

EXPERIMENTAL STUDY OF ENERGY DISSIPATION OVER STEPPED GABION SPILLWAYS WITH LOW HEIGHTS*

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Abstract– Stepped gabion spillways have many applications in dam structures, river engineering, and soil conservation works. They are more stable and flexible than their rigid (impervious) counterparts. Moreover, their stilling basins can be constructed at lower costs as energy dissipation in these spillways is high due to both over-flow and through-flow. This study aims to study the over-flow and through-flow in gabion stepped spillways and to evaluate their energy dissipation. For this purpose, eight physical models of gabion stepped spillways with three different porosities (38, 40 and 42%) and two slopes (1:1 & 1:2) ($V:H$) were made with permeable and impermeable faces of both horizontal and vertical types. Results showed that at higher discharges, energy dissipation was greater in pervious (gabion) spillways than those with impermeable horizontal or vertical faces. At lower discharge rates, however, energy dissipation was greater in impervious stepped spillways. On the other hand, steps with impervious vertical faces had more energy dissipated than those with impervious horizontal faces. Increasing gabion porosity increased energy dissipation, but this effect was minor at higher discharges. Finally, it was found that decreasing slope led to more energy dissipated.

Keywords– Energy dissipation, porosity, spillway slope, stepped gabion spillway

1. INTRODUCTION

Gabion spillways are frequently used in small earth dams, soil conservation works, retaining walls, and in river training works at bends, intakes, and so on. Gabion structures are stable, flexible, and easy to build, while they also withstand considerable differential settlement without the loss of structural integrity. In areas where plenty of stones are available, this type of structure will be an economical alternative. Gabion consists of a porous medium filled with stone maintained in a mesh grid. Its porosity helps drain water and reduce the water load behind the structure. Stepped spillways can also be made in gabion style. At low discharge rates, water flows only through the pervious body of the spillway, while at high discharge rates, the flow over the steps also cascades down the spillway face.

Energy dissipation at gabion stepped spillways may be higher than rigid (impervious) stepped spillways due to the extra resistance offered by both the surface and the through-flow, thus reducing the cost of the stilling basins constructed. Figure 1 shows two applications of gabion structures built on Onebne-Ali mountain, north of Tabriz, Iran.

Although many studies have been carried out to investigate the different aspects of over-flow in stepped chutes and spillways, the hydraulics of through-flow gabions has rarely ever been adequately investigated due to the complexity of their flow patterns and resistance. For a given stepped chute, the water flows as a succession of free-falling nappes (nappe or jet flow regime) at small discharges (Toombes

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and Chanson, 2008). For an intermediate range of flow rates, a transition flow regime is observed. Most prototype spillways operate at large discharges per unit width for which the water skims as a coherent stream over the pseudo-bottom formed by step edges. The skimming flows are characterized by significant form losses and momentum transfer from the main stream to the recirculation zones [1-4].

Stephenson [5] studied the energy dissipation on stepped gabions of two to four steps with different slopes of 1:1, 1:2, 1:3 and 2:3 ($V:H$). The relative energy dissipation, $\Delta E/H_w$, was evaluated using the measured upstream and downstream depths, where $\Delta E = E_0 - E_1$, E_0 and E_1 are the upstream and downstream energy heads, respectively, and H_w is the total gabion-weir height. Relative energy dissipation ranges from about 25% to 85%. It is shown that relative energy dissipation increases with the number of steps up to three, but reduces with more steps. Kells [6] studied experimentally the relative energy dissipation, $\Delta E/E_0$, on stepped gabions for the two slopes of 1:1 and 1:2 ($V:H$) to find that energy dissipation over a stepped gabion weir decreased with increasing critical flow depth over gabion weir (or discharge) and that it increased by as much as 20 percent when through-flow was allowed to occur. It was also found that approximately 80 to 85 percent of the total energy was dissipated in passing through the rock fill in cases where overtopping did not occur at the crest. No significant changes were observed in energy dissipation for different values of slope. Peyras et al. [7] performed an experimental study of stepped gabion spillways to estimate energy loss and to establish stilling basin design criteria. They constructed models with 1:1, 1:2, and 1:3 slopes and three to five steps in four configurations of plain gabion, horizontal impervious concrete slabs, adverse impervious concrete slabs, and end sills. Both nappe (or jet) and skimming flows were observed during the tests. Relative energy dissipation, $\Delta E/H_w$, ranged from about 25% to 95%. Chinnarasri et al. [8] maintain that energy loss ratios in the gabion-stepped weirs are greater than those in the corresponding horizontal stepped weirs by approximately 7, 10, and 14% for weir slopes of 30°, 45°, and 60° degrees, respectively. It may, therefore, be concluded that, compared to weir slope, stone size and shape have smaller effects on energy loss and flow velocity. Salmasi [9] applied ANNs for calculating the energy dissipation of flow over stepped spillway chute using his experimental work based on large-size stepped spillways. Results demonstrate the feasibility of obtaining sensible results by ANN modelling for a range of stepped chute geometry and flow conditions. In another study Salmasi [10] demonstrated that maximum energy dissipation takes place at a specified number of steps.



Fig. 1. Gabion stepped spillway used to reduce water velocity and to collect sediments in mountain valley (left), and gabion structure in a retaining wall for slope stability (right) on Onebne-Ali mountain, north of Tabriz (IRAN)

In the present study, experiments have been conducted on low-height gabion stepped spillways. The over- and through-flows in the gabion stepped spillway body were controlled by employing impervious iron sheets on the vertical or horizontal faces. The effects of step porosity and weir slope on energy dissipation have also been studied experimentally.

2. EXPERIMENTAL SETUP

Experiments on gabion-weir models were carried out at the Hydraulic Laboratory of Water Engineering Department, Faculty of Agriculture, the University of Tabriz. The models were installed in a flume, 0.25 m wide, 10 m in length, and 0.60 m in height. All the models had three steps, each with a height of 0.10 m. The spillway slopes selected were 1:1 and 1:2 ($V: H$). Gabions were filled with three different stone diameter ranges of 6 to 19 mm, 19 to 25 mm, and 25 to 38 mm with three porosity levels of approximately 38, 40, and 42%. If one assumes a model scale of 1:10, which is a reasonable scale in hydraulic structures, gabion stone sizes will be 160 to 380 mm in the full scale gabion structures. Several earlier studies suggest that the porosity values between 30 to 40% work well for gabion weirs [5, 6 and 11]. A diagram of the weir with step configuration is provided in Fig. 2.

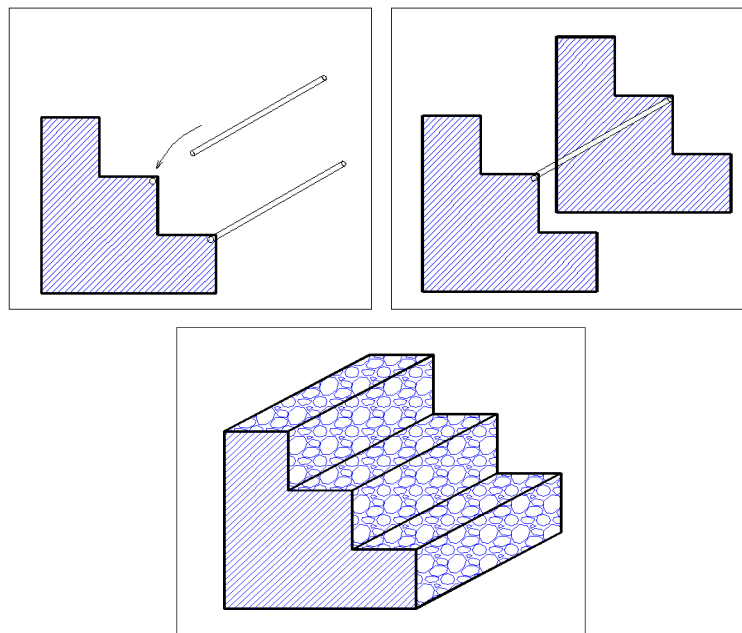


Fig. 2. Construction of gabion stepped weir with two plates and rods (above) and covering with mesh and filling with stone (below)

Iron plates were placed at vertical or horizontal step faces to study the effect of step porosity on energy dissipation. For each spillway slope, four step arrangements were made. They are symbolically shown as:

GH- Gabion stepped spillway with horizontal impervious plates;

GV- Gabion stepped spillway with vertical impervious plates;

G- Gabion stepped spillway with no impervious plates; and

GHV- Gabion stepped spillway with horizontal- vertical impervious plates.

Figure 3 shows two stepped gabion spillways with a slope of 1:2 ($V: H$), with and without vertical impervious plates. The physical models were installed 4.0 m downstream the flume inlet. The flow was controlled at the end of the laboratory flume with a gate to form a hydraulic jump at the weir toe. The discharge was measured by a calibrated sharp triangle weir (53° angle) installed at the downstream of the flume. Water discharge was supplied by pumps (maximum value 50 l/s). Discharges ranged from 7 to 50 l/sec with an accuracy level of ± 0.9 l/sec. A total of 267 tests were conducted with two different slopes, three different porosities, and varying discharge rates. In each run, water depth was measured 0.60 m upstream of the spillway, y_0 , and after the hydraulic jump, y_2 . The thin flow and air entrainment at the spillway toe made it difficult to measure the flow depth (y_1) accurately. Matos and Quintela [12], Diez-Cascon et al. [13], Tozzi [14], and Pegram et al. [15] calculated energy dissipation using the conjugate

water depths of the hydraulic jump. In the present study, y_2 was measured with an accuracy level of ± 2 mm, where there were few bubbles and less undulation in the tail water. Water levels at the upstream were measured using a point gauge within ± 0.1 mm accuracy. All measurements were made in the centerline of the flume. The average flow velocity at any section ($V=q/y$) was calculated as the measured flow rate per unit width ($q = Q/b$), where Q is total discharge and b is the spillway width. Upstream (E_0) and downstream (E_1) energy heads and relative energy dissipation ($\Delta E/ E_0$) were calculated as follows:



Fig. 3. Two gabion stepped spillways with a slope of 1:2, without (left) and with (right) vertical impervious plates

$$E_0 = H_w + y_0 + \frac{V_0^2}{2g} = H_w + y_0 + \frac{q^2}{2gy_0^2} \quad (1)$$

$$E_1 = y_1 + \frac{V_1^2}{2g} = y_1 + \frac{q^2}{2gy_1^2} \quad (2)$$

$$\frac{\Delta E}{E_0} = \frac{E_0 - E_1}{E_0} = 1 - \frac{E_1}{E_0} \quad (3)$$

where, g is gravity acceleration, H_w is total gabion-weir height measured with a point gauge after installation of weir at flume, y_0 is the depth of flow about 60 cm upstream of weir and above weir crest and V_0 is the approach velocity. The depth, y_1 , was calculated using the conjugate depth (y_2) expressed by:

$$y_1 = \frac{y_2}{2} \left(\sqrt{1 + 8Fr_2^2} - 1 \right) \quad (4)$$

where, $Fr_2 = V_2 / \sqrt{gy_2}$. Generally, energy dissipation depends on hydraulic and geometric variables expressed by:

$$\frac{\Delta E}{E_0} = f(q, l, h, H_w, g, n) \quad (5)$$

where, l is step length, h is step height, and n is porosity.

Location of measured y_1 and y_2 depths are shown in Fig. 4. In all tests, discharge was regulated in a way to form hydraulic jump at weir toe, so that supercritical flow at the downstream of the weir toe may

occur (Froude number > 1). Although both depth y_1 and y_2 were measured, only depth y_2 was used in calculating energy dissipation.

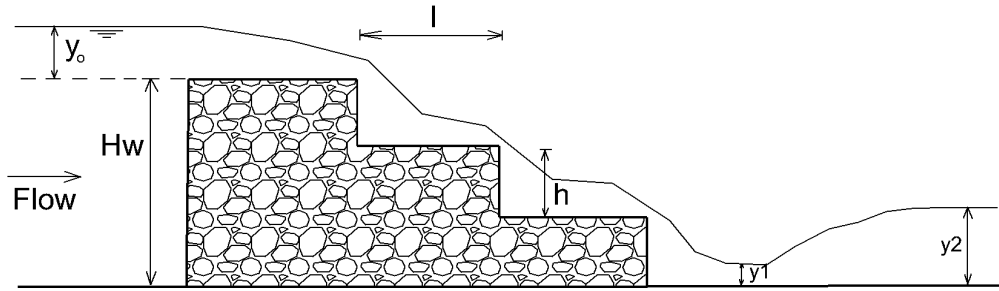


Fig. 4. Location for measured y_1 and y_2 depths at the downstream of weir

3. DIMENSIONAL ANALYSIS

The fundamental variables that are important in the hydraulics of gabion-stepped weir are geometrical parameters like: total gabion-weir height (H_w), each step length (l), each step height (h), weir slope (S), stone size filled in gabion (d_{50}); and hydraulic parameters like: discharge per unit width of canal (q), energy at upstream of weir (E_0) define with Eq. (1), energy at downstream of weir (E_1) define with Eq. (2), and material porosity (n).

Using the Buckingham π -theorem, relative energy dissipation can be expressed as:

$$\frac{\Delta E}{E_0} = f\left(q^2 / gH_w^3, h/l, n\right) \tag{6}$$

Equation (6) can be rewritten as Eq. (7):

$$1/(1 - K) = f(GN, S, n) \tag{7}$$

Where, $K = (E_0 - E_1)/H_w$, $GN = q^2/gH_w^3$, and $S = h/l$ is spillway slope. The parameter GN is termed as gabion number, similar to drop number presented first by Rand [16].

4. RESULTS AND DISCUSSION

Table 1 presents some primary experimental data for gabion G -setup. Froude and Reynolds numbers at section 1 are defined as $Fr_1 = V_1/\sqrt{gy_1}$ and $Re_1 = V_1y_1/\nu$, where ν is water kinematic viscosity at 20°C. Due to space limitations, only the data for G type spillways are presented here.

Figure 5 presents relative energy dissipation vs. unit discharge. It can be seen that with increasing q , relative energy dissipation reduces in all spillway arrangements (GH , GV , G , and GHV). As shown in Fig. 6, there are different trend lines for energy dissipation in each of the GH , GV , G , and GHV arrangements. Figure 6 shows that at low discharges, GHV has more energy dissipated than any other arrangement. Energy dissipation becomes greater in the order G , GV , and GHV with increasing gabion number ($GN > 0.05$), although the values of energy dissipation in the last three are close. This demonstrates that at low discharges, when only through-flow occurs, energy dissipation is less in G , GV , and GH compared to that in GHV . With increasing discharge, over- and through-flows occur in G , GV , and GH , leading to increasing energy dissipation compared to GHV . Energy dissipation is greater in G than in either GV or GH , which indicates that the more porous the structure, the more energy is dissipated. Energy dissipation is also higher in GV than in GH , which shows that the interaction between upward flow (from step thread) and impinging jet will be more effective for energy dissipation.

Table 1. Experimental results of G setup for slope 1:2 ($V:H$)

n (%)	q (m^2/sec)	Y_1 (m)	Y_2 (m)	V_1 (m/s)	E_o (m)	E_1 (m)	$GN=$ q^2 / gH_w^3	$1/(1-K)$	F_{r1}	R_{e1}
38	0.100	0.039	0.211	2.573	0.460	0.377	0.038	1.383	4.159	1.0E+05
	0.084	0.033	0.191	2.516	0.446	0.356	0.027	1.427	4.401	8.4E+04
	0.074	0.031	0.174	2.374	0.432	0.319	0.021	1.605	4.299	7.4E+04
	0.058	0.023	0.160	2.481	0.416	0.337	0.013	1.356	5.172	5.8E+04
	0.048	0.024	0.126	1.963	0.401	0.221	0.009	2.507	4.026	4.8E+04
	0.036	0.020	0.106	1.820	0.385	0.188	0.005	2.892	4.160	3.6E+04
	0.029	0.015	0.097	1.857	0.372	0.191	0.003	2.521	4.768	2.9E+04
	0.021	0.013	0.080	1.699	0.360	0.160	0.002	2.999	4.835	2.1E+04
40	0.104	0.042	0.210	2.497	0.450	0.360	0.041	1.434	3.903	1.0E+05
	0.087	0.037	0.187	2.353	0.433	0.320	0.029	1.604	3.898	8.7E+04
	0.071	0.034	0.157	2.078	0.414	0.254	0.019	2.143	3.586	7.1E+04
	0.060	0.031	0.139	1.937	0.398	0.222	0.014	2.408	3.511	6.0E+04
	0.054	0.028	0.133	1.938	0.391	0.220	0.011	2.332	3.693	5.4E+04
	0.045	0.032	0.099	1.397	0.378	0.132	0.008	5.550	2.476	4.5E+04
	0.036	0.024	0.093	1.502	0.360	0.139	0.005	3.838	3.115	3.6E+04
	0.029	0.026	0.070	1.127	0.348	0.091	0.003	7.043	2.225	2.9E+04
	0.024	0.020	0.066	1.180	0.336	0.091	0.002	5.450	2.652	2.4E+04
	0.019	0.020	0.051	0.943	0.324	0.065	0.001	7.299	2.129	1.9E+04
	0.015	0.015	0.049	1.010	0.312	0.067	0.001	5.452	2.608	1.5E+04
42	0.133	0.057	0.226	2.349	0.476	0.338	0.067	1.851	3.147	1.3E+05
	0.121	0.050	0.220	2.406	0.459	0.345	0.055	1.607	3.429	1.2E+05
	0.108	0.046	0.206	2.367	0.449	0.331	0.044	1.647	3.542	1.1E+05
	0.094	0.041	0.189	2.265	0.434	0.303	0.033	1.779	3.549	9.4E+04
	0.077	0.039	0.158	1.992	0.415	0.241	0.022	2.377	3.238	7.7E+04
	0.063	0.034	0.138	1.844	0.398	0.208	0.015	2.736	3.189	6.3E+04
	0.048	0.028	0.114	1.674	0.375	0.171	0.009	3.121	3.170	4.8E+04
	0.038	0.028	0.088	1.337	0.359	0.119	0.005	4.994	2.537	3.8E+04
	0.031	0.024	0.079	1.302	0.345	0.110	0.004	4.607	2.705	3.1E+04
	0.025	0.020	0.070	1.245	0.331	0.099	0.002	4.432	2.832	2.5E+04
	0.020	0.017	0.062	1.190	0.318	0.089	0.001	4.262	2.939	2.0E+04

Figure 7 presents the results of the present study for a spillway slope of 1:1 along with those of Peyras et al. [7] for the same slope. As can be seen, a good agreement exists between our data and those of Peyras et al. [7]. Based on this Figure, stone size has a slight influence on energy loss. Another comparison between the data obtained in the present study and that reported by Peyras et al. [7] for a spillway slope of 1:2 is presented in Fig. 8, which again reveals the good agreement between the data obtained from the two studies.

Although a few more discrepancies exist in energy loss at 1:2 slope with respect to 1:1 slope, overall, increasing gabion porosity increased energy dissipation, but this effect was minor at higher discharges. This is perhaps due to more contact surface in 1:2 slope with respect to 1:1 slope which causes more energy dissipation in 1:2 slope.

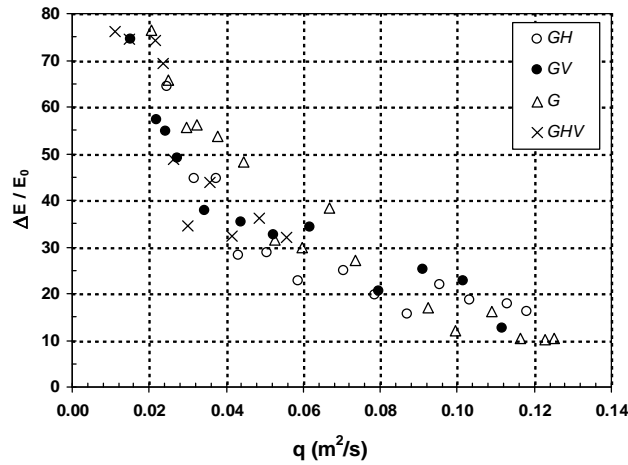


Fig. 5. Variation of relative energy dissipation and unit discharge for a slope of 1:1 ($V:H$) and a porosity of 38%

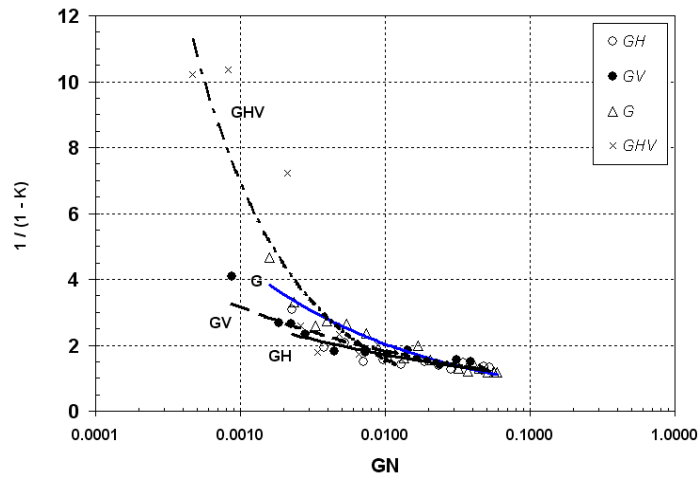


Fig. 6. Variation in $1/(1-K)$ vs. $GN = q^2 / gH_w^3$ for four spillway setups with a slope of 1:1 and a porosity of 38%

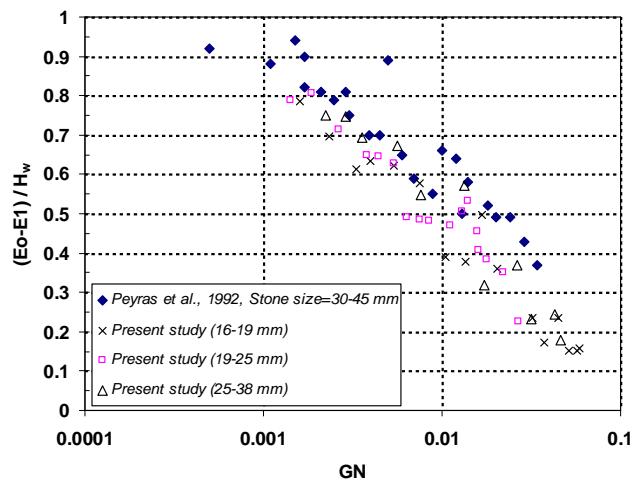


Fig. 7. Comparison of experimental data for a spillway slope of 1:1 obtained in the present study (G type) and in Peyras et al. [7]

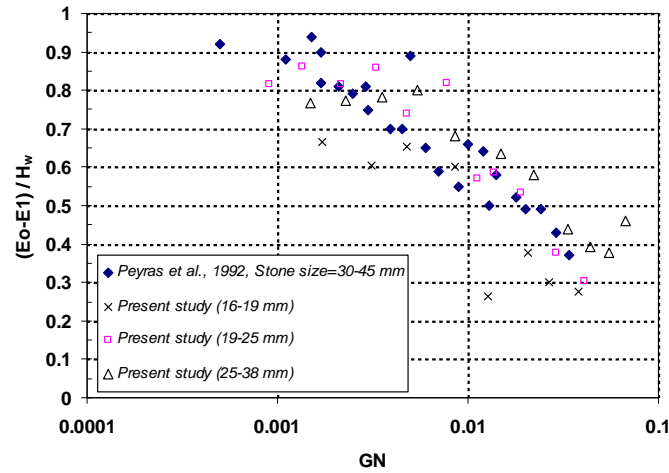


Fig. 8. Comparison of experimental data for a spillway slope of 1:2 obtained in the present study (*G* type) and in Peyras et al. [7]

The experiments reported in Kells [6] and those in the present study for a slope of 1:1 are compared in Fig. 9. Kells' [6] physical gabion models had three steps, each having a height of 12.5 cm, an average porosity of 37.7%, and two slopes of 1:1 and 1:2 (*V:H*). These experiments involved four test configurations: with/without upstream barrier and/or horizontal step capping. In Fig. 9, Kells' [6] model tests are designated as *K11* (no barrier, no capping), *K12* (with barrier, no capping), *K13* (with barrier, with capping), and *K14* (no barrier, with capping). In fact, *K11*, *K13*, *K14* test conditions are, respectively, similar to *G*, *GH*, and *GHV* setups in our study. In *K13* test, there was a very small through-flow, while most of the water entering the gabion over-flowed. Thus, the energy loss for the *K13* test configuration cannot be perfectly compared with the other results.

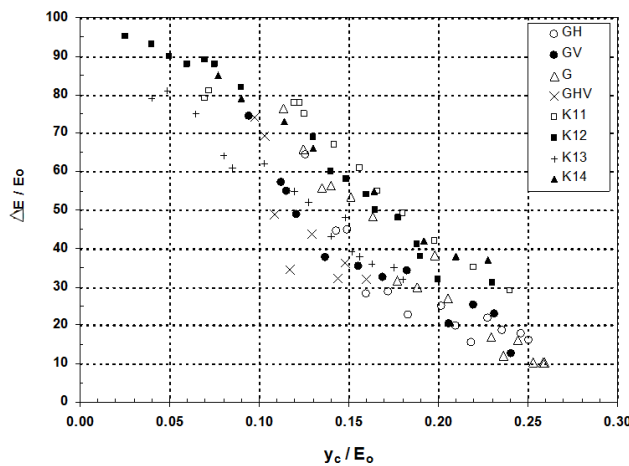


Fig. 9. Comparison of experimental data for a spillway slope of 1:1 obtained in the present study and in Kells [6]

Figure 10 shows the comparison between the data reported by Chinnarasri et al. [8] and those of the present work for the *G* setup. In Chinnarasri et al. [8], spillway heights (H_w) were 1.50, 2.12, and 2.60 m for $\alpha = 30^\circ$, 45° , and 60° , respectively, and the number of steps were 20, where α is the gabion stepped spillway slope. It is seen that the energy dissipation occurring in Chinnarasri et al. [8] is higher than those in either the present work, in Kells [6], or in Peyras et al. [7]. This is most probably due to the greater spillway height selected in the experiments by Chinnarasri et al. [8]. Note that in the Chinnarasri et al. [8] study, gabion was present only in the steps and not in spillway/weir body (Fig. 2 in Chinnarasri et al., [8]). In the present experiments, the whole weir was built with gabion. This type of weir has many applications

in low height spillway and soil and water conservation works. The vertical face of weir is impervious in the Chinnarasri et al. [8] study, but in the present experimental study, it is pervious (see Fig. 4). This difference in the setup may alter the energy dissipation rate.

According to Chinnarasri et al. [8], the relationship between the energy loss in the gabion-stepped weirs and the modified drop number as $D_m = q^2 (\tan \alpha)^2 / gH_w^3$ can be expressed by:

$$\frac{\Delta E}{E_o} = 0.53D_m^{-0.05} \tag{8}$$

Whereas in the present study, it has the following form:

$$\frac{\Delta E}{E_o} = 0.106D_m^{-0.29} \tag{9}$$

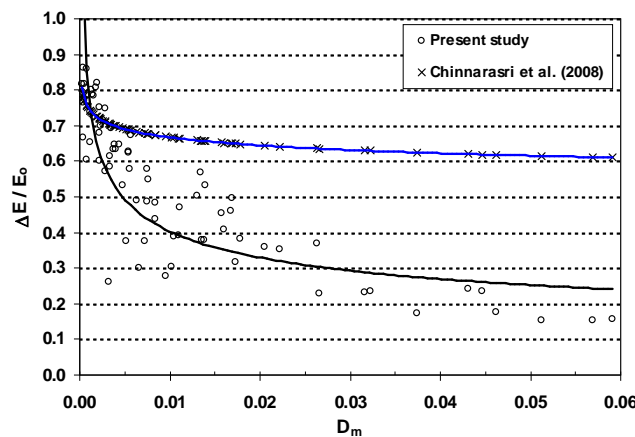


Fig. 10. Comparison of the data in the present study (*G* type) and those in Chinnarasri et al. [8] for different slopes

Figure 11 presents the variation in energy dissipation for three stone sizes and a slope of 1:1. It is clear that stone size (or porosity) has a small effect on energy dissipation. Figure 12 compares energy dissipations for the two slopes of 1:1 and 1:2 along with the fitness equations for each slope. Gabion stepped spillway with the milder slope (1:2) shows a higher energy dissipation than the steeper slope of 1:1. At lower slope values, the interaction between over-flow and through-flow is due to the increased length of flow path, which results in more energy being dissipated.

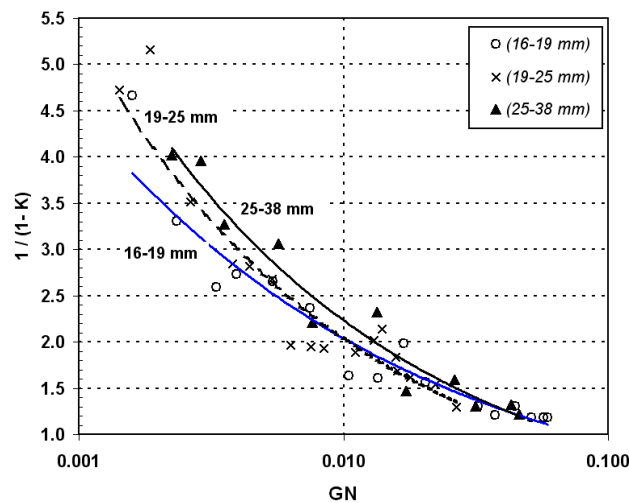


Fig. 11. Variation in energy dissipation for three stone sizes and a slope of 1:1.

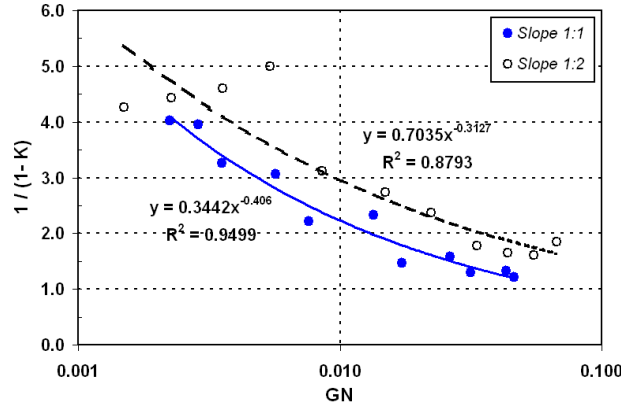


Fig. 12. Energy dissipation for the two spillway slopes of 1:1 and 1:2 with $n = 42\%$

Multiple regression analysis was performed with different combinations of the dimensionless parameters in Eq. (6). Several linear and non-linear multiple regressions were conducted using the SPSS software. The results are reported in Table 2. Using Eq. (14), the values for energy dissipation for different spillway slopes ranging from 1:1 to 1:4 ($V:H$) are presented in Fig. 13. It can be seen that when G increases, energy dissipation for different spillway slopes tends to converge. Thus, at higher discharge rates (q), the effect of slope on energy dissipation is less predominant. Using Eq. (15), variations of energy dissipation are shown in Fig. 14 for the different porosities of 20 to 60%. It can be seen that porosity (n) has a smaller effect on energy dissipation.

Table 2. Fitness equations for physical models

Spillway type	Slope (S)	Porosity (n)	Fitness equation	R^2	Eq. No.
GHV	1:1	38%	$1/(1-K) = 0.080(GN)^{-0.644}$	0.80	10
G			$1/(1-K) = 0.420(GN)^{-0.343}$	0.94	11
GV			$1/(1-K) = 0.613(GN)^{-0.238}$	0.88	12
GH			$1/(1-K) = 0.664(GN)^{-0.206}$	0.74	13
G	All slopes	All porosity	$1/(1-K) = 0.417(GN)^{-0.359}(S)^{0.338}$	0.73	14
G	All slopes	All porosity	$1/(1-K) = 0.312(n)^{0.079}(GN)^{-0.377}$	0.68	15
G	All slopes	All porosity	$1/(1-K) = -0.781(S)^{-3.305} - 90.182(n)^{-27.121} + 0.680(GN)^{-0.316}$	0.74	16

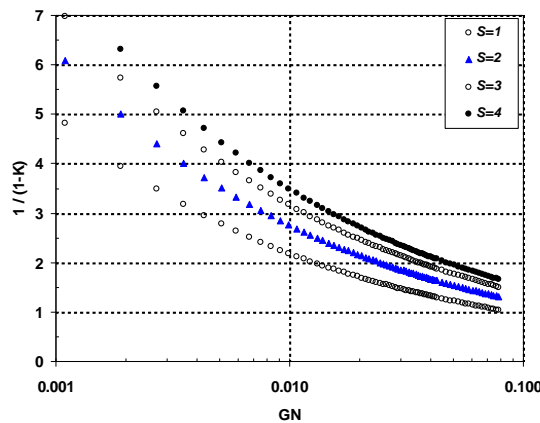


Fig. 13. Energy loss for different spillway slopes from 1:1 to 1:4

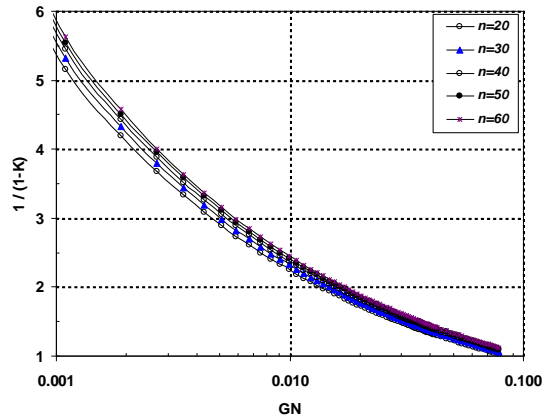


Fig. 14. Energy loss for different stone porosities

5. CONCLUSION

The experimental study of eight physical models of low height gabion stepped spillway was presented. It was shown that, at high discharge rates, gabion stepped spillways have more of the flow energy dissipated than their impervious counterparts. Comparison of semi-pervious step faces (*GH* or *GV* type) revealed that a layer on the vertical face of each step (*GV*) has a greater effect on increasing energy dissipation than a horizontal layer (*GH*). Physically it can be explained that when flow through the gabion medium hits the vertical face exerted on each step, more energy dissipation occurs than in horizontal interaction. This is because of flow net inclination results flow impinging on the vertical faces.

At low discharge rates with a nappe flow regime, energy dissipation was found to be less than that of the *GHV* setup only when through-flow occurs in *G*, *GV*, and *GH* setups. In a nappe flow in *GHV*, step roughness against flow had a significant resistance effect, whereas in *G*, *GV*, or *GH* with only a through-flow, the flow resistance was lower. More energy loss was observed to occur for a smaller slope (1:2) than for the higher one (1:1). Stone size seems to have only a small effect on energy loss compared to the spillway slope. The experimental data obtained in this study were compared with the results reported by other researchers. A good agreement was observed between the results obtained from the present study and those of Peyras et al. [7] and Kells [6]. The results reported in Chinnarasri et al. [8], however, showed a higher energy loss than that observed in the present study.

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NOMENCLATURE

b	spillway width
E_1	energy at the downstream of spillway before hydraulic jump
E_o	total energy at the upstream of spillway
ΔE	the difference between energy at the upstream and at the downstream of the spillway ($\Delta E = E_o - E_1$)
F_r	supercritical Froude number $= V_1 / \sqrt{g y_1}$
g	acceleration due to gravity
h	each step height
H_w	total spillway height from flume bed
L	each step length
K	relative energy dissipation defined as $K = (E_o - E_1) / H_w$

n	stone porosity filled in gabion
q	discharge per unit width
Q	discharge
R_e	Reynolds number = $V_1 y_1 / \nu$
S	weir / spillway slope ($V: H$)
V_a	approach velocity = (q / y)
V_1	velocity at the toe of the spillway
y_0	depth of flow about 0.60 m upstream of the spillway above the spillway crest
y_1	depth before hydraulic jump at the spillway toe
y_2	depth after hydraulic jump
α	weir / spillway angle (degree) with horizontal line

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