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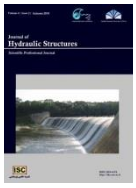

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# Hydraulics of flow in gabion stepped spillways, an experimental study

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## Abstract

In this study, the effect of different hydraulic parameters on the energy loss of flow over gabion stepped spillways are examined using physical models and comparisons are made with the other studies. Two end sills including rectangular and inclined shapes are used on each spillway step. The results showed that the influence of end sills in gabion stepped spillways with lower slopes is greater than that of spillways with higher slopes. The influence of end sills on energy loss in spillways with $d_{50}$=40 mm and $S$ = 1:2 is about 10% more than the spillways with $d_{50}$=10 mm and $S$ = 1:1 ($d_{50}$ is the mean diameter of gravel in the gabion and $S$ is the downstream slope of the gabion stepped spillways, vertical: horizontal). Energy dissipation in spillways with $d_{50}$=10 mm and $S$ = 1:2 is about 30 to 35 percent more than spillways with $d_{50}$=10 mm and $S$ = 1:1. Hence, end sills in spillways with gravel size of $d_{50}$ = 10 mm have the most significant impact on the energy loss. Instead, the influence of the rectangular end sill on the energy loss is about 3-4% more than the effect of a triangular (inclined) end sill.

**Keywords:** Energy Loss; Gabion; Inclined End Sill; Rectangular End Sill; Stepped Spillway.

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## 1. Introduction

Stepped spillways consist of a set of steps that start at the crest of the spillway and continue to the downstream toe. Due to the effects of steps on increasing energy dissipation, in recent years, much attention has been paid to this type of spillway. High energy dissipation created by steps reduces cutting depth, length and height of stilling basin, and stilling basin construction costs [1].

Cascade channels/stepped spillways are the oldest hydraulic structures and their application in dam engineering date back about 3500 years [2]. Gabion stepped spillways in catchments are used to control flood erosion and raise water levels for diverting water in irrigation canals. Most studies have been carried out on impermeable/rigid spillways and fewer studies have been done on permeable (gabion) spillways despite the fact that they have many advantages. Among the advantages of gabion spillways are ease of implementation, flexibility, high permeability, stability, cost-effectiveness, and most importantly, environmental friendliness [3]. These types of spillways have more flexibility than rigid spillways and are resistant to pressure loads. The energy dissipation of flow from such structures is high because of the presence of through flow and overflow and therefore the costs of constructing a stilling basin are reduced [4, 5].

From a water quality perspective, chemical and physical materials such as suspended organic matter and sediment can pass through the porous grains, minimizing the deposition and accumulation of sediment upstream of the spillway [6]. Bacteria that reside on the grain surface may cause organic matter to break down on these rocks. This biochemical reaction leads to the decontamination of river water as it passes through the rocks. Also, turbulence in the aggregate environment enhances the total aeration by aerobic decomposition of organic matters. Therefore, gabion spillways are more hydraulically efficient than impermeable spillways [7].

Roushangar et al. [8] calculated the energy dissipation rate (EDR) using the following equation:

$$EDR = \frac{100\left(E_1^{smooth} - E_1^{stepped}\right)}{E_1^{smooth}} \tag{1}$$

where $E_1^{smooth}$ is the specific energy downstream of the smooth spillway and $E_1^{stepped}$ is the specific energy downstream of a stepped spillway.

Salmasi et al. [4] performed experiments on gabion stepped spillways with porosities of 38, 40 and 42% and slopes of 1:1 and 1:2 (V: H). Their experiments consisted of vertical and horizontal impervious iron plates on steps. The results showed that steps with vertical impermeable faces have more energy loss than horizontal impermeable faces. They also found that with increasing porosity and decreasing slope, the flow energy loss increases.

Tuna [9] and Tiona and Emiroglu [10] carried out experiments on local scouring downstream of stepped spillways. Their results showed that by increasing the slope of the spillway and the discharge, the scour depth downstream of the spillway increases. Their results also showed that the ratio of step height to step length has a noteworthy effect on downstream scour depth. For the lowest ratio of step height to step length (equal to 0.577), the greatest amount of scouring occurs. Zare and Doering [11] performed experiments on stepped spillways with rounded and sharp corner steps. The results showed that round steps dissipate 3% more flow energy than sharp steps in spillways. Felder and Chanson [12] conducted experiments on stepped spillways with a slope of 26.6 degrees. The spillways had three end sills with porosities of zero, 5, and 31%. The results showed that the energy remaining in the toe of stepped spillways comprising end sills with porosities of 5 and 31% is about 1.3 and 1.5-2 times more than the energy remaining in the stepped spillways with end sills that were non-porous. They also suggested the use of flat plates (without sills) due to flow stability and better energy loss performance.

Wuthrich and Chanson [13] conducted experiments on gabion stepped spillways with and without rigid covers on the steps and examined the aeration rate. The results indicated that at lower discharge, the production of aeration in a gabion stepped spillway increases and with increasing flow and the formation of a skimming flow regime, the production of aeration in the spillways (including those with impermeable smooth steps) increases. They also reported that the number of bubbles and the intensity of the turbulence in the escalators of gabion stepped spillways decreases. The energy loss for a gabion stepped spillway is less than that for an impermeable stepped spillway at larger discharge rates.

Parsaie and Haghiabi [14] studied the hydraulic properties of circular crested stepped spillways (CCSS) including the stage-discharge relation and the discharge coefficient ($C_d$). Results revealed that the most important factor in estimation of $C_d$ is relative head flow, $h_{up}/R$. Parsaie and Haghiabi [15] investigated the hydraulic properties of the finite-crested stepped spillway (FCSS) including $C_d$ and the energy dissipation rate (EDR). Results indicated that the $C_d$ of the FCSS changes between 0.9 and 1.2.

The goal of application of a sill in a stepped spillway is to increase energy dissipation. Application of a sill can be seen in other hydraulic structures. For example, Daneshfaraz et al. [16] used a cubic sill with different widths under a vertical sluice gate to investigate $C_d$. The results of that study showed that the placement of the sill with a width of 7.5 and 20 cm, increased the $C_d$ by an average of 5.3% and 15.5% in the experimental tests. In another study, Daneshfaraz et al. [17] conducted a series of experiments to investigate the effect of sill geometry and sill width on the $C_d$ and hydraulic jump characteristics. Results indicated that increasing the sill width increased the sluice gate $C_d$ compared to the gate without sill. Placing a sill with different geometric shapes specifies that using a semi-cylindrical sill increases the $C_d$.

Daneshfaraz et al. [18] investigated the simultaneous effect of the gabion and vertical screens on the flow energy loss in the inclined drop structure. The results show that the use of a vertical screen in a gabion motivated drop has little influence on flow energy loss so that the increase in depreciation compared to a simple inclined drop equipped with vertical screens is 2.23%.

As described above, most studies have been carried out on rigid/impermeable stepped spillways. On the other hand, the importance of gabion spillways for the environment and the applicability of these structures in river engineering projects is clear. Therefore, the purpose of this study is to conduct laboratory tests on gabion stepped spillways and to study the effect of rectangular and inclined sills on energy loss. Application of sills in a gabion stepped spillway and its effect on energy dissipation has not seen previously in literature review. In addition, distinguishing a skimming flow regime from a nappe flow regime in these spillways and the development of mathematical relationships for estimating energy loss are the aspects of innovation in this study.

## 2. Material and methods
### 2.1. Experimental setup

The experiments were performed in the hydraulic laboratory in University of Tabriz, Department of Water Engineering, Iran. As shown in Fig. 1, the experiments used a metal-glass flume with a length of 10 m and a width of 0.4 m. The first 2 m of flume is 1 m high and the rest of the length is 0.5 m high, with a fixed inverted slope. The invert of the flume is made of galvanized iron and its walls are made of glass with a thickness of 10 mm. The flow rate was measured using an ultrasonic device installed at the beginning of the inlet pipe to the flume. The discharges measured by the ultrasonic device were compared with the discharges measured by a pre-calibrated rectangular weir downstream of flume and the average difference was ~ 2.5%. A porous metal box was used to calm the water flow at the beginning of the flume.

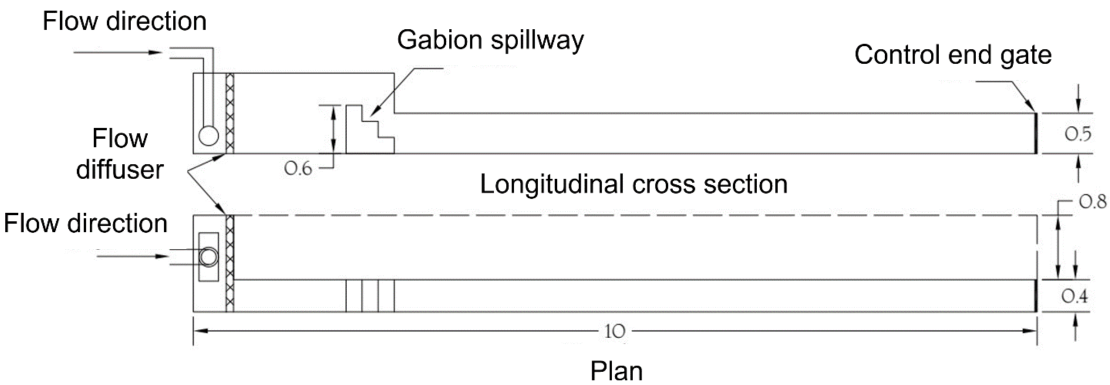



**Figure 1. View of the experimental facility and the location of the stepped gabion spillway (dimensions in meters)**

**a) View of rectangular weir at downstream of flume**


**b) View of the acoustic depth gauge**

**Figure 2. Photograph of the experimental flume and upstream stepped gabion spillway**

In this study, uniform gravel particles with three average diameters ($d_{50}$) of 10, 25 and 40 mm have been used. Normally, it is reasonable for physical model scale to be 1:10 (model: prototype). With this value, the gravel particles in a real spillway (prototype) become 100, 250 and 400 mm and these are the normal sizes of available gravel and boulders in natural settings.

To determine the porosity of a gabion basket, a specific volume of the gabion was placed inside a dish containing an overflowing water. Then, by determining the amount of water poured out of the dish, the volume of gabion, and using the relationship $e=V_{void}/V_{total}$, the porosity of the particles was determined. It can be mentioned that $V_{void}$ is the volume of void in the gabion basket (here is the volume of water poured out) and that $V_{total}$ is the total volume of the gabion basket.

Two parallel rails were installed at the top of the flume to move the acoustic depth gauge with a sampling frequency of 20 Hz and a measurement accuracy of 12 bits to measure the water depth. For calibrating the acoustic gauge, boxes with specific calibrated dimensions were put under the gauge, then the height of the boxes was introduced to the software for the gauge and the coefficients related to the calibration after trial and error was calculated using the relationships provided by its manufacturer and finally introduced to the software. Because measuring the depth of water downstream of the last step of the spillway due to high turbulence can lead to incorrect results, the depth of the downstream flow was measured three to four times the length of the steps and the maximum distance of 1 m was measured from the last side of the spillway step, where the mixing of water with air is minimized. This method has been utilized by Chinnarasri and Wongwises [19]; and Stephenson [20]. The height and width of the physical models made of the stepped gabion spillways were fixed at 60 and 40 cm, respectively. There are 3 steps and the downstream slope of the spillways was 1:1, 1:2 and 1:3. The end sills are rectangular and inclined (in the form of gabion baskets), the details of which are given in Table 1 and Fig. 3.

In Table 1, $h_s$ is the step height, $h_b$ is the rectangular sill height, $h_a$ is the inclined sill height, $l_b$ is the rectangular sill length and $l_a$ is the inclined sill length. Values of $h_s$, $h_b$, $h_a$, $l_b$ and $l_a$ were 40, 80 and 100 mm. These values can be used for a real stepped spillway with a scale about 1:10.

The total number of experiments performed and the range of variation of the variables are presented in Table 2 (kinematic viscosity of water at 20 °C is assumed to be equal to $v=10^{-6}$ $m^2/s$).

**Table 1. Details of geometrical dimensions used in this study**

| Sill type | Dimensionless parameter | Value | | | |
|---|---|---|---|---|---|
| Rectangular | $h_b/h_s$ | 0.5 | 0.4 | 0.2 | 0 |
| | $l_b/h_s$ | 0.25 | 0.25 | 0.25 | - |
| Inclined | $h_a/h_s$ | 0.5 | 0.25 | 0 | - |
| | $l_a/h_s$ | 0.5 | 0.5 | - | - |

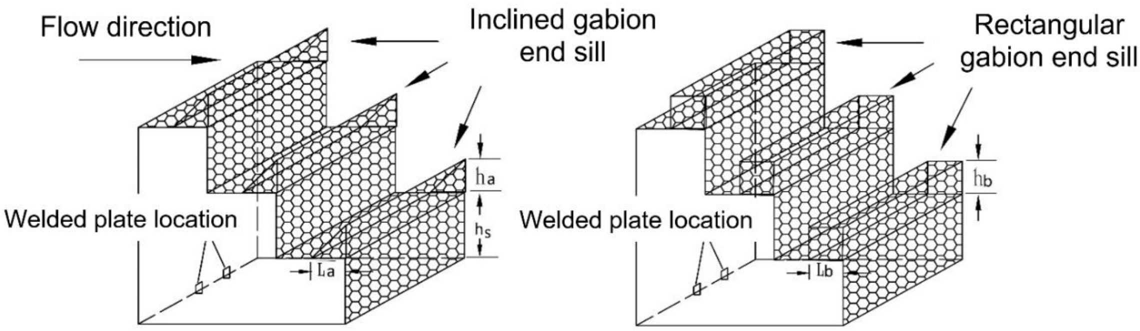



**Figure 3. A 3D view of the gabion stepped spillways comprising rectangular and inclined end sills**

**Table 2. Range of input parameters and number of experiments**

| Discharge variations (l/s) | Reynolds number, $R_e$ | Froude number, $F_r$ | Total number of experiments |
|---|---|---|---|
| 5-65 | $1.3\times10^4$ - $5.7\times10^5$ | 0.4-4.8 | 540 |

In Table (2), the Froude and Reynolds numbers are determined from the relations $F_r=V_1/(gy_1)^{0.5}$ and $R_e=V_1R_1/v$, respectively. In these relations $V_1$ and $y_1$ are the mean velocity and depth of the flow downstream, respectively, $R_1$ is the hydraulic radius, $g$ is the acceleration of the earth's gravity and $v$ is the kinematic viscosity of water.

According to Table (2), the subcritical flow upstream of the spillway turns into a supercritical flow as it passes over the spillway where Froude numbers become greater than unity. Of course, Froude numbers greater than unity are related to high discharge. Because through flow also occurs in pervious gabion spillways, Froude numbers less than unity are also related to lower discharges but high velocity collisions of the flow with gravel particles occur inside the gabion.

## 2.2. Flow regimes

There are three types of flow regime over stepped spillways which will now be discussed (Rajaratnam, [21]; Chanson, [22]): nappe, skimming and transition flow regimes. In Fig. 4, sketches of the three flow regimes are presented.

Nappe flow regime over a stepped spillway happens when discharge is low or the slope of spillway is mild (α in Fig. 4). In this regime, a number of free jets are impinging on the steps and high water surface fluctuation occur. Energy dissipation occurs by impinging of the upper jet with the downstream step or by creation of a hydraulic jump in each horizontal step invert.

An skimming flow regime occurs when discharge is high or the slope of the spillway is steep. In this flow regime, all of the steps are submerged under the water surface. The depth of water over the stepped spillway is high and the roughness effect of each step is reduced; more of the energy dissipation occurs by recirculating vortices (Fig. 4). Usually when a flood happens in an upstream watershed, skimming regime is formed. Most currently available research has been done for skimming flow regime.

Transition flow occurs when the discharge is medium. This type of regime is accompanied with splashing of water around the spillway. The flow regime is neither nappe nor skimming. This type of regime is not recommended for design, because of enormous water surface fluctuations.

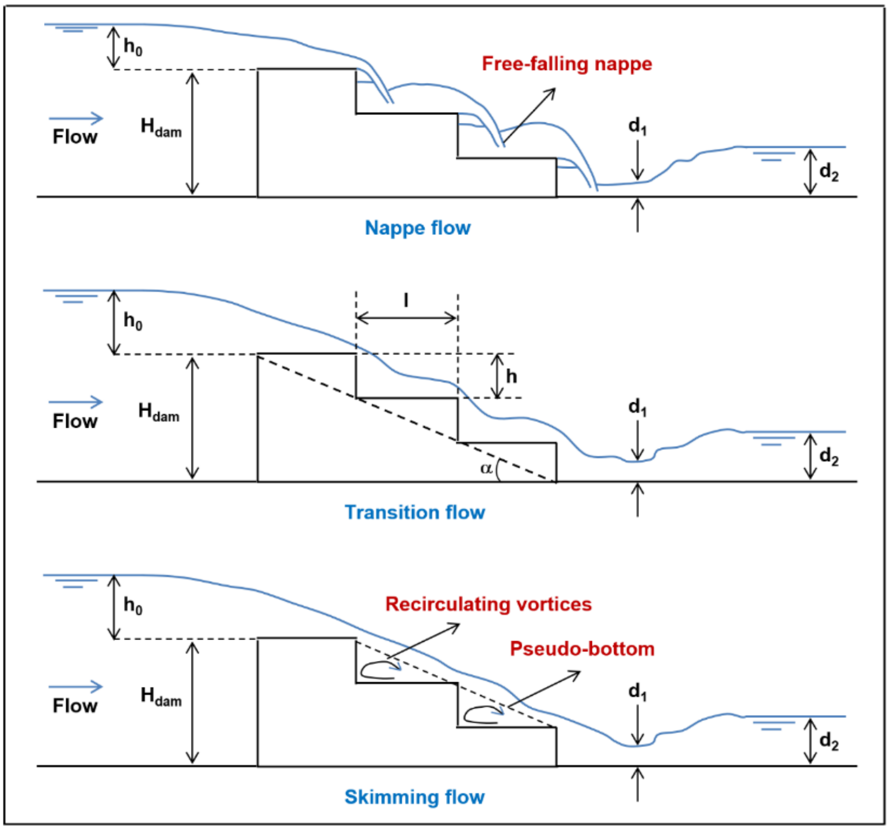



**Figure 4. Three types of flow regimes over stepped spillways**

## 2.3. Dimensional analysis

Effective parameters in dimensional analysis include factors related to the geometric and hydraulic properties of the flow over the stepped spillways. Parameters related to geometric properties are: triangular/inclined sill height ($h_a$), rectangular sill height ($h_b$), spillway height ($H_w$), step length ($l_s$), step height ($h_s$), rectangular sill length ($l_b$), length of the triangular sill ($l_a$) and average diameter of gravel particles ($d_{50}$).

Parameters related to hydraulic properties are: critical depth ($y_c$), upstream water depth ($y$), upstream water velocity ($V$), water specific gravity (ρ), kinematic viscosity of water ($v$), water surface tension ($\sigma$), discharge per unit of width ($q$), kinetic energy correction factor ($\alpha$), and gravitational acceleration ($g$).

The kinetic energy correction factor ($\alpha$) is in the range of 1.05 to 1.08 and since it will not have much effect on the results, its value in this study is set equal to one. According to the above variables, Eq. (2) can be written:

$$f_1(h_a.h_b.y_c.g.y.V.H_w.l_s.h_s.l_b.l_a.d_{50}.\rho.v.\sigma.q) = 0 \quad (2)$$

where $f_1$ is the functional.

There are 16 variables in Eq. (2). Considering the factors ρ, $V$ and $y$ as iterative variables and using Buckingham's $\pi$ theory, the following dimensionless functional relationship is obtained:

$$f_2\left(\frac{\Delta E}{E_0}.\frac{q^2}{gH_w{}^3}.\frac{d_{50}}{y_c}.\frac{y_c}{H_w}.\frac{y_c}{h_s}.\frac{h_s}{l_s}.\frac{h_a}{h_s}.\frac{h_b}{h_s}.\frac{l_a}{l_s}.\frac{l_b}{l_s}{}_r.\frac{V}{\sqrt{gy}}.\frac{Vy}{\nu}.\frac{\rho V^2 y}{\sigma}\right)=0 \quad (3)$$

In Eq. (3), $E_0$ is the specific energy upstream the spillway, $E_1$ is the specific energy downstream of the spillway, and $\Delta E$ represents the energy loss between the upstream and downstream of the spillway. Also, $S = h_s/l_s$ represents the spillway slope, $F_r=V/(gy)^{0.5}$ represents the Froude number, $R_e=Vy/\nu$ is the Reynolds number, and $W_n=\rho V^2 y/\sigma$ is the Weber number. In Eq. (3), the Weber number ($W_n$) can be omitted due to the low surface tension effect. The Reynolds number ($R_e$) is also ignored due to the turbulence conditions over the stepped spillway [23]. The variable $q^2/gH_w{}^3$ is the relative discharge and in some studies it is also known as the drop number (Khatibi et al., [24]). In Eq. (3), the dimensionless factors $l_a/l_s$ and $l_b/l_s$ are constant and are therefore omitted in this study. The three factors $E_0$, $E_1$, $\Delta E$ are defined by Eqs. 4-6.

$$E_0 = H_w + y + \frac{V_0{}^2}{2g} = H_w + y + \frac{q^2}{2gy^2} = H_w + 1.5y_c \quad (4)$$

$$E_1 = y_1 + \frac{V_1{}^2}{2g} = y_1 + \frac{q^2}{2gy_1{}^2} \quad (5)$$

$$\Delta E = E_0 - E_1 \quad (6)$$

According to the above discussion, the final equation for calculating energy loss is summarized in Eq. (7).

$$\frac{\Delta E}{E_0} = f_1\left(\frac{q^2}{gH_w{}^3}.\frac{d_{50}}{y_c}.\frac{y_c}{H_w}.\frac{y_c}{h_s}.\frac{h_a}{h_s}.\frac{h_b}{h_s}.S\right) \quad (7)$$

## 3. Results and discussion

In Figs. 4-6, flows are presented from gabion stepped spillways with different hydraulic conditions. The flow regime on the spillways can be divided into nappe and skimming regimes. During the nappe regime, the water jet falls from one step to another. In this flow regime, water hits the steps and energy loss occurs due to this impact and mixing of water jets on each of the steps and complete or partial hydraulic jumps may occur. To create a nappe flow, the height of the steps must be considered relatively high, and this occurs for low discharges and low spillway slopes. On the other hand, for the skimming flow regime, water flows completely over the steps. Skimming flow occurs at high discharge, so the design of stepped spillways is based on the skimming flow regime.

**Figure 4. Spillway with 3 steps, slope=1:3 (V: H) and Q=66 l/s, d50=25 mm including rectangular sills (d50=40 mm, hb/hs=0.4)**

**Figure 5. Spillway with 3 steps, slope=1:2 (V: H) and Q=45 l/s, d50=10 mm including inclined sills (d50=10 mm, ha/hs=0.25)**


**Figure 6. Spillway with 3 steps, slope=1:1 (V: H) and Q=55 l/s, d50=40 mm including inclined sills (d50=40 mm, ha/hs=0.5)**

Figure 7 shows the changes of relative flow energy loss ($\Delta E/E_0$) against relative critical depth ($y_c/H_w$) for 3-step gabion stepped spillways. In addition, in Fig. 7 the average particle diameters in the baskets are 10 and 40 mm and spillway slopes are 1:1, 1:2 and 1:3 (V:H). In Fig. 7, a comparisons with other studies is shown. It should be noted that the symbols specified in the following figures have the following meanings:

For example, the symbol "1:2, 10 mm, steps 3" means a 3-step gabion stepped spillway with an average particle diameter of 10 mm and a spillway slope of 1:2 (vertical to horizontal).

According to Fig. 7, as the discharge increases, the energy loss decreases and for $d_{50}$=10 mm, the energy dissipation is somewhat greater than for $d_{50}$=40 mm. In addition, with increasing discharge, the through flow role in the energy dissipation decreases and it is the overflow that plays the key role in the energy loss of flow over stepped spillways. Therefore, with increasing discharge, rigid/impervious stepped spillways and gabion stepped spillway will have similar performance with respect to energy dissipation. The lowest energy dissipation occurred in the 1:1, 10 mm, steps 3 spillway case. The spillway slope of the gabion stepped spillway has little effect on the energy loss.

According to Fig. (7), the results of this study are compared with data from other studies. It is observed that the results of current study are in agreement with the results of Zare and Doering [8], Christodoulou [25] and Peyras et al. [26]. The differences between these studies with the results of the present study are due to the fact that in most of the experiments of other studies, the flow is only in the form of overflow (rigid spillway), but in the present study, the flow is in the form of both overflow and through flow.

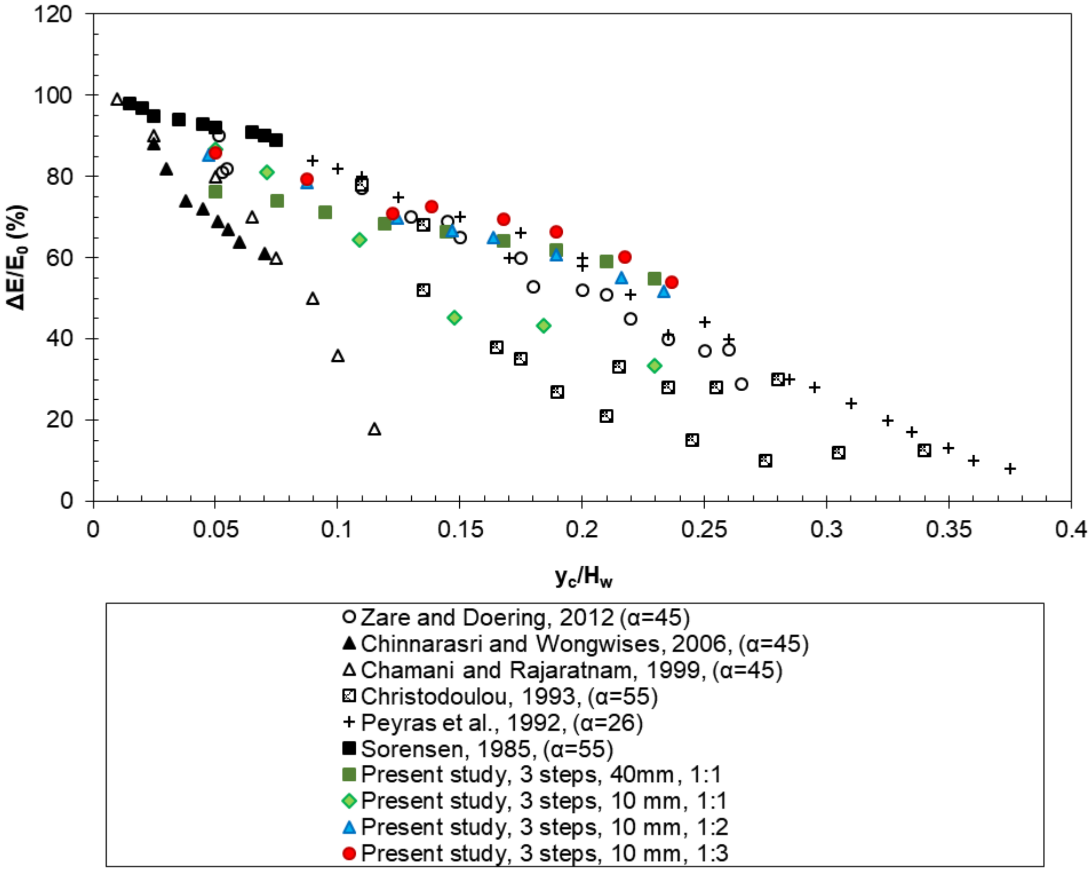



**Figure 7. Relative energy dissipation vs. relative critical depth and comparison with other studies**

Figure (8) presents a comparison between the results of this study with the laboratory study of Rajaei et al. [27]. In the Rajaei et al. [27] study, three physical models of gabion stepped spillways were fabricated including 1, 2 and 3 steps. The symbol $G_n$ refers to the gabion model and the subscript *n* represents the number of steps in the Rajaei et al. [27] study. In that study, the height of each step was 20 cm, with the slope of spillway 1:1; the flume width was 50 cm and the length was 11 m. They tested these three physical models of gabion stepped spillways under different discharges (Fig. 8).

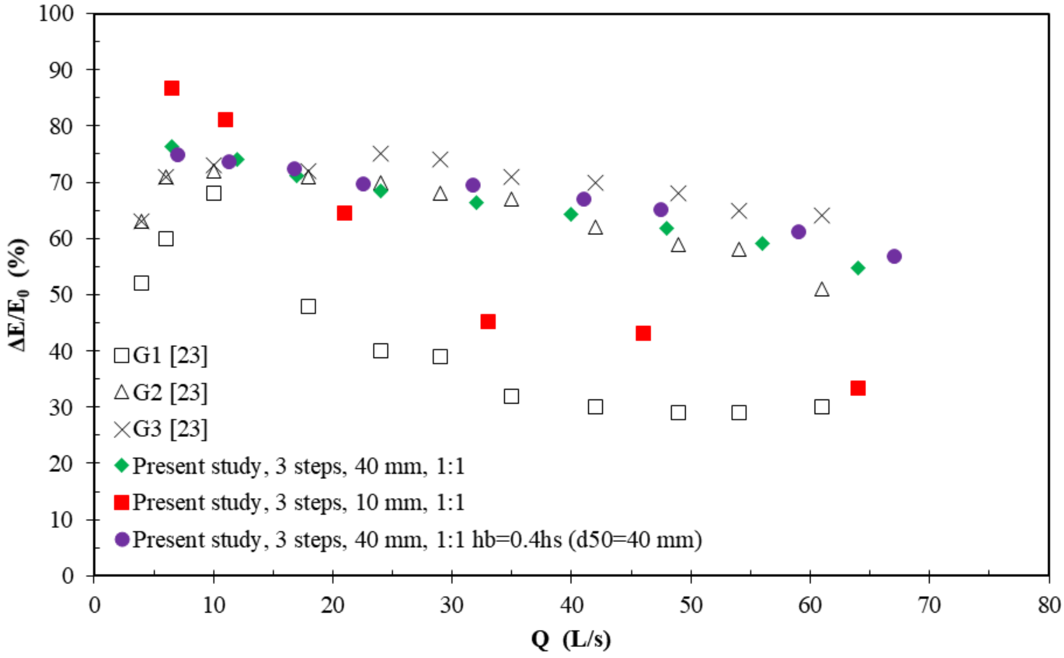



**Figure 8. Comparison of results of this study with Rajaei et al. [27] studies**

According to Fig. (8), energy loss in gabion spillway without sediment deposition behind it can reach up to 75%. Energy dissipation in the Rajaei et al. [27] experiments for a gabion spillway with one step is less than that with two or three steps and the two and three step spillways are almost equal in their energy dissipations. However, it has been shown that there is a slight increase of energy loss for the three-step spillway with respect to the two-step spillway. The results of present study are in close agreement with the results of Rajaei et al. [27] for two and three-stepped spillways, and the slight difference can be due to differences in the size of rock particles used in the gabion type spillways.

Previous studies show that increasing the discharge or increasing the spillway slope leads to the formation skimming flow regime. The most important quantitative parameter for a skimming flow regime is $y_c/h$. Chanson [22] and Chinnarasri [28] collected laboratory data from studies on stepped spillways and showed that formation of a skimming flow regime is a function of height, length of stepped spillways and discharge (Beitz and Lawless [29]). Table 3 provides data for the critical discharge values at which the skimming flow regime begins to appear.

According to the functional relationships presented by Chanson [22]; Chinnarasri and Wongwises [30] (Eqs. 8 and 10 in Table 4), a skimming flow regime occurs at discharges greater than the specified critical value ($y_c/h$). In the present study, an attempt has been made to investigate the accuracy of the relationships to identify the skimming flow regime and compare it with the observations obtained in this study.

**Table 3. Experimental data for onset of skimming regime**

| Reference | $h_s/l_s$ | $y_c/h_s$ |
|---|---|---|
| Essery and Horner [31] | 0.2 | 1.15 |
| | 0.42 | 0.84 |
| | 0.53 | 0.82 |
| | 0.74 | 0.82 |
| | 0.84 | 0.80 |
| Peyras et al. [26] | 0.33 | 0.74 |
| | 0.50 | 0.67 |
| | 1.00 | 0.61 |
| Beitz and Lawless [29] | 1.25 | 0.40 |
| Present study | 1.00 | 0.688 |
| | 0.50 | 0.688 |
| | 0.33 | 0.688 |

In Fig. 9, an attempt is made to provide a relation using the parameters $y_c/h_s$ and $h_s/l_s$ ($y_c$ is the critical depth, $h_s$ and $l_s$, are the height and length of the spillway step, respectively) in order to detect the onset conditions for skimming flow. With skimming flow, the water flows completely through the steps. Observations in stepped spillways showed that apart from the type of material used in the gabion stepped spillways ($d_{50}$), when the spillway slope is 1:1 (V: H), skimming flow regime occurs at a maximum discharge of 65 l/s. However, as the spillway slope is decreased to 1:2 and 1:3 (V: H) and for the same discharge ($Q$=65 l/s.), nappe flow regime is formed and the formation of the skimming flow regime requires higher discharge. Therefore, according to the results obtained from previous studies and comparing them with the present study, functional relationships to identify the skimming flow regime are presented in Table 4.

It is necessary to mention that the Eqs. 8 and 10 are valid for $h_s/l_s$ in the range of 0.2-1.3. Therefore, caution should be exercised outside this range (Fig. 9).

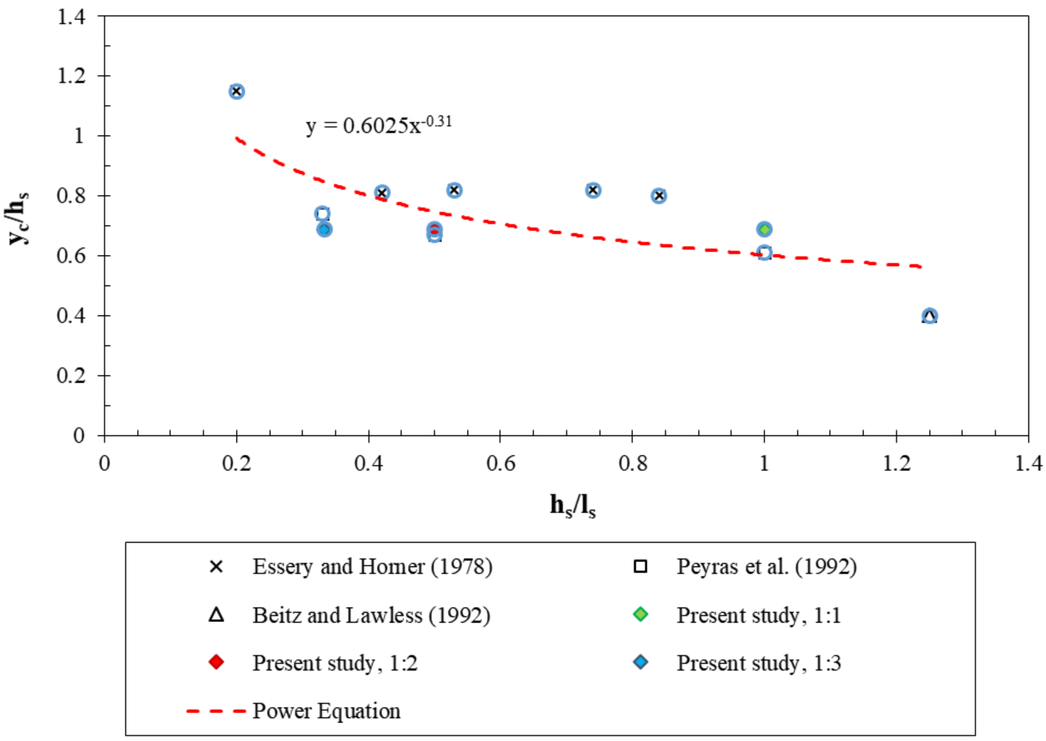



**Figure 9. Onset of skimming flow regime in stepped spillways**

**Table 4. Equations for determining skimming flow regime**

| Reference | Equation No. | Mathematical function |
|---|---|---|
| Chanson [22] | 8 | $\frac{(d_c)_{onset}}{h} \geq 1.057 - 0.465\frac{h}{l}$ |
| Present study (linear equation) | 9 | $\frac{(y_c)_{onset}}{h_s} \geq 0.972 - 0.364\frac{h_s}{l_s}$ |
| Chinnarasri [28] | 10 | $\frac{d_c}{h} \geq 0.80(\frac{h}{l})^{-0.22}$ |
| Present study (nonlinear equation) | 11 | $\frac{y_c}{h_s} \geq 0.602(\frac{h_s}{l_s})^{-0.31}$ |

Figure 10 shows the changes in relative energy loss against the relative roughness of the materials used in the gabion stepped spillways. Figure 10 shows that the changes in relative energy loss with increasing discharge for large-scale roughness are gradual. But these changes are sudden for small-scale roughness. Figure 10 also shows that up to a certain discharge, the relative energy loss for small-scale particle diameters ($d_{50}$=10 mm) is greater than that for medium-sized and large-scale particle diameters ($d_{50}$=25 and 40 mm, respectively). But for a certain flow rate onwards, the relative energy loss for large-sized particles (40 mm) becomes greater than that for medium-sized and small-sized particle diameters (25 and 10 mm, respectively). The main reason for this trend is the permeability of the materials used in the gabion spillways. In other words, when the grain size in the gabion spillways is 10 mm, with increasing discharge, the water level behind the gabion spillway rises faster than when the grain size of the gabion spillways is 40 mm. Therefore an overflow is formed, and low permeability of small diameter particles causes sudden changes in the relative energy loss in small-scale roughness.

Three different ranges of material roughness conditions in rivers, first classified and introduced by Bathurst [32] and Bathurst et al. [33], included small scale roughness (SR), large scale roughness (LR) and intermediate scale roughness (IR).

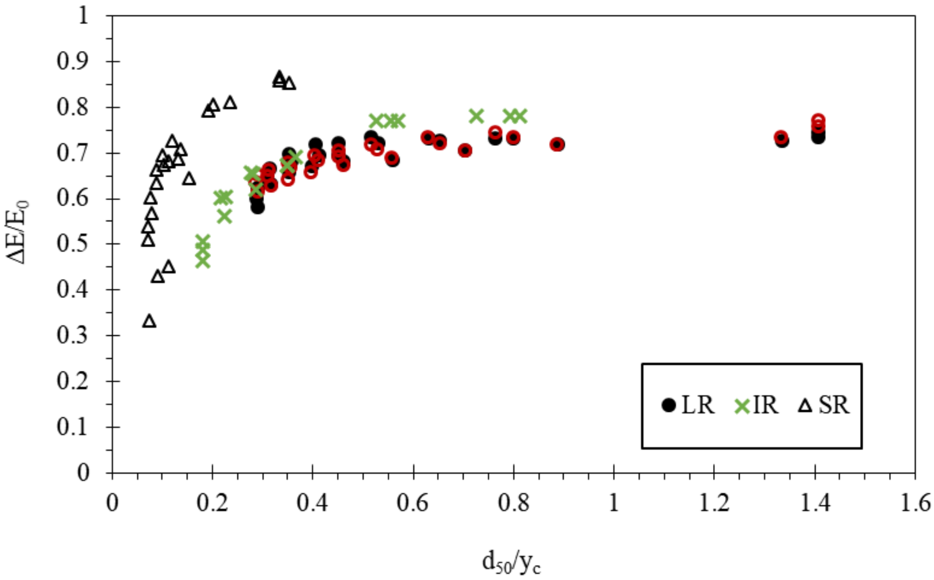



**Figure 10. Variation of relative energy dissipation vs. relative roughness**

In this study, an attempt has been made to provide the roughness conditions based on the dimensionless parameter $d_{50}/y_c$ (Table 5). An effort is also made to provide an equation for calculating the relative energy loss based on the roughness conditions defined in Table 5 and the spillway slope (*S*). For this purpose, Eq. 12 and its coefficients are presented in Table 6. The indicator $R^2$ in in Table is the determination coefficient. In Eq. 12, *S* is the spillway slope and its change domain is between 0.33 and 1.0.

**Table 5. Roughness conditions in this and other studies**

| Roughness conditions | Present study | Pagliara and Chiavaccini [34] | Bathurst [32] |
|---|---|---|---|
| Large scale roughness (LR) | $0.75<y_c/d_{50}<2.99$ | $h_c/d_{50}<2.5$ | $h_u/d_{84}<1.2$ |
| Intermediate scale roughness (IR) ) | $2.99<y_c/d_{50}<5.50$ | $2.5<h_c/d_{50}<6.6$ | $1.2<h_u/d_{84}<4.0$ |
| Small scale roughness (SR) | $5.50<y_c/d_{50}<13.76$ | $6.6<h_c/d_{50}<42$ | $h_u/d_{84}>4.0$ |

$$\frac{\Delta E}{E_0} = A + \frac{B}{(d_{50}/y_c)} + C \times Ln(S) \qquad (12)$$

In Eq. (12), A, B and C are the constant coefficients and are obtained from table (6).

**Table 6. Coefficients in Eq. (12) related to roughness conditions**

| Roughness conditions | A | B | C | $R^2$ |
|---|---|---|---|---|
| Large scale roughness (LR) | 0.766 | -0.0436 | 0.766 | 0.83 |
| Intermediate scale roughness (IR) ) | 0.868 | -0.0686 | -0.0221 | 0.975 |
| Small scale roughness (SR) | 0.871 | -0.0342 | -0.136 | 0.87 |

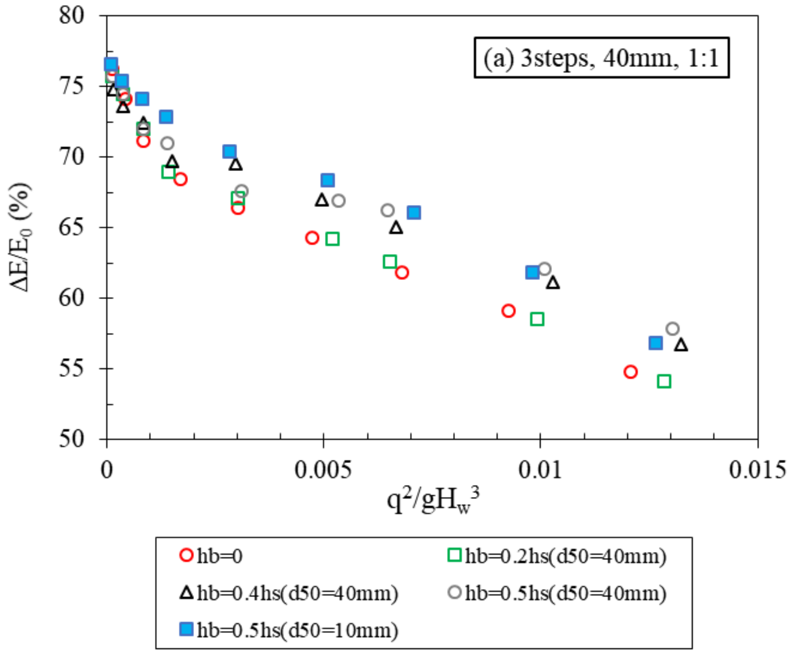
**Note:** $R^2$ is the regression determination coefficient.

Figures 11 and 12 show the changes in relative energy loss vs. relative discharge (drop number) for the gabion stepped spillways with rectangular and inclined sills. It can be noted that in these figures, multiple plots with on particle diameter typically are showed and then one plot with a different diameter is presented for comparison of $d_{50}$=10 and 40 mm.

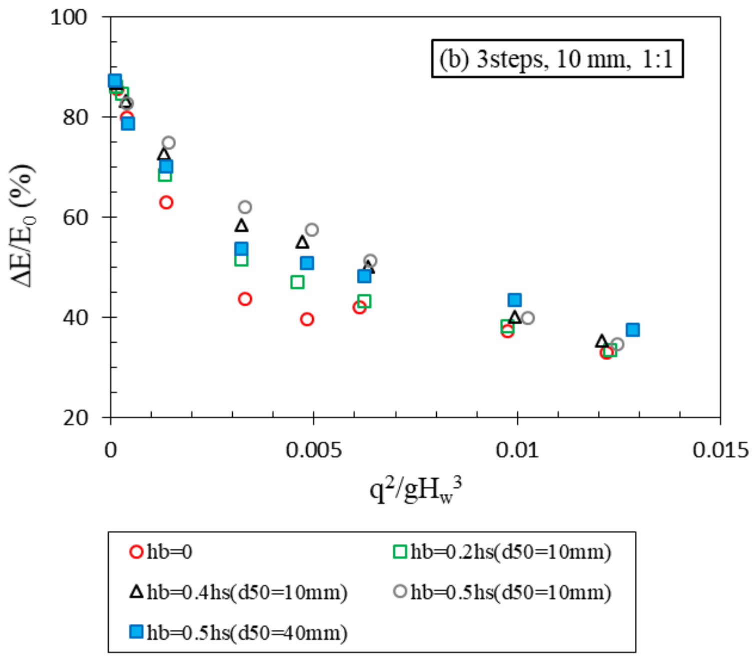
According to Fig. 10 (a and c) and Fig. 11 (a and c), when the average diameter of the material particles in the gabion spillways is 40 mm, installation of the sills (rectangular and inclined) do not significantly affect relative energy loss in the gabion spillways. However, according to Fig. 10 (b and d) and Fig. 11 (b and d), when the average diameter of the material particles in the gabion spillway is 10 mm, the effect of the sills on the energy loss is more evident.

The reason for this can be explained by the experimental observations that for particles with larger average diameter ($d_{50}$=40 mm), a greater share of energy loss happens as the flow passes through the particles. However, this energy dissipation is small due to the lower permeability of the water flow through the fine-grained particles ($d_{50}$=10 mm). Thus, it can be said that the use of end sills (rectangular or inclined) with large grain particle diameters in gabion steeped spillway will have little effect on energy dissipation, and the effect of sill installation becomes almost negligible as the spillway slope decreases (Figs. 10-c and 11-c). Therefore, it can be expected that the effect of the sill on the energy dissipation in rigid stepped spillways is greater than for gabion stepped spillways.

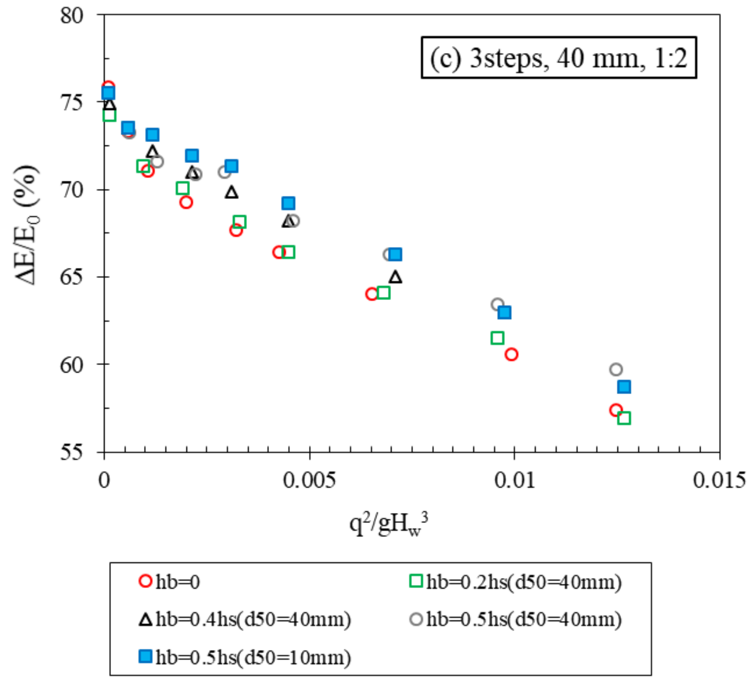
According to Figs. 10 and 11, relative energy loss increases as the height of rectangular and inclined sills become larger (increasing the $h_b/h_s$ and $h_a/h_s$ ratios). In Figs. 10-b and 10-d, where the experiments are performed on a 3-step gabion spillway with $d_{50}$=10 mm and 1:1 and 1:2 slopes (V:H), the effect of a rectangular sill with specifications of $h_b$=0.5$h_s$ and $d_{50}$=10 mm is greater than that of a rectangular sill with $h_b$=0.5$h_s$ and $d_{50}$=40 mm. But with the increase in discharge, this trend is reversed. This trend also exists for inclined sills (Figs. 11-b and 11-d). The reason for such a trend is that when the discharge is low and with low permeability sills with $d_{50}$=10 mm, more water can accumulate behind the sills and thus the sills act more like a stilling basin. In this condition, the ability of energy loss of sills is limited. As the discharge increases, the efficiency of the sills decreases.



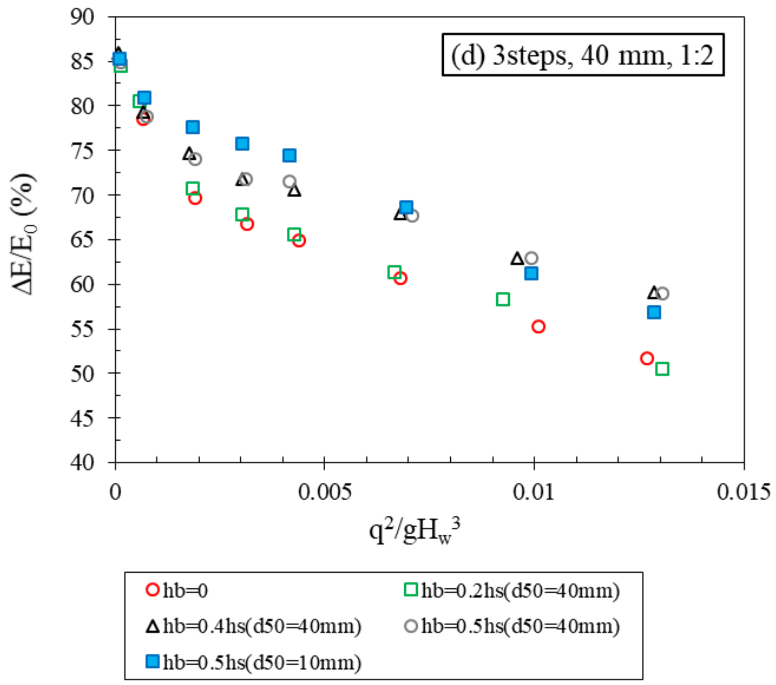

**a) 3-step, d50=40 mm and S=1:1 (V:H) and comparison with the same but d50=10**




**b) 3-step, d50=10 mm and S=1:1 (V:H) and comparison with the same but d50=40**

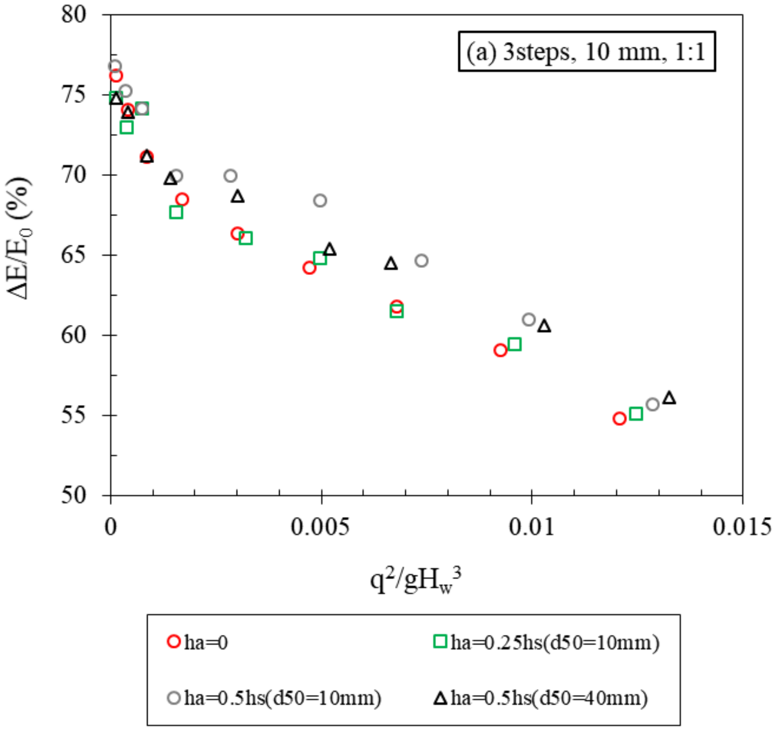



**c) 3-step, d50=40 mm and S=1:2 (V:H) and comparison with the same but d50=10**

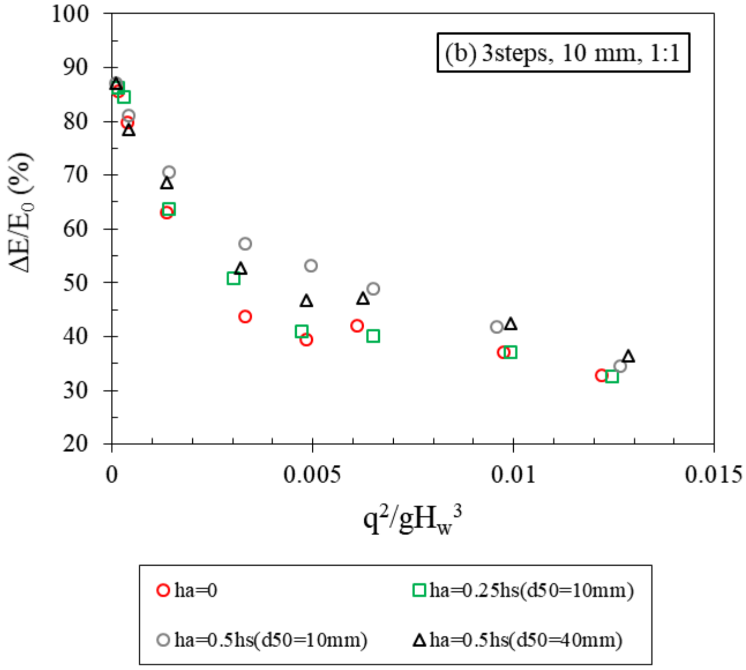



**d) 3-step, d50=40 mm and S=1:2 (V:H) and comparison with the same but d50=10**

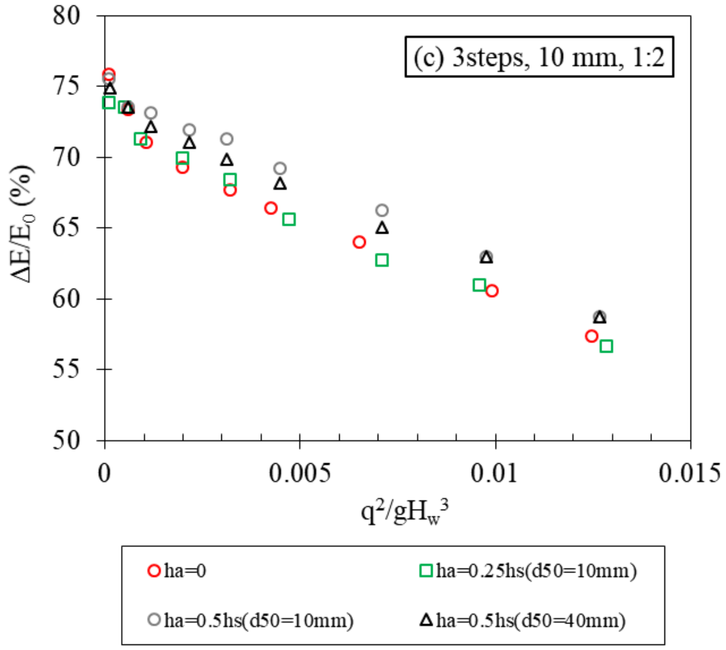
**Figure 11. Variation of relative energy dissipation vs. drop number for rectangular gabion end sills including different sand diameters**



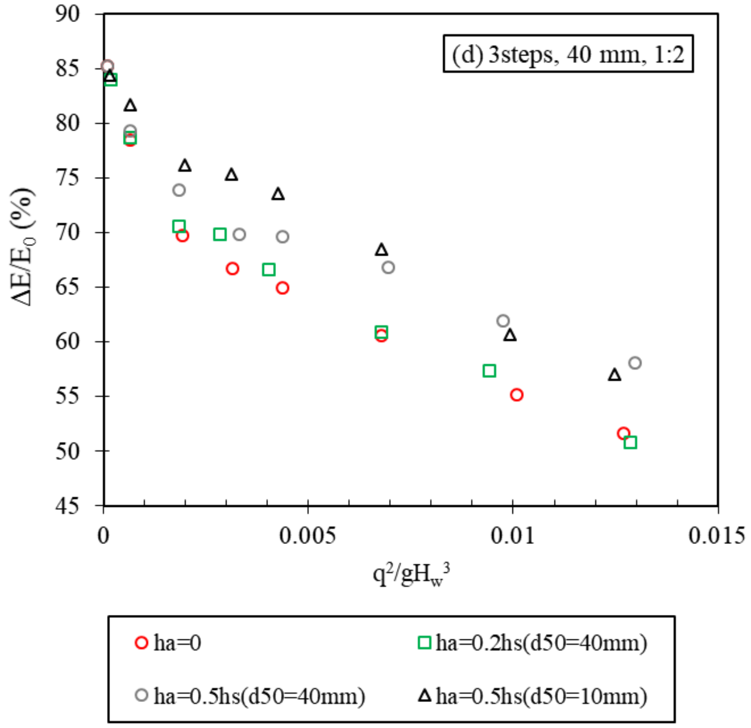

**a) 3-step, d50=10 mm and S=1:1 (V: H) and comparison with the same but d50=40**




**b) 3-step, d50=10 mm and S=1:1 (V:H) and comparison with the same but d50=40**




**c) 3-step, d50=10 mm and S=1:2 (V:H) and comparison with the same but d50=40**




**d) 3-step, sd50=40 mm and S=1:2 (V:H) and comparison with the same but d50=10**

**Figure 12. Variation of relative energy dissipation vs. drop number for inclined gabion end sills with different sand diameters**

When sills containing particles with an average diameter of 40 mm were used and discharge is low, the sills effect on the relative energy loss was less than when 10 mm particles are used. Less energy loss occurs at low discharge due to the high permeability of the sills containing coarse particles. However, when the discharge increases and a greater proportion of the flow passes over the stepped spillway, more energy loss occurs with the more coarse particles.

On the other hand, when the spillway slope with $d_{50}$=40 mm decreases, the effect of sills (rectangular or inclined) on the energy loss is weakened (compare Figs. 11-c and 12-c). This behavior is due to high permeability of coarse-grained materials. However, with the reduction of spillway slope with $d_{50}$=10 mm, the effect of the sills on energy loss is more pronounced (compare Figs. 11-d and 12-d). In other words, for rigid stepped spillways with a low slope, the effect of step end sills on energy loss is greater than that for stepped spillways with high slopes.

The results also showed that the effect of rectangular sills on energy loss is greater than inclined sills and the size of rotating vortices in steps with rectangular sills are larger than those of the inclined sills.

In Table (7), the range of discharge, Froude ($F_r$) and Reynolds Numbers ($R_n$) are provided. Table (7) is presented here for investigation of the scale effect. For Reynolds numbers greater than $1\times10^4$, the effect of water viscosity is insignificant and has no effect on the energy loss. Table (7) shows that this condition is valid both upstream and downstream of the gabion stepped spillways. Froude numbers vary from subcritical to supercritical. The two dimensionless parameters (Froude and Reynolds numbers) show that the flow conditions ($F_r$) and the turbulence of water flow ($R_n$) in this experimental study are in agreement with the real conditions and the results of this study can be used for low-height gabion stepped spillways with a scale ratio about 1:10 (model: prototype).

**Table 7 Range of discharge, Froude and Reynolds numbers**

| Discharge ($ls^{-1}$) | Downstream of spillway | | Upstream of spillway | | Number of experiments |
|---|---|---|---|---|---|
| | Reynolds Number | Froude Number | Reynolds Number | Froude Number | |
| 5-65 | $1.3\times10^4$ - $5.7\times10^5$ | 0.4 - 4.8 | $1.01\times10^4$ – $1.1\times10^4$ | 0.01 – 0.1 | 540 |

## 4. Conclusions

In this study, various physical models of gabion stepped spillways were constructed and tested. The purpose is to investigate the rate of energy loss in these spillways. Design variables include discharge, spillway slope, step end sill and spillway roughness conditions. The results showed that:

- As the discharge increases, the energy loss decreases. According to Eq. 11, the roughness play the most important role in assessing the energy loss.
- The change of energy loss with discharge is gradual for large-scale roughness, and these changes are sudden for spillways with small-scale roughness.
- Skimming flow regime is a function of discharge, length, and height of spillway steps.
- Increasing the discharge or increasing the spillway slope, facilitates the formation of a skimming flow regime. The creation of skimming flow in gabion stepped spillways with low slopes requires higher discharges.
- A three-step gabion stepped spillway with large-scale roughness ($d_{50}$=40 mm) incurs about 23% more energy loss than the same spillway with small-scale roughness ($d_{50}$=10 mm). In gabion stepped spillways with $d_{50}$=40 mm, the sills (rectangular or inclined) have little effect on the relative energy loss. However, for gabion stepped spillways with $d_{50}$=10 mm, part of the energy loss is due to the pervious end sills. In spillways with $d_{50}$= 10 mm, in a range of discharge of $Q$=45 l/s the effect of a rectangular sill with $h_b$=0.5$h_s$ and $d_{50}$ = 10 mm is greater than that of rectangular sill with $h_b$=0.5$h_s$ and $d_{50}$=40 mm. But with the increase in discharge, this trend is reversed.
- Gabion stepped spillways with $d_{50}$=40 mm and spillway slopes of 1:2 (V:H) incurs 10% more energy loss than the same spillways with a 1:1 slope. The rate of energy loss in the spillways with $d_{50}$=10 mm and the slope of 1:2 is about 30 to 35% more than the same spillways with the slope of 1: 1. Therefore, the presence of sills in a gabion stepped spillway with grain sizes of 10 and 40 mm have the greatest and least effect on the energy loss, respectively. The influence of rectangular sills on energy loss is about 3 to 4% greater than the effect of inclined sills. Depending on the type of application, using a stepped spillway with large scale materials may obviate the need for end sills located on steps. For the case of using stepped spillways with small grain materials (which have the same function as rigid/impervious spillways), using rectangular sill on steps are necessary to achieve maximum energy dissipation.
- The size of rotating vortices in stepped spillways including rectangular sills are larger than those of spillways with inclined sills.

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