INVESTIGATION OF FLOW REGIMES AND ENERGY DISSIPATION IN GABION STEPPED WEIRS

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ABSTRACT

Weirs are hydraulic structures generally used in open channels to regulate and control flow. Gabion weirs are considered an economical alternative to use in areas where rock-fill materials are available Energy dissipation in weirs and spillways is critical as uncontrolled dissipation can cause damage to hydraulic structures and the downstream channel. The investigation of the flow regime is an important aspect in the design of stepped weir due to its effect on the rate of energy dissipation. The aim of this study was to investigate the effect of downstream slope (of the stepped weir) and rock fill materials on flow regimes and energy dissipation in gabion stepped weirs. For this purpose, eight physical models of gabion weirs with slopes of 1:0.5, 1:1, 1:2, and 1:3 (V:H) and two types of rock fill materials were tested over a range of discharges. The number of steps used was four for all experiments with step height of 100 mm (scale 1:10). The rock fill material was crushed stone of nominal size (37.5 mm–13.2 mm) D_{50} = 23 mm, and rounded gravel of nominal size (26.5 mm–13.2 mm) D_{50} = 16 mm. Results showed that the effect of downstream slope on flow regime is significant at medium discharge, and less at low and high discharges. Moreover, it was found that the downstream slope has a significant effect on energy dissipation, increasing as the downstream slope decreased especially at the transition and skimming flow regimes.

Keywords: Gabion, stepped weir, flow regime, energy dissipation.

1. INTRODUCTION

Weirs are hydraulic structures widely used in open channels to control and regulate flow. Gabion weirs are made of wire mesh baskets filled with stones, and are considered as an economical alternative to use in areas where rock-fill materials are available. A gabion structure is stable, flexible, durable, and easy to install. Gabion weirs are frequently used in rivers as small dams, energy dissipaters, for flood control works, and check dams, among other uses, and can also be used to build a stepped weir to increase energy dissipation. In gabion structures, flow conditions are more complex due to flow through the gabion interior. At low discharge, flow is entirely through the voids of the gabion, and through and over the gabion at higher discharge.

For stepped weirs, the flow regime depends on the amount of discharge and the step height. In general, two flow regimes can be distinguished: nappe flow and skimming flow with the zone between the upper limit of nappe flow and the lower limit of skimming flow referred to as a transition regime (Chanson, 2002, Boes and Hager, 2003, Chinnarasri and Wongwises, 2004, Felder, 2013). In gabion stepped weirs, due to porous body of the weir, the water pass through the rock fill materials, then there is an additional flow regime, known as a through-flow regime (Stephenson, 1979). The energy of flow is dissipated depending on flow regime and the nappe flow regime has more effective in energy dissipation than the skimming flow regime (Andre and Schleiss, 2004).

Stephenson (1979) carried out a series of tests to estimate the energy dissipation on a rectangular gabion weir and stepped gabion weir of two, three, and four steps. Four downstream slopes were used, at vertical to horizontal (V:H) ratios of 1:1, 1:2, 1:3, and 2:3. The results show that the energy dissipation increases as the downstream weir slope decreased. Peyras et al. (1992) studied the energy dissipation over stepped gabion weirs using physical models with downstream slopes of 1:1, 1:2, and 1:3 (numbers of steps tested were 3, 4, and 5). Three types of overflow were observed: isolated nappe flow, partial nappe flow, and skimming flow. In addition, increasing the downstream slope led to a decrease in the rate of energy dissipation at high discharge. Kells

(1994) conducted an experimental study to estimate energy dissipation over three steps of a gabion stepped weir at 2 values of V:H, 1:1 and 1:2. The author indicated that there was no clear effect of downstream slopes on the rate of energy dissipation for the two slopes used. Chinnarasri et al. (2008) showed that at the skimming flow regime, the gabion stepped weirs had a higher energy loss ratio than horizontal stepped weirs, of 7%, 10%, and 14% for V:H of 1:1.73, 1:1, and 1:0.5, respectively. Furthermore, it was observed that downstream slope had more effect on energy dissipation than the stone size and shape. Salmasi et al. (2012) examine the behavior of gabion stepped weirs for energy dissipation. Models with three steps with porosities of 0.38, 0.40, and 0.42 were tested with V:H of 1:1 and 1:2, were used. Results indicated that increasing rock-fill porosity led to increases in energy dissipation, but at high rate of flow this was not active. Moreover, decreasing the downstream slope produced an increase in energy dissipation. Wuthrich and Chanson (2014c) studied the hydraulic performance of gabion stepped weirs. They illustrated that the rate of energy dissipation on the gabion stepped weir was less than that of an impervious weir at the highest discharge, although this results could be counterintuitive (Wuthrich & Chanson, 2014c; Wuthrich & Chanson, 2015). In contrast, at low discharge under through-flow conditions, the stepped gabion showed a higher energy dissipation than the impervious steps. Zuhaira et al. (2017) utilized a two-dimensional numerical model to study the energy dissipation over gabion stepped weir. Results show that the downstream slope is a significant parameter in the design of stepped weirs for energy dissipation. In summary, numerous studies have been conducted on gabion stepped weirs, but the results appear to be inconsistent, especially in terms of the effect of downstream slope on energy dissipation, in addition to the lack of studies characterizing flow regimes and how it affects energy dissipation. The aim of the present study was to investigate and relate flow regimes with energy dissipation for gabion stepped weirs with different downstream slopes and rock fill materials.

2. EXPERIMENTAL SETUP

The experimental work was conducted in a flume measuring 6400 mm length, 500 mm width, and 600 mm height with walls made from acrylic. The water tank capacity is 2200 liters, and water was recirculated with two pumps, each with a maximum discharge of 35 l/sec to provide a maximum flow rate of 70 l/sec. The flow rate was regulated manually using a valve. The flume was equipped with sluice gate at the downstream end to control tail water depth and the hydraulic jump position. A flow meter was installed to measure flow rate, up to an accuracy of ± 3%. Point gauges with an accuracy of ± 0.1 mm were used to measure water depth at three positions: upstream of the weir, downstream of the weir before the hydraulic jump, and after the hydraulic jump. Eight physical models of gabion weirs were studied in this investigation. The models have four downstream slopes 1:0.5, 1:1, 1:2, and 1:3 (V:H). Two types of rock fill materials were used, crushed stone of nominal size (37.5 mm–13.2 mm) D_{50} = 23 mm and rounded gravel of nominal size (26.5 mm–13.2 mm) D_{50} = 16 mm. The average porosity was 0.42 for crushed stone and 0.38 for rounded gravel which was measured three times by direct method for each sample. The gabion baskets were made of 1.5 mm galvanised wire mesh with square openings of 12.7 mm x 12.7 mm. All models were designed to a scale of 1:10 with four steps and had the same height, width, step height, and broad crest (height 400 mm, width 500 mm, step height 100 mm, and broad crest 200 mm) (Figure 1).

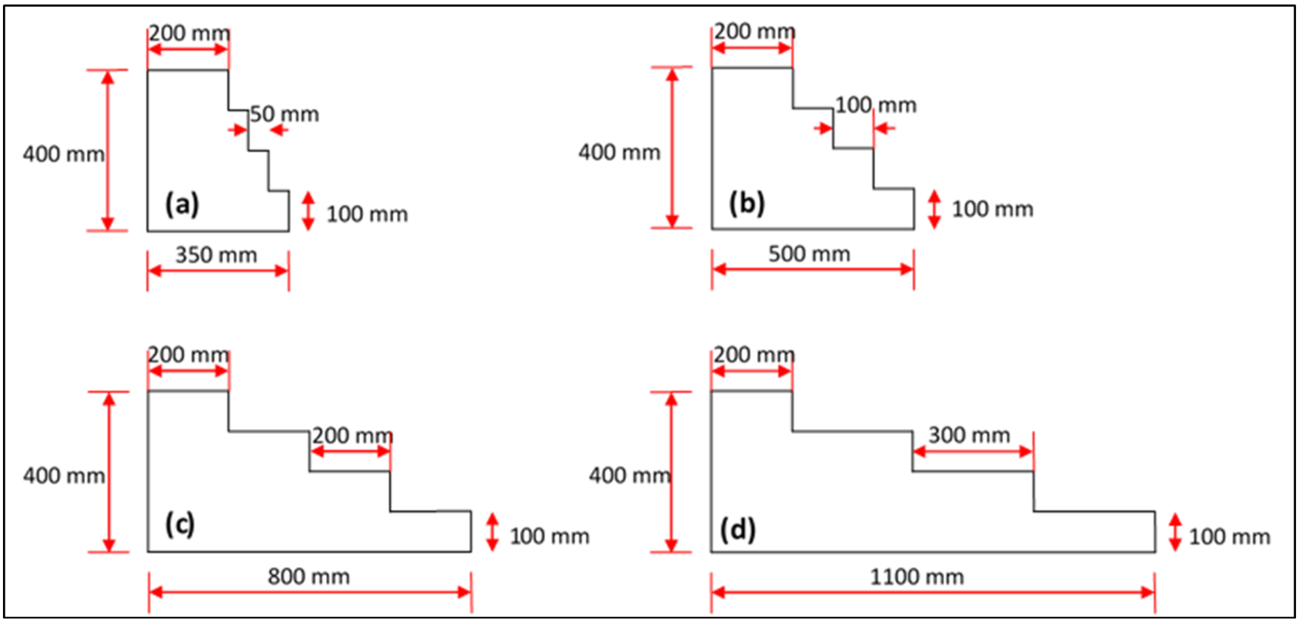

Figure 1 Details of physical models: (a) Slope 0.5:1, (b) Slope 1:1, (c) Slope 1:2, and (d) Slope 1:3

3. FLOW REGIMES LIMITATIONS AND ENERGY DISSIPATION CALCULATION

3.1 Flow regime limitations

There is a significant relation between the flow regimes and the rate of energy dissipation. The determination of the onset of regimes usually depends on visual interpretation. Table 1 shows the criteria which utilized to determination the flow regimes. However, several studies have suggested empirical limits to predict the onset of flow regimes as shown in table 2, (where Y_c is the critical depth of flow, h_s is the step height, and l_s is the step length).

Table 1 Flow regimes description

Flow regime	**Regime description**
Through flow	No overflow at outer edge of steps.
Transition I flow	Overflow began at the first step.
Nappe flow	Free falling nappes and jet impact from one step onto the next one.
Transition II flow	Nappe on the upper steps with skimming on the lower steps
Skimming flow	Water moving down the steps with recirculating vortices restricted between the steps, and water then skimming over the pseudo-bottom formed by outer edge of steps.

Table 2 Limits of flow regimes on gabion stepped weir

Flow regime	**Author**	**Regime limits**
Through flow	Wuthrich and Chanson (2014c)	$Y_c/h_s < 0.3$
Nappe flow	Wuthrich and Chanson (2014b) and Zhang and Chanson (2015)	$0.3 < Y_c/h_s < 0.6$
Transition flow	Wuthrich and Chanson (2015) and Zhang and Chanson (2015)	$0.6 < Y_c/h_s$
Skimming flow	Wuthrich and Chanson (2015) and Zhang and Chanson (2015)	$Y_c/h_s > 0.9$

3.2 Energy dissipation calculation

Energy dissipation across the weir can be estimated from the difference between the energy of flow upstream and downstream of the weir. Figure 2 shows a schematic and definitions parameters relevant to the energy loss estimation.

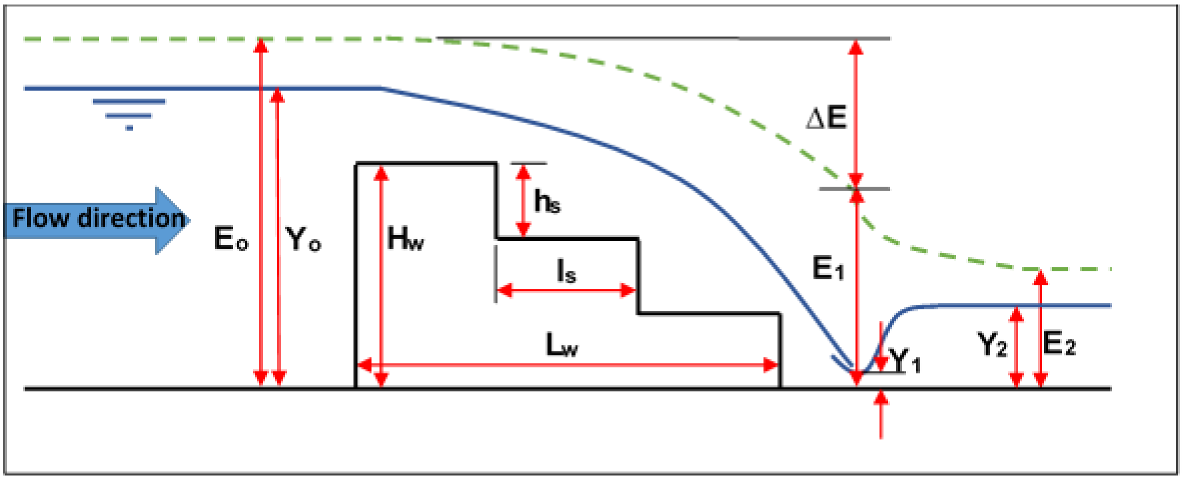

Figure 2 Typical weir hydraulic section

The total energy upstream the weir (E_o) can be estimated by

$$E_O = Y_0 + \frac{V_0^{\,2}}{2g} \tag{1}$$

where Y_0 is the water depth upstream the weir, g is gravitational acceleration, and V_0 is the mean velocity upstream the weir:

$$V_0 = \frac{q}{Y_0} \tag{2}$$

where q is the discharge per unit width. The energy downstream the weir (E_1) can be estimated from:

$$E_1 = Y_1 + \frac{{V_1}^2}{2g} \tag{3}$$

where E_1 is the total energy downstream of the weir, Y_1 is the water depth at the toe of the weir, and V_1 is the mean velocity of flowat the toe of the weir:

$$V_1 = \frac{q}{Y_1} \tag{4}$$

It is difficult to measure Y_1 accurately because the flow is highly disturbed at that location. Several researchers, such as (Diez-Cascon et al., 1991, Matos and Quintela, 1995, Pegram et al., 1999, Chinnarasri et al., 2008), have used the conjugate water depth calculated from momentum conservation assuming a horizontal bed:

$$Y_1 = \frac{Y_2}{2}\left(\sqrt{1 + 8\,Fr_2^2} - 1\right) \tag{5}$$

where Y_2 is the water depth after the hydraulic jump, and Fr_2 the Froude number after the hydraulic jump ($Fr_2 = V_2/\sqrt{g\,Y_2}$). According to Pegram et al. (1999), the hydraulic jump should be located as close as possible to the weir toe without drowning the last step. Then, the energy dissipation efficiency can be calculated using the following equation:

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

where ΔE is the energy dissipation across the weir ($\Delta E = E_o - E_1$).

4. RESULTS AND ANALYSIS

4.1 Flow regimes

The flow regimes were determined from visual interpretation and are presented in Table 3. It can be seen that at low discharge (0.006 – 0.04 m^3/sec/m), the through-flow, and Transition I flow regimes were not affected by downstream slope and materials type, where for all rock fill materials and downstream slopes, the flow regime at a certain discharge was the same for the first four runs except run no. 3 for slope 1:0.5 crushed stone. On the

Table 3 Observed flow regimes

Run No.	$\frac{Y_c}{h_s}$	Visual interpretation								Wuthrich & Chanson (2015) and Zhang & Chanson (2015)							
		1:0.5		1:1		1:2		1:3		1:0.5		1:1		1:2		1:3	
		RG	CS	RG	CS	RG	CS	RG	CS	RG	CS	RG	CS	RG	CS	RG	CS
1	0.12	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.
2	0.21	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.	Thr.
3	0.31	T-I	Thr.	T-I	T-I	T-I	T-I	T-I	T-I	N	N	N	N	N	N	N	N
4	0.40	T-I	T-I	T-I	T-I	T-I	T-I	T-I	T-I	N	N	N	N	N	N	N	N
5	0.48	N	T-I	T-I	T-I	N	T-I	N	N	N	N	N	N	N	N	N	N
6	0.61	T-II	T-II	N	T-II	N	N	N	N	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II
7	0.65	T-II	T-II	N	T-II	T-II	N	T-II	N	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II
8	0.71	Sk	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II
9	0.77	Sk	Sk	Sk	Sk	Sk	T-II	Sk	Sk	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II
10	0.86	Sk	Sk	Sk	Sk	Sk	Sk	Sk	Sk	T-II	T-II	T-II	T-II	T-II	T-II	T-II	T-II

RG is rounded gravel and CS is crushed stone. Thr is through flow regime, T-I is transition flow regime between through flow and nappe flow regimes, N is nappe flow regime, T-II is transition flow regime between nappe flow and skimming flow regimes, and Sk is skimming flow regime.

other hand, at medium discharge (0.05 – 0.08 m^3/sec/m), the effect of downstream slope was clear. For high downstream slopes (1:0.5, and 1:1), there was no clear nappe flow but nappe regime on upper steps and skimming regime on lower steps, referred to as Transition II regime, while at low downstream slopes (1:2, and 1:3), there were clear nappe, transition II, and skimming flow regimes. At high discharge (0.09 – 0.11 m^3/sec/m), the effect of downstream slopes and rock fill materials on flow regimes was not clear, were the flow regime was skimming flow for the last two runs for most of downstream slopes and material type. As a result, the effect of downstream slope on flow regime appeared significant at medium discharge, while it was not as clear at low or high discharges. The rock fill material had no significant effect on flow regime. Figure 3 shows flow regimes on gabion stepped weir (slope 1:3).

In a comparison of observed flow regime limits on a gabion weir with the limits obtained by relationships of Wuthrich and Chanson (2014b), Wuthrich and Chanson (2014c), Wuthrich and Chanson (2015) and Zhang and Chanson (2015), the results have some similarities, especially at through flow regime. On the other hand, at nappe, transition, and skimming flow regimes, there was a disagreement. This disagreement in results possibly due to neglecting the step length (downstream slope) in these relationships.

(a) Through flow regime

(b) Transition I flow regime

(c) Nappe flow regime

(d) Transition II flow regime

(e) Skimming flow regime

Figure 3 Flow regimes on gabion stepped weir (slope 1:3)

4.2 Energy dissipation

Figures 4 presents energy dissipation efficiency (ΔE / E_o) vs. drop number (q^2 / g H_w^3) for four downstream slopes 1:0.5, 1:1, 1:2, and 1:3 (V:H), and two rock fill materials (rounded gravel, and crushed stone), respectively. With increasing drop number (increasing discharge), dissipation efficiency decreases for all downstream slopes for both material tested. For low discharges, the flow regime was through-flow and the energy dissipation was at highest values due to the higher energy losses associated with flow through the porous media. At the lowest discharge, the efficiency of energy dissipation was similar for both materials, ranging between 78% to 81% for rounded gravel and 82% to 85% for crushed stone. The slightly higher efficiency for crushed rock is due to greater energy loss associated with the larger angularity of crush stone. For through-flow, the downstream slope was not a factor because there was no overflow. The effect of downstream slope appears when overflow was present, energy dissipation decreasing with increasing downstream slope. This effect due perhaps to more resistance provided by the step face, which is longer for low slope than higher slopes. This result has good agreement with previous studies such as Peyras et al. (1992), Chinnarasri et al. (2008), Salmasi et al. (2012), and Zuhaira et al. (2017). However, Kells (1994) observed that there was no significant difference in energy dissipation between 1:1 and 1:2 downstream slopes. In general, however, our results indicate that at overflow regimes (nappe, transition, and skimming), the lowest slope (1:3) offered 10% more energy dissipation than the highest slope (1:0.5).

Figure 5 illustrate the effect of rock fill materials on the rate of energy dissipation for four downstream slopes 1:0.5, 1:1, 1:2, and 1:3 (V:H) respectively. At low discharge, when the flow regime is through flow, the crushed stone has about 4 % more energy dissipation than rounded gravel for all downstream slopes used in this study. At medium discharge, (nappe, and transition flow), the difference in energy dissipation between the rounded gravel and crushed stone reduced to less than 2%. At high discharge, (skimming flow regime), the curves tended to converge and the effect of rock fill materials disappears as the flow skimming over the weir structure is much higher than the flow through the interior of the weir. As a result, the rock fill material (shape, and size) has no significant effect on energy dissipation, especially at medium and high discharges. This result is consistent with the findings of Chinnarasri et al. (2008), and Salmasi et al. (2012).

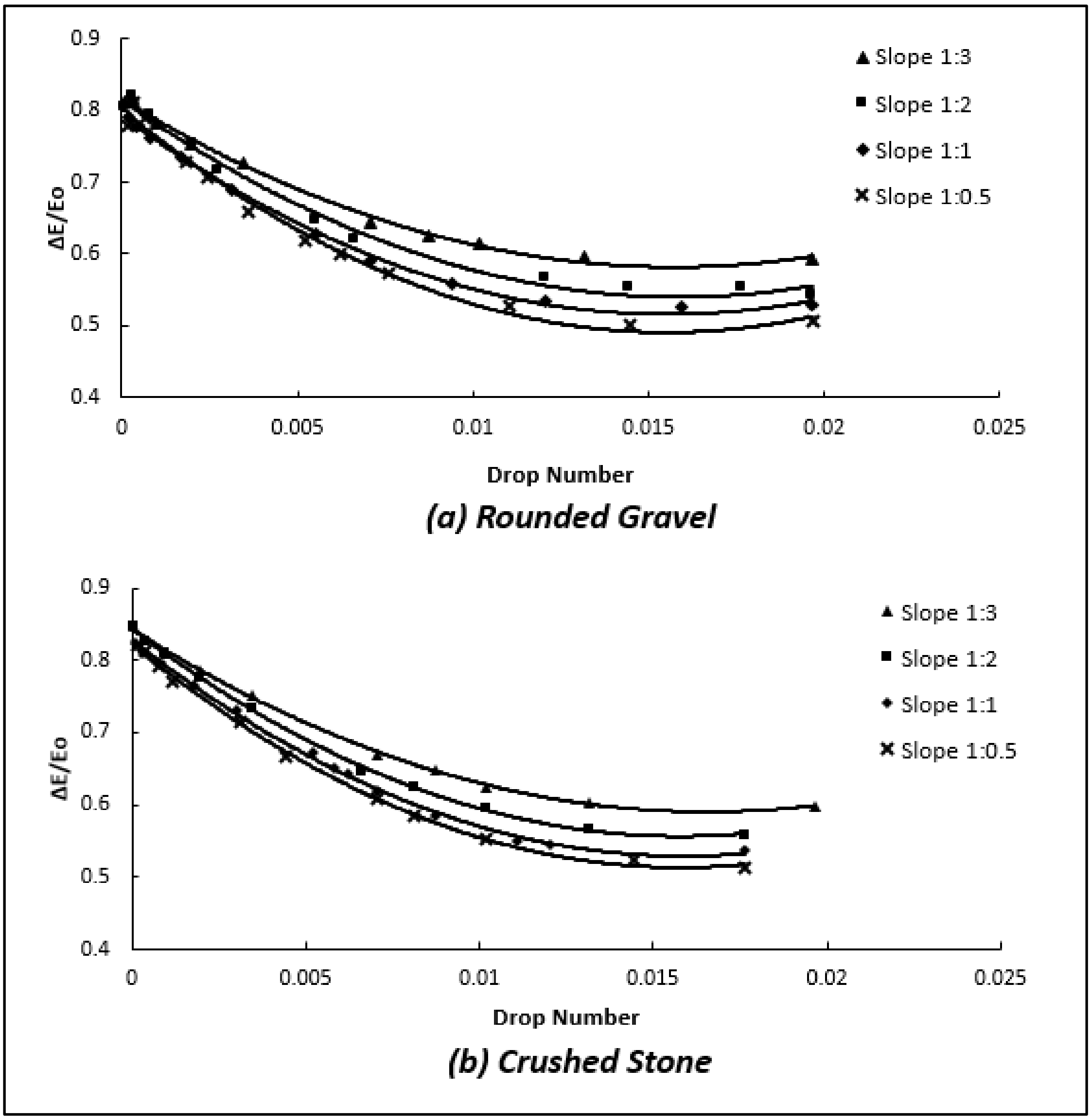

Figure 4 Energy dissipation on gabion stepped weir: (a) rounded gravel, (b) crushed stone

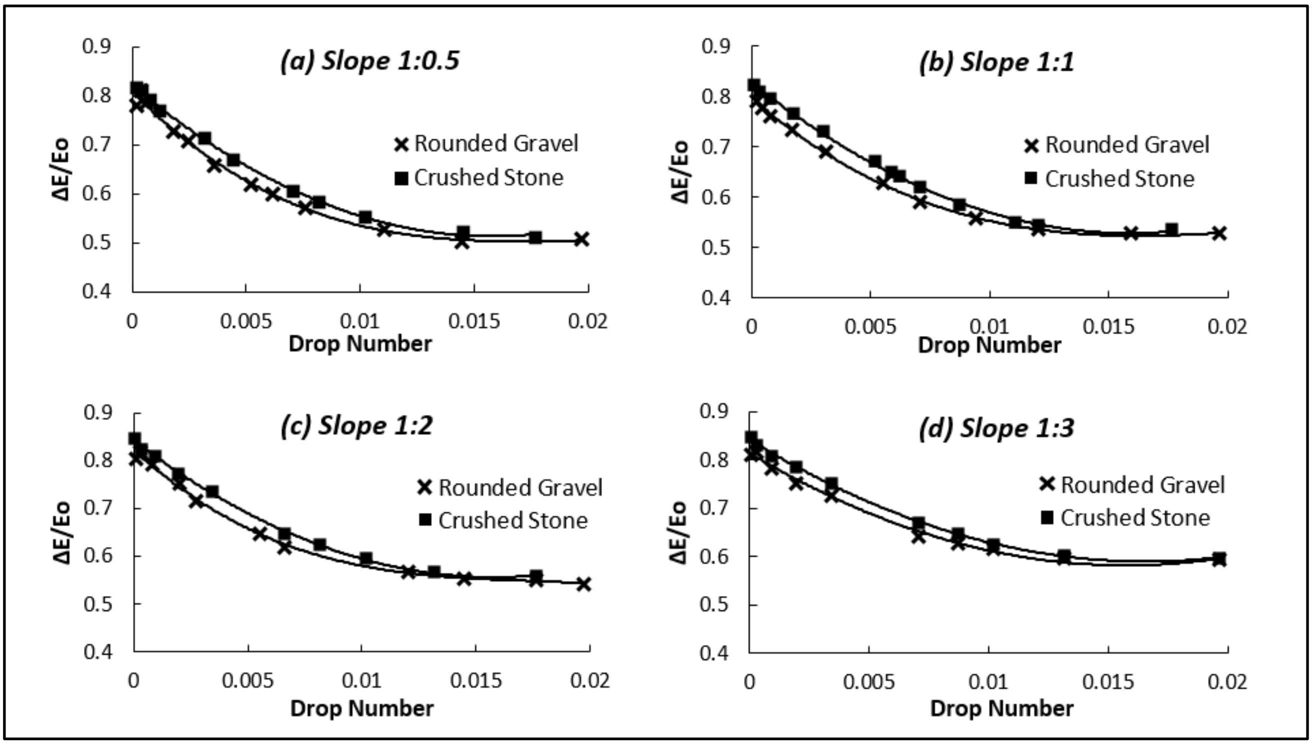

Figure 5 Effect of rockfill materials on energy dissipation: (a) slope 1:0.5, (b) slope 1:1, (c) slope 1:2, (d) slope 1:3

5. CONCLUSIONS

Four downstream slopes with two types of rock fill materials of gabion stepped weirs were tested over a range of discharge in this study. The following conclusions can be drawn:

1. The effect of downstream slope on flow regime is clear with medium discharge, while it was not clear at low and high discharges.
2. The rock fill material did not affect the flow regime and energy dissipation, which depended on flow only.
3. Energy dissipation efficiency decreases with increases in flow rate for all slopes and rock fill materials.
4. Energy dissipation increased with decreases in the downstream slope, and the lowest slope (1:3) offered 10% more energy dissipation than the highest slope (1:0.5).

ACKNOWLEDGMENTS

The authors acknowledgement the support provided by the technical staff in the school of engineering at Deakin University- Australia. Also, the first author would like to thank the Ministry of Higher Education and Scientific Research (MoHESR) of Iraq and Babylon University in Iraq for supporting his PhD scholarship.

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