins Downstream of Gabion Stepped Chutes

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Abstract

Flows in stepped chutes built with gabions have been studied for about four decades and have found applications mainly in small dams and drainage systems. This paper presents a literature review of experimental studies on the subject, especially those that published data and methodologies for designing stepped chutes in gabions. A dimensionless methodology for predicting the main design variables is proposed, and equations were proposed for this purpose. These equations, based on physical principles and statistically supported, involve characteristics of stilling basins of hydraulic jump downstream of stepped chutes formed by gabions and the main quantities related to the design of these hydraulic structures. More than 160 data points were used, each of them involving several parameters of the adopted physical models, making the proposed methodology valid for five different slopes of the downstream face of the stepped chutes. The new equations allow for calculating the length and elevation of the stilling basin bottom. They also allow the determination of the supercritical depth at the basin inlet and the estimation of the height of the continuous end sill of the stilling basin. The proposed equations present strong correlations and adherence to the experimental data in the literature and reveal the missing data about the subject considering the existing literature. In addition, an application example illustrates the use of the developed methodology and compares the present results with those obtained from a methodology available in the literature.

Keywords: energy dissipation; gabion structures; hydraulic jump; stepped chutes; stilling basin.

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1. Introduction

The understanding of flow characteristics in stepped spillways has advanced significantly over the past four decades, leading to an increase in the number of dams incorporating stepped chutes. This research has not only improved the design of larger structures but has also helped the development of smaller hydraulic structures, such as "water cascades" on steep terrains, drainage stairways, and decorative architectural features. Additionally, exploring alternative materials for constructing small dams with stepped spillways has promoted the use of gabions, which offer stability and substantial energy dissipation, as noted by [1].

Considering the study of gabions as porous/permeable materials to build weirs, several studies considering only one step, or, in other words, a weir using only one gabion, may be found in the literature. These studies involve general characteristics of the flows, like weir height and length, discharge, upstream and downstream water depths, gravel mean size, porosity, among others [2]; the relation between the flows over and through the gabion [3, 4]; the measurement of velocities and flow rates [5]; the study of the hydrodynamics of the porous weir and the proposition of nondimensional equations [6]; the energy dissipation [7]; dimensional analyses for discharge coefficients [8, 9]; and upstream and downstream slopes [10]. The conclusions of one-gabion weirs are also used to understand better the characteristics of stepped chutes and spillways built with multiple gabions.

Considering stepped chutes, [11] conducted experiments on gabion-formed stepped chutes with values of s/l of 1.0, 0.67, 0.50, and 0.33, where s represents the step height, and l denotes the length of the step floor. Among [11] contributions, the equation for the energy dissipated by the steps is well known, having been developed using the energy equation and the empirical equations of [12], who studied flow over a one-step dam. The comparison between the experimental data obtained for gabion chutes and the developed equation led to the proposition of some trend lines, albeit with some dispersion of points around the lines.

In the sequence, [1] experimentally studied flows in gabion-formed stepped chutes with s/l ratios of 1.0, 0.50, and 0.33, and for s/h_c ratios ranging from 1.08 to 2.72, where h_c represents the critical depth for a rectangular channel. The authors observed nappe and skimming flow regimes. Among their findings, [1] proposed graphs and equations for calculating the dissipated energy and determining the supercritical depth at the inlet of the stilling basin. The proposed curves exhibit adherence to experimental data with coefficients of determination greater than 0.874. In the same study, [1] suggested using Bélanger's equation for calculating the subcritical depth of the hydraulic jump, h_2, and the equation $L_j = 6h_2$ for calculating the stilling basin length. Bélanger's equation is traditional in the studies of hydraulic jumps, although it does not consider the bottom shear when quantifying the sequent depths. In this sense, [13] showed that the bottom shear can be considered through conservation principles, a method that can be extended to future studies on energy dissipation.

Further, [14] conducted experiments on gabion-constructed stepped chutes with s/l ratios of 0.58, 1.0, and 1.73, and for s/h_c ratios ranging from 0.52 to 6.02. The authors measured pressures, flow depths, and velocities, calculated head losses, and presented nondimensional empirical equations for these variables. They concluded that flows in gabion-constructed stepped chutes may exhibit dimensionless head losses up to 14% higher than flows in conventional stepped chutes. By analyzing data from other authors, [14] proposed Equation 1 for the occurrence of the skimming flow regime in gabion-constructed stepped chutes.

$$\frac{h_c}{s} \geq 0.61\left(\frac{s}{l}\right)^{-0.26} \tag{1}$$

Still further, [15] investigated volumetric air fraction distributions, velocity distributions, flow patterns, and energy dissipation in a gabion stepped chute with s/l = 0.50. Based on their experimental data, the authors concluded that energy dissipation is lower in gabion-constructed stepped chutes than in conventional stepped chutes. This result indicates a discrepancy with the conclusions presented in the literature (for example, [14]), suggesting a potential knowledge gap and the need for further studies.

Using an experimental setup different from the previously described, [16] conducted experiments on a stepped chute with s/l= 1.0, constructed with a structure wrapped in a mesh and filled with stones, which the author claimed represents a structure similar to gabions. The experiments were conducted for s/h_c ratios ranging from 0.94 to 1.2, and the author presented results for specific energy and total energy as a function of the discharge.

[17] conducted experiments on a gabion-stepped chute with s/l = 1.0 and s/h_c ratios ranging from 2.6 to 12.2. The authors measured flow depths and discharges, presenting results for the dimensionless head loss as a function of the discharge and the dimensionless parameter $(h_c/H_{dam})^3$, employed by [1], where H_{dam} is the height from the crest to the bottom elevation of the energy dissipation basin. By comparing the results obtained in a stepped chute with smooth floors, [17] concluded that gabions dissipate up to 16.9% more energy compared to chutes with conventional steps.

Using different gravels, [18] investigated the dissipated energy employing physical models of gabion stepped chutes filled with gravel of mean diameters of 10 mm, 25 mm, and 40 mm in channels with s/l ratios of 1.0, 0.50, and 0.33, and for s/h_c ranging from 0.29 to 4.0. The models utilized in the study included end sills on each step, and flow depths were measured using an ultrasonic sensor at a sampling rate of 20 Hz. The results demonstrated nearly equal energy dissipation, except for s/l = 1.0 and gravel mean diameter equal to 40 mm, resulting in lower dissipation than the other results.

Considering the dimension of hydraulic structures, [19] conducted experiments on a model with dimensions of 1.2 m width, 0.60 m height, s = 0.06 m, s/l = 0.50, and a mean gravel diameter of 24.1 mm for the gabion. The authors compared the energy dissipated by a smooth stepped chute with that dissipated by a gabion-stepped chute. They studied the length of hydraulic jumps established in a stilling basin with blocks, downstream of smooth steps and gabion steps, concluding that an 8.14% average reduction occurs in the hydraulic jump length when using gabions.

The eight articles shown in Table 1 in the present literature review of gabion stepped chutes contain experimental data related to energy dissipation. The Table summarizes the main geometrical characteristics of the physical models. The s/l ratios range from 0.33 to 1.73. The ranges of the dimensionless parameters s/h_c and s/l, together with the descriptions provided by the cited authors, indicate that nappe flow, transition flow, and skimming flow regimes occurred during their experiments.

Table 1. Characteristics of experimental studies on step chutes with gabions

Authors	s/l	s/h_c	H_{dam}/h_c
Stephenson [11]	1.0	-	1.3 - 4.9
	0.67		
	0.50		
	0.33		
Peyras *et al*. [1]	1.0	1.08 - 2.72	3.1 - 12.7
	0.50		3.2 - 12.4
	0.33		3.3 - 12.5
Chinnarasri *et al*. [14]	0.58	0.52 - 3.4	10.5 - 68.2
	1.0	0.74 - 2.4	14.8 - 48.4
	1.73	0.91 - 6.02	18.1 - 120.1
Wüthrich and Chanson [15]	0.50	0.59 - 2.0	5.9 - 20.1
Vashisth [16]	1.0	0.94 - 1.2	3.7 - 4.7
Rajaei *et al*. [17]	1.0	2.6 - 12.2	5.9 - 36.5
Salmasi et al. [18]	1.0	0.29 - 4.0	4.4 - 20.0
	0.50		4.3 - 21.1
	0.33		4.2 - 20.0
Daneshfaraz et al. [19]	0.50	0.97 - 1.75	9.8 - 17.1

Stepped gabion chutes are hydraulic structures that differ from conventional stepped chutes due to their porosity, roughness resulting from the natural irregularities of the rocks and grids, and the flexibility of the structure.

The flow in stepped gabion chute, less studied than in concrete structures, may exhibit different behaviors due to the interaction between the porous medium of the gabions and the overflow. [20] observed this distinction, identifying the hysteresis phenomenon and its influence on energy dissipation.

When designing stepped chute with gabions, it is essential to account for the inherent flexibility of the structure, which allows for a certain degree of deformation. In this context, the frontal slope of the chute may be altered, leading to a corresponding change in the energy dissipation that would be expected based on a conventionally shaped stepped spillway, as demonstrated numerically by [21]. Modifications in the shape of the steps can also lead to significant changes in energy dissipation. In this context, [22] used CFD (Computational Fluid Dynamics) to study stepped spillways with a trapezoidal labyrinth shape and found that these steps exhibited greater energy dissipation compared to conventional ones.

This study aimed to develop new dimensionless equations for designing hydraulic jump stilling basins downstream of gabion stepped chutes. The specific objectives were: (1) to develop equations for calculating the length of the stilling basin, considering state of the art on the length of the hydraulic jump; (2) to propose equations that allow the direct calculation of the elevation of the stilling basin bottom, in such a way that the hydraulic jump is established within it; (3) to propose an equation for calculating the height of the supercritical depth at the stilling basin inlet;

and (4) to demonstrate a methodology for the pre-design of the height of a continuous end sill in gabion stepped chutes.

Methodology

The energy dissipated, and the residual energy at the base of the stepped chute are quantities used to determine the supercritical depth h_1 (of the hydraulic jump) at the inlet of the stilling basin, a parameter used to quantify its size. To ensure that the hydraulic jump is established within the physical limits of the stilling basin, it is necessary to calculate the length and bottom elevation of the basin. All the cited works provide data that allow the calculation of the dimensionless parameter L_j/H_{dam} as a function of H_{dam}/h_c, proposed by [23], where L_j is the length of the hydraulic jump and H_{dam} is the height from the crest to the bottom elevation of the energy dissipation basin (Figure 1). The data also enable the calculation of H_{dam}/h_c as a function of D/h_c, where D is the vertical distance from the crest of the spillway to the water level in the tailwater channel, as indicated in Figure 1.

For the calculation of the mentioned dimensionless parameters, the Bélanger's equation (equation 2) is traditionally used, together with an equation for the length of the hydraulic jump, L_j. In the present description, equation 3 presented by [23] is the key tool for the calculation of the bottom elevation of the energy dissipation basin.

$$\frac{h_2}{h_1} = \frac{1}{2}\left(\sqrt{1 + 8Fr_1^2} - 1\right) \tag{2}$$

where Fr_1 is the supercritical Froude number.

$$\frac{H_{dam}}{h_c} = \frac{D}{h_c} + \frac{h_1}{h_c}\frac{1}{2}\left(\sqrt{1 + 8\left(\frac{h_1}{h_c}\right)^{-3}} - 1\right) \tag{3}$$

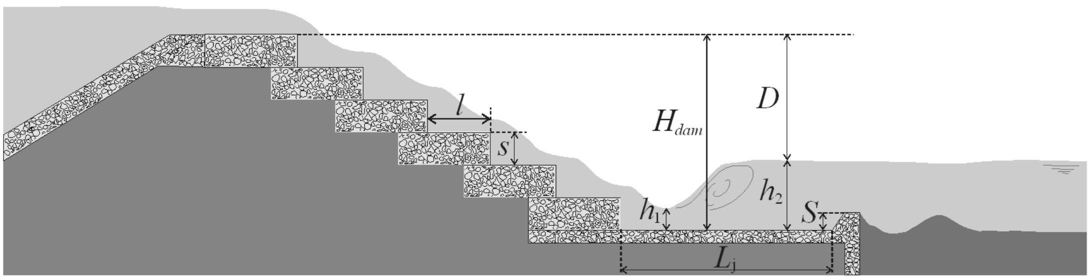


Figure 1. Sketch of stepped chute, variables from equations 1 and 2, and end sill height, *S*.

There are at least twenty equations available for calculating the length of the hydraulic jump, proposed since the early 20th century, which exhibit discrepancies with deviations exceeding 100% [13]. This discrepancy largely arises from the difficulty in defining the final position of the hydraulic jump. [21], using pressure transducers installed near the bottom of the channel and along the hydraulic jump, studied the statistical behavior of pressure distributions and identified the position from which the jump ceases to influence the subcritical flow, thus defining a methodology that can be replicated objectively and takes into account the statistical behavior of pressure near the bottom of the channel. The results of [21] revealed a final position for the jump around 8.5 times the height of the hydraulic jump, for the range $4.9 \leq Fr_1 \leq 9.3$.

Subsequently, [25], employing a methodology akin to that of [24] and focusing on jumps downstream of stepped spillways, measured that the terminal position of the jump was around eight times the jump height (as per equation 4). This proposal was verified in subsequent experimental investigations, like the study of [26], performed for the Froude Fr_1 number within the $1.9 \leq Fr_1 \leq 4.6$ range.

$$L_j = 8.0(h_2 - h_1) \quad (4)$$

As mentioned, [1] recommends that the length of the hydraulic jump stilling basin be calculated as $L_j= 6h_2$. This recommendation is found in the reference book "*Design of Small Dams*" from 1987. It is based on the detailed study of [27] about the length of hydraulic jumps in rectangular channels with horizontal bottoms. Its use for sizing the length of stilling basins without continuous terminal sill results in shorter basins when compared to equation 4 or the proposal of [24]. This occurs because, on average, $L_j = 6h_2$ is equivalent to $L_j = 6.8(h_2-h_1)$, for $4.5 \leq Fr_1 \leq 9.0$, with the coefficient 6.8 growing to 7.2 when the Froude number attains $Fr_1 = 4.5$. [24] studied the pressure fluctuations that can induce bed erosion, indicating that lower coefficients of the pressure fluctuation at the end of the hydraulic jump imply safer conditions. In this case, if taking $L_j = 6.8(h_2-h_1)$, those authors showed that the pressure fluctuation coefficient is around 0.2 for $Fr_1 = 4.5$. On the other hand, taking $L_j = 8.5(h_2-h_1)$, the same coefficient is around 0.08, which is a difference of about 150%. Consequently, performing a project of a dissipation basin following [27] implies that part of the hydraulic jump may be located on the riverbed, potentially causing erosion and compromising the structure's structural integrity that the correct positioning of the jump should protect.

As known, the length of the stilling basin downstream of stepped spillways can be reduced provided that deflector blocks and an end sill are used, as shown, for example, by the experimental results of [28] and [29], for physical models of stepped spillways with a ratio of 1V:0.75H. In further work, [30] studied four heights of end sills downstream of a physical model of a stepped spillway also with a ratio of 1V:0.75H, concluding that end sills enable the design stilling basins with lengths $L_j \geq 6.9(h_2-h_1)$, for situations with easily erodible soil.

The three experimental studies of the former paragraph demonstrated that using end sills reduces the length of dissipation basins downstream of stepped spillways. However, applying $L_j \geq 6.9(h_2-h_1)$ is still limited because of the conditions imposed by the experiments to stepped spillways with a ratio of 1V:0.75H and for concrete as the used building material. In this sense, the presented review highlights the need for specific studies on the characteristics of hydraulic jumps downstream of stepped chutes and spillways constructed with gabions with different inclinations.

The introduction to this study shows that a survey was first conducted about published data of flows in physical models of stepped chutes built with gabions or similar mesh-gravel structures. The valuable studies that described the experiments and published the obtained data in tables and graphs allowed to conduct of the present analysis, enabling proper quantifications of the relevant dimensionless parameters L_j/H_{dam}, D/h_c, and h_1/H_{dam} and the subsequent regression analyses.

Considering the presented arguments for stepped chutes of concrete and the absence of information for gabion stepped chutes, equation 4 was used in favor of security to calculate the length of the stilling basin. The information on the influence of the end sill on the pressure distribution near the channel bed and the risk of erosion downstream of the basin was also taken into account. The methodology involved the use of nonlinear regression to determine the coefficients of the proposed equations for calculating the length and bottom elevation of the stilling basin. The coefficients were calculated using custom programming in Python, C, MATLAB, and, occasionally, Excel.

Results

As a synthesis of the conducted analyses, the data of the studies of Table 1 were compiled in Figure 2a, including the curves obtained by calculating the coefficients *a* and *b* of equation 5, a model similar to that of [23] and [31] for conventional stepped spillways. The data from [16] were not included in the fit because they exhibited significantly different behavior from the others, likely due to the geometrical differences of the steps implied by the adopted constructive method (rounded steps). The coefficients *a* and *b*, their respective correlation coefficients, and validity intervals are presented in Table 2. The graph and correlation coefficients show that equation 5 [31] adequately represents the trend of those experimental data and that there is adherence between the model and experimentation.

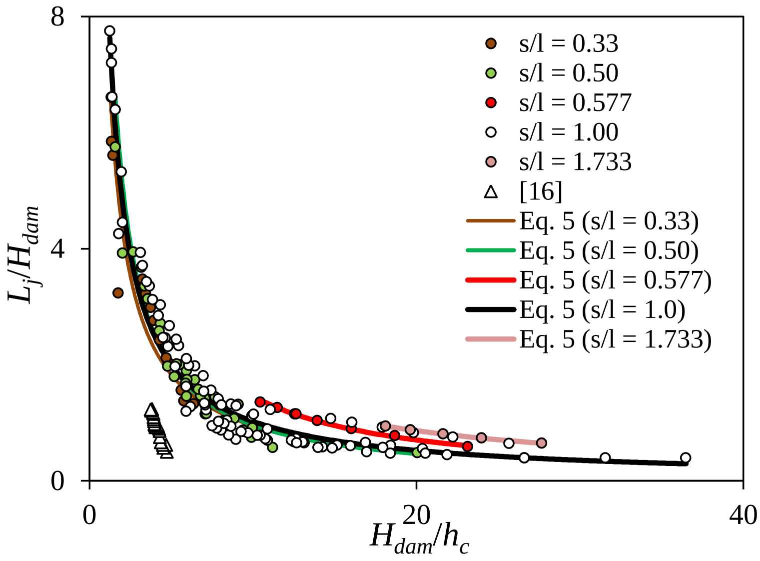
$$\frac{L_j}{H_{dam}} = \mathrm{a}\left(\frac{H_{dam}}{h_c}\right)^b \tag{5}$$

The average trend of equation 7 is obtained by taking the data of different origins as a single set and including the additional point from [14] for s/l = 1.0, (48.4; 0.27), where “tgh” is the hyperbolic tangent. The lower and upper envelopes given by equations 6 and 8 were calculated to indicate the observable variations. The coefficients of equation 7 were obtained through nonlinear regression applied to equation (5) for the interval 1.25 < H_{dam}/h_c < 48.4, resulting in a correlation coefficient 0.970. The maximum relative deviation around equation 7 obtained with equation 6 is 39%, and with equation 8 is 47%.

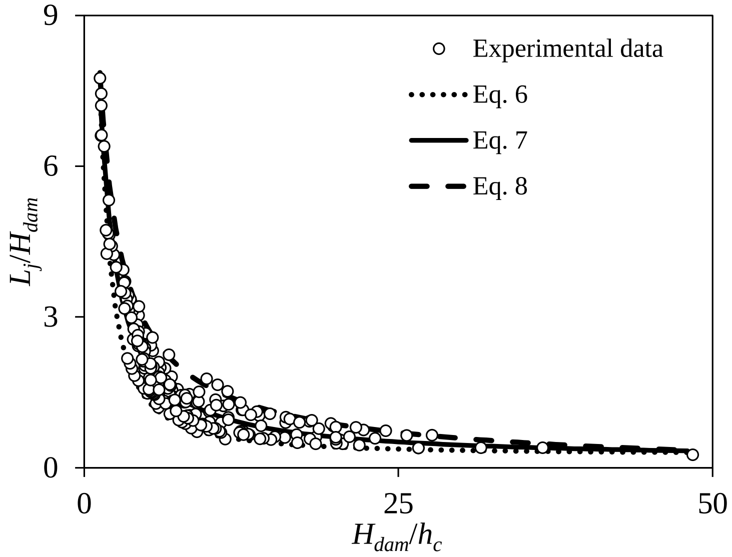
$$\frac{L_j}{H_{dam}} = -22.0\mathrm{tgh}\left[-0.48\left(\frac{H_{dam}}{h_c}\right)^{-1.41}\right] + 0.26 \tag{6}$$

$$\frac{L_j}{H_{dam}} = -15{,}1\mathrm{tgh}\left[-0{,}67\left(\frac{H_{dam}}{h_c}\right)^{-1{,}03}\right] + 0{,}15 \tag{7}$$

$$\frac{L_j}{H_{dam}} = -22{,}2\mathrm{tgh}\left[-0{,}45\left(\frac{H_{dam}}{h_c}\right)^{-0{,}74}\right] - 0{,}22 \tag{8}$$



(a)



(b)

Figure 2. Fitting of equation 5 to the experimental data (a) and equations 6, 7 and 8 (b).

The relationship between the dimensionless parameters H_{dam}/h_c and D/h_c (see Figure 1) followed the linear trend also observed for smooth and conventional stepped spillways. Equation 9 shows the basic linear trend between both variables and Table 2 shows the *c* and *d* values for each set of data. The correlation coefficients are greater than 0.98 for all values of *s*/*l*. The analysis of the unified data produced equation 10, with a correlation coefficient of 0.999, a spreading of data as shown in Figure 3, and valid for the interval 0.17 < D/h_c < 34.33.

$$\frac{H_{dam}}{h_c} = c\frac{D}{h_c} + d \tag{9}$$

$$\frac{H_{dam}}{h_c} = 1.01\frac{D}{h_c} + 1.7 \tag{10}$$

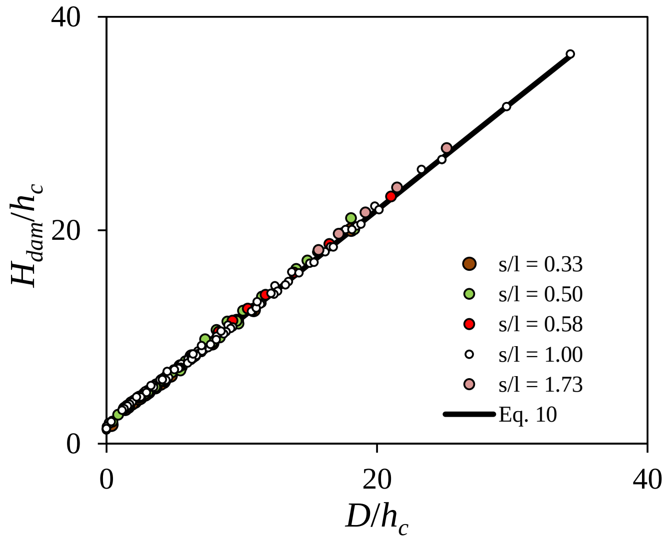


Figure 3. Fitting of equation 10.

Table 2. Coefficients of equations 5 and 9

s/l	a	b	R (eq. 5)	(*) H_{dam}/h_c	c	d	R (eq. 9)	(**) D/h_c
0.333	8.010	-0.895	0.952	1.35 - 20.04	1.010	1.703	0.999	0.36 - 18.09
0.500	8.480	-0.872	0.959	1.58 - 20.12	1.040	1.640	0.998	0.46 - 18.34
0.577	16.370	-1.050	0.994	10.46 - 23.14	0.982	2.385	0.999	8.31 - 21.06
1.000	9.670	-0.961	0.982	1.25 - 36.49	0.988	1.689	0.999	0.17 - 34.33
1.733	12.390	-0.889	0.999	18.12 - 27.68	1.010	2.297	0.999	15.69 - 25.17

Symbol: R = correlation coefficient; *validity interval for equation 5; **validity interval for equation 9.

For the calculations of the supercritical conjugate depth h_1 at the entrance of the stilling basin, the dimensionless parameter h_1/H_{dam} proposed by [1] showed a strong correlation with H_{dam}/h_c, leading to equation 11, valid for $1.74 < H_{dam}/h_c < 48.4$ and $1.18 < Fr_1 < 6.61$, with $R = 0.973$. The data and the equation are shown in Figure 4a, and the relatively small spreading of the data around the exact fit line is shown in Figure 4b.

$$\frac{h_1}{H_{dam}} = 18.1\text{tgh}\left[0.030\left(\frac{H_{dam}}{h_c}\right)^{-1.09}\right] + 0.005 \tag{11}$$

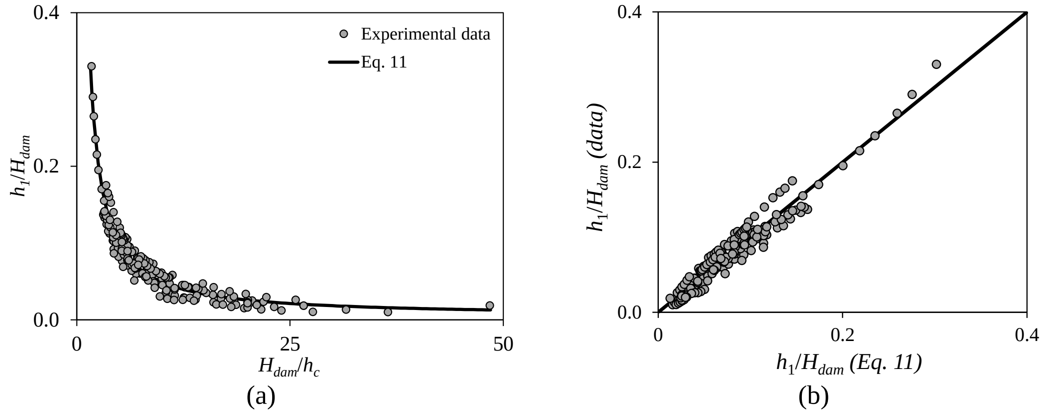
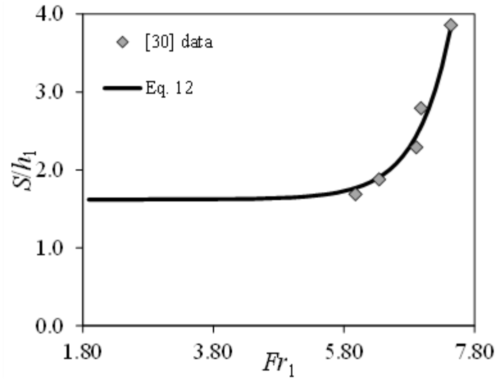


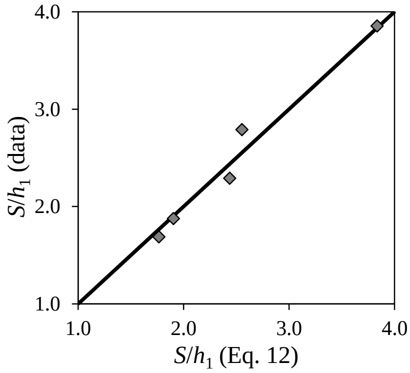
Figure 4. Relationship between h_1/H_{dam} and H_{dam}/h_c (a); comparison with the exact fit line (b)

The data of [30] were used to quantify the sill height S shown in Figure 1. Following the mentioned author, the data were expressed in the dimensionless form S/h_1 and as a function of the Froude number at the entrance of the stilling basin. The work of [30] considered the interval $5.44 \leq Fr_1 \leq 7.44$. Observing further the trend line inserted by [30], a possible constant value of S/h_1 for $Fr_1 \leq 5.44$ was noted. Considering this conjecture, Equation 12 is recommended here for the broader interval $1.89 \leq Fr_1 \leq 7.44$, being this a first quantification for pre-designs. It must be noted that the scarcity of data impedes a more definitive affirmation. Figure 5a shows the data graph and Equation 12, and Figure 5b shows the adjustment between the data and the proposed equation.

$$\frac{S}{h_1} = 2.1.10^{-5}\exp\left(Fr_1^{1.22}\right) + 1.62. \tag{12}$$



(a)



(b)

Figure 5. Relationship between S/h_1 and Fr_1 (a); comparison with the exact fitting line (b).

Example of Application

For the application of equations derived from researches that must consider some more profound scientific questions to attain their objectives, a practical sequence of steps considering the use of the main conclusions is very welcomed.

In this sense, the present example considers a spillway system to be designed with a rectangular stepped chute and a stilling basin of the same width to meet the following design conditions: (1) flow rate, Q = 204.2 m³/s; (2) width, B = 40 m; (3) s = 0.35 m and l = 1.05 m; (4) crest elevation of the weir, z_0 = 27.6 m; (5) elevation of the water level in the tailwater channel, z_2 = 20 m.

The practical steps are as follows:

For H_{dam} and L_j:

1) Initially, the specific discharge should be calculated, which leads to $q = Q/B \approx$ 5.11 m²/s. The critical depth, used in the dimensionless parameters, follows immediately as $h_c = (q^2/g)^{1/3} = (5.11^2/9.8)^{1/3} \approx 1.39$ m.

2) In the sequence, the value of D (see figure 1) is obtained as $D = z_0 - z_2 = 27.6 - 20 = 7.6$ m, which produces $D/h_c \approx 5.49$.

3) Knowing the ratio of s/l = 0.35/1.05 = 0.33, it is possible to identify the values of c = 1.01 and d = 1.703 in Table 2 for the use of Equation 9, which leads to H_{dam}/h_c = (1.01)(5.49)+1.703 = 7.24 and, in the sequence, H_{dam} = 10.04 m. Table 2 allows interpolations of c and d for values of s/l not explicit in the table. It is noted that the values of D/h_c and H_{dam}/h_c are within the corresponding range for Equation 9, as shown in Table 2, enabling the use of Equation 5 with the respective coefficients.

4) Knowing s/l = 0.33, the coefficients of Equation 5 are a = 8.01 and b = -0.895; which lead to $L_j/H_{dam} = 8.01(7.17^{-0.895}) = 1.36$ and, in the sequence, L_j = 13.7 m.

Thus, H_{dam} and L_j were calculated. For further information, applying the values s/l = 0.33 and s/h_c = 0.25 to equation 1 indicates the occurrence of the transition flow regime.

To exemplify the use of Equations 7 and 10 for the unified set of data and compare their results with the equations developed for each s/l separately, we have the following steps:

1) Equation 10 provides the value of H_{dam}/h_c = (1.01)(5.49)+1.7 = 7.24 and, in the sequence, H_{dam} = 10.03 m. A relative deviation of only 0.04% is observed compared to Equation 9.

2) Equation 7 provides the value L_j/H_{dam} = -15.1tgh[(-0.67)($7.24^{-1.03}$)]+0.15 = 1.463 and, in the sequence, L_j = 14.7 m. A relative deviation of 7.4% is observed when compared to Equation 5. It is understood as acceptable for the pre-design phase.

For S:

1) Equation 11 provides the value h_1/H_{dam} = 18.1tgh[(0.030)$(7.24)^{-1.09}$]+0.005 = 0.06776 and, in the sequence, h_1 = (0.06776)(10.03) = 0.68 m.). With this h_1 value, the Froude number is Fr_1 = 2.91.

2) Equation 12 provides then the value S/h_1 = 2.1.10^{-5}exp($2.91^{1.22}$)+1.62 ≈ 1.621, and, in the sequence, S = 1.10 m.

S was thus calculated. As mentioned before, the scarceness of data for establishing equation 12 implies that this value should be taken for the pre-design phase. Certainly, more experimental data will improve the assurance of the proposed methodology.

Using the methodology of [1]:

1) For s/l = 0.33, the mentioned authors propose $h_1/H_{dam} = 0.3416[q^2/(gH_{dam}^3)]^{0.248}$ = $0.3416[5.11^2/((9.8)10.03^3)]^{0.248}$ = 0.0783 and, in the sequence, h_1 = 0.779 m.

2) The sequence of calculations furnishes, then: $V_1 = q/h_1$ = 6.56 m/s, Fr_1 = 2.37 and $h_2 = 0.5h_1[(1+8Fr_1^2)^{1/2}-1]$ = 2.25 m.

3) The mentioned authors recommend the use of $L_j = 6h_2$ = (6)(2.25) = 13.5 m.

L_j was thus calculated. However, the mentioned authors did not present a way to calculate H_{dam}, probably using the value measured in the experimental device in their calculations. Taking the shortest length obtained in the present study, the relative deviation about the result of [1] is (13.7-13.5)100/13.5 = 1.5%. The result of [1] is shorter, being eventually seen as economically more attractive. However, the formulation proposed here involves data from different origins, corresponding to a broader coverage of possible cases, where different practical conditions were employed. Additionally, the present result favors the security of the dissipation basin, avoiding the risk of intense fluctuations downstream of its end, thus avoiding the risk of erosion after the basin. As a further advantage of the present method, the sill height is also calculated.

Conclusions

The present literature review of gabion stepped chutes identified six experimental studies with adequate sets of data, conducted for the ratio s/l between 0.33 and 1.73. Although somewhat scattered, the data exhibited well-defined nondimensional trends for the length and bottom elevation of the stilling basin, as well as for the supercritical depth at the stilling basin inlet. One of the obtained datasets showed a significant deviation from the others, likely due to geometric differences (rounded steps due to the building procedures). This dataset was not used to obtain the here obtained equations, but suggests further studies involving geometry variations. The here proposed equations for the length of the stilling basin exhibited adherence to the experimental data through a power law, for both situations: 1) when used for each s/l separately, and 2) when used for the unified set of data. In the last case the envelopes of the dataset indicate relative deviations between 35% and 58%. Analyses regarding the bottom elevation of the stilling basin for the formation of the hydraulic jump within the basin limits led to linear equations between H_{dam}/h_c and D/h_c for each value of s/l, and also for the unified analysis, resulting in high correlations and adherence to the experimental data. The relatively non-dispersed characteristic of the data allows to propose the equation for the unified data, as the one to be used in the calculations of such basins. Further, the evident relationship between h_1/H_{dam} and H_{dam}/h_c induced to a new equation for the calculation of h_1, with high adherence to the data and consequently a strong statistical correlation. Finally a methodology for calculating the height of the continuous end sill, was proposed, being mentioned that this topic requires further investigation, considering the current lack of data for gabion stepped chutes. An example of application was presented in a detailed step by step manner, where the present methodology was compared to a methodology available in the literature. The results show compatible results between the two methodologies, but point to the higher security of the present methodology, which considers sets of data of different sources.

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References

1. Peyras, L.; Royet, P.; Degoutte, G. (1992). "Flow and energy dissipation over stepped gabion weirs". *Journal of Hydraulic Engineering*, Vol. 118, No.5, May, 1992, pp.707-717.
2. Mohamed, H.I. (2010) Flow over Gabion Weirs. *Journal of Irrigation and Drainage Engineering*, ASCE, August 2010, pp. 573-577. DOI: 10.1061/(ASCE)IR.1943-4774.0000215.
3. Al-Mohammed, F.M.; Mohammed, S.H. (2015) Flow Through and Over Gravel Gabion Weirs. *Journal of Kerbala University*, Vol. 13 No.2 Scientific, pp. 193-205.
4. Velázquez-Luna, L; Ventura-Ramos, E. (2017) Concentrated Flow through Gabions Weirs. *Hydraulics Conference of Autónoma de Querétaro*, IEEE, Querétaro, México, May 15-19, pp.1-4.
5. Pallavi, M.; Harashit, L. (2018) Open Channel Flow Characteristics Using Gabion Weir. *International Research Journal of Engineering and Technology* (IRJET) Vol. 5, No. 12, pp. 928-933.
6. Safarzadeh, A.; Mohajeri, S.H.; (2018) Hydrodynamics of Rectangular Broad-Crested Porous Weirs. *J. Irrig. Drain Eng.* ASCE, Vol. 144, No 10, 04018028.
7. Al-Fawzy, A.M.; Al- Mohammed, F.M.; Alwan, H. (2020) Energy dissipation in gabion weirs. *3rd International Conference on Engineering Sciences*, IOP Conf. Series: Materials Science and Engineering 671, pp.1-12.
8. Salmasi, F.; Sabahi, N.; John Abraham, J. (2021) Discharge Coefficients for Rectangular Broad-Crested Gabion Weirs: Experimental Study. *J. Irrig. Drain Eng*., ASCE, Vol. 147, No. 3, 04021001.
9. Azma, A.; Sadrabadi, M.T.; Liu, Y.; Azma, M.; Zhang, D.; Cao, Z.; Li, Z. (2023) Boosting ensembles for estimation of discharge coefficient and through flow discharge in broad-crested gabion weirs. *Applied Water Science* 13:45. https://doi.org/10.1007/s13201-022-01841-x

10. Biabani, R.; Salmasi, F.; Nouri, M.; Abraham, J. (2022) Flow Over Embankment Gabion Weirs in Free Flow Conditions. *Journal of Hydro-environment Research*, ELSEVIER, Vol. 44, pp. 65-76.
11. Stephenson, D. (1979). “Gabion energy dissipators”. *Proc. 13th ICOLD Congress*, New Delhi, Q. 50, R.3, p. 33-34, 1979.
12. Rand, W. (1955). Flow geometry at straight drop spillways. Journal of the Hydraulics Division, Proceedings, ASCE, v. 81, n. 791, Sept., p. 1-13, 1955.
13. Schulz, H.E.; Nóbrega, J.D.; Simões, A.L.A.; Schulz, H; Porto, R.M. (2015). *Details of Hydraulic Jumps for Design Criteria of Hydraulic Structures*, *Hydrodynamics - Concepts and Experiments*, Prof. Harry Schulz (Ed.), ISBN: 978-953-51-2034-6, InTech.
14. Chinnarasri, C.; Donjadee, S.; Israngkura, U. (2008). “Hydraulic Characteristics of Gabion-Stepped Weirs”. *Journal of Hydraulic Engineering*, ASCE, Vol. 134, No. 8, August 2008, pp. 1147-1152.
15. Wüthrich, D.; Chanson, H. (2014). “Hydraulics, Air Entrainment, and Energy Dissipation on a Gabion Stepped Weir”. *Journal of Hydraulic Engineering*, ASCE, June 2014, Vol. 140, No. 9, pp. 04014046.
16. Vashisth, A. (2017). “Energy Dissipation over Stepped Gabion Weir”. *International Journal of Dynamics of Fluids* Vol. 13, No. 1, pp. 153-159.
17. Rajaei, S.H.; Khodashenas, S.R.; Esmaili, K. (2020). “Comparative evaluation of energy dissipation over short stepped gabion and rigid spillways”. *Journal of Hydraulic Research*, Vol. 58, No. 2, pp. 262-273.
18. Salmasi, F.; Razi, S.; Abraham, J. (2023). Hydraulics of flow in gabion stepped spillways, an experimental study. Journal of Hydraulic Structure. 9, p. 75-100. 2023.
19. Daneshfaraz, Rasoul; Sadeghi, Hojjat; Ghaderi, Amir; Abraham, John Patrick (2024) The effect of gabion steps on the hydraulic jump characteristics downstream of stepped spillways, Water Science, 38:1, 128-139, DOI: 10.1080/23570008.2024.2307243
20. Daneshfaraz, Rasoul; Aminvash, Ehsan; Najibi, Amir. Experimental Study of Hysteretic Behavior of Supercritical Regime on Hydraulic parameters of Flow against Gabion Contraction. Iranian Journal of Soil and Water Research, [S.l.], v. 53, n. 1, p. 33-44, mar. 2022. University of Tehran. DOI: 10.22059/ijswr.2022.334538.669141
21. Aminvash, E.; Roushangar, K. (2023). Numerical Investigation of the Effect of the Frontal Slope of Simple and Blocky Stepped Spillway with Semi-Circular Crest on Its Hydraulic Parameters. Iranian Journal of Irrigation and Drainage, 17(1), 102-116.
22. Ghaderi, A., Abbasi, S., Abraham, J.; Azamathulla, H. M. (2020). Efficiency of Trapezoidal Labyrinth Shaped stepped spillways. Flow Measurement and Instrumentation, 72, 101711. https://doi.org/10.1016/j.flowmeasinst.2020.101711
23. Simões, A.L.A. (2008). Considerações sobre a hidráulica de vertedores em degraus: metodologias adimensionais para pré-dimensionamento. Dissertação (Mestrado) – Escola de Engenharia de São Carlos – Universidade de São Paulo, São Carlos.
24. Marques, M.G.; Drapeau, J.; Verrette, J-L. (1997). “Flutuação de pressão em um ressalto hidráulico”. *Revista Brasileira de Recursos Hídricos*, Vol. 2, No. 2, Jul/Dez 1997, pp. 45-52.
25. Novakoski, C. K. (2016). Análise da distribuição longitudinal das pressões em um ressalto hidráulico formado a jusante de vertedouro em degraus. Dissertação (Mestrado em Recursos Hídricos)—Porto Alegre: Universidade Federal do Rio Grande do Sul - UFRGS, 2016.

26. Steinke Júnior, R. (2020). Caracterização das pressões em bacias de dissipação por ressalto hidráulico livre com baixo número de Froude. Dissertação (Mestrado em Recursos Hídricos)—Porto Alegre: Universidade Federal do Rio Grande do Sul - UFRGS, 2020.
27. Bradley, J. N.; Peterka, A. J. (1957). “The hydraulic design of stilling basins”. ASCE, *Journal of Hydraulic Engineering*. Vol.83, n.HY5, p.1401-1406, Oct., 1957.
28. Cardoso, F.G. (2006). Estudo do ressalto hidráulico em bacias de dissipação de energia a jusante de descarregadores de cheias em degraus. 2006. 143f. Trabalho de Conclusão de Curso (Engenharia Civil) – Instituto Superior Técnico, Universidade Técnica de Lisboa.
29. Meireles, I.O.C; Matos, J.; Silva Afonso, A. (2010). Flow characteristics along USBR type III stilling basin downstream of stepped spillways. Hydraulic Structures: Useful Water Harvesting Systems or Relics? Third International Junior Researcher and Engineer Workshop oh Hydraulic Structures, May, 2010, Edinburgh, Scotland. R, Janssen and H. Chanson (eds). Hydraulic Model Report CH80/10, School of Civil Engineering, The University of Queensland, Brisbane, Australia, 211 pp.
30. Conterato, E. (2014). Determinação de critérios de dimensionamento de soleira terminal em bacia de dissipação a jusante de vertedouro em degraus. Dissertação (Mestrado em Recursos Hídricos)—Porto Alegre: Universidade Federal do Rio Grande do Sul - UFRGS, 2014.
31. Simões, A. L. A., Schulz, H. E. and Porto, R. M. (2010) Stepped and smooth spillways: resistance effects on stilling basin lengths, Journal of Hydraulic Research, 48: 3, 329 — 337.