Pol. J. Environ. Stud. Vol. 32, No. 4 (2023), 3481-3490
DOI: *10.15244/pjoes/161667* ONLINE PUBLICATION DATE: 2023-06-30

Original Research

Investigation of the Effect of Downstream Slope and Rockfill Materials on Flow Regimes over Gabion Stepped Weirs

Mohammed A Almajeed A Alabas[1], Udai A. Jahad[2], Riyadh Al-Ameri[3], Ali Chabuk[4], Mubeen Isam[5], Ali Majdi[6], Nadhir Al-Ansari[7]*

[1]Department of Civil Engineering, Faculty of Engineering, University of Babylon, Hillah, Babylon 51001, Iraq
[2]Department of Environment Engineering, Faculty of Engineering, University of Babylon, Hillah, Babylon 51001, Iraq
[3]School of Engineering, Faculty of Science Engineering & Built Environment, Deakin University,
75 Pigdons Road, Waurn Ponds, VIC 3220, Australia
[4]Department of Environment Engineering, College of Engineering, University of Babylon, Babylon 51001, Iraq
[5]Research and Studies Unit, Al-Mustaqbal University College, 51001, Babylon, Iraq
[6]Building and Construction Techniques Engineering, Al-Mustaqbal University College, 51001, Babylon, Iraq
[7]Department of Civil Environmental and Natural Resources Engineering, Lulea University of Technology,
SE-971 87 Lulea

Received: 7 November 2022
Accepted: 25 February 2023

Abstract

It is important to determine the limits of flow regimes in the design of stepped weirs because of the hydraulic performance of each regime. The present study investigates the effect of downstream slope and rock fill materials on flow regimes in gabion stepped weirs. Nine physical models of gabion weirs were used in the experiments. The models' downstream slopes ranged from 1:05 to 1:4 V:H. In addition, two types of rockfill materials: crushed stone of 0.42 porosity and rounded gravel of 0.38 porosity were used to study the effect of rockfill materials on flow regimes. The nominal size of the crushed stone was (37.5 mm - 13.2 mm) D50 = 23 mm and the nominal size of the rounded gravel was (26.5 mm - 13.2 mm) D50 = 16 mm. Each model has been tested with ten runs for discharge per unit width ranging (from 0.006 to 0.105 m^3/sec. m) to cover all flow conditions and flow regimes. The onset of each flow regime for all physical models has been observed. The experimental data of the gabion stepped weirs have been used to develop equations to estimate the onset of each flow regime. The coefficient of correlation (R) of the developed equations ranged between 0.95 to 0.97. The results indicated on the steeper downstream slope models (1:0.5, 1:0.83), there is interference between the nappe and transition flow regimes. The nappe flow regime has not appeared on all steps at the same

---

*e-mail: Nadhir.alansari@ltu.se
alansari@ltu.se

time. Moreover, the shape and size of the rockfill materials have an insignificant effect on flow regimes, especially at a high flow rate.

Keywords: flow regimes, gabion, stepped weirs, downstream slope, rockfill materials

Introduction

Gabion weir structures are considered an economical alternative compared with the other types. Indeed, the filling material used in its body formation is the most abundant and economical material in hydraulic engineering practice. Gabion structures are considered environmentally friendly structures due to the ecological performance of their porous body [1-3]. Furthermore, there is a biochemical reaction due to the decomposition of organic matter by the bacteria inhabiting the rocks' surfaces. This can contribute to purifying water as it passes through the weir body at the same procedure as water purification and sewage water plants [4-6]. Studying the hydraulics of flow over gabion weirs is essential to understand the complexity of flow regimes and other hydraulic parameters, such as flow-through rockfill. In general, for the impervious stepped weirs, two flow regimes are employed: the nappe flow and the skimming flow. The zone between the upper limit of the nappe flow and the lower limit of the skimming flow can be called a transition flow regime [7-10]. In a gabion weir, the flow can pass through its body in addition to the overflow of the weir [6]. Therefore, there is an additional flow regime, which is known as a through-flow regime [11]. The throughflow has a high impact on the energy dissipation over the gabion weirs. At a low discharge, the water passes through the voids between rockfill particles. This type of flow is the through-flow regime. With an increase in the discharge, the overflow begins at the first step (lowest step), while the flow still passes through the gabion at the upper steps. This regime can be called a transition flow regime between the through-flow and nappe flow regimes. With a continued increase in discharge, at a medium discharge, the flow of the water cascading down a stepped weir has a series of free-falling nappes, which forms the nappe flow regime [12]. At a high rate of flow, the water moves down the steps with recirculating vortices restricted between the steps. Water, then, skims over the pseudo-bottom formed by the outer edge of steps. This regime is called the skimming flow regime. The flow regime changes from the nappe flow to the skimming flow with increases in the flow rate through the transition regime [13-15]. This change occurs gradually and continuously. In the transition flow, the regime can begin as a nappe regime on the upper steps, becoming a skimming regime on the lower steps [11]. The nappe flow regime can be classified into three types: the nappe flow with a complete hydraulic jump at a small discharge, the nappe flow with a partial hydraulic jump, and the nappe flow without a hydraulic jump. This classification of the nappe flow regime is based on flow turbulence. The first type started supercritical flow, then through the hydraulic jump changed to sub-critical flow. The second type is for supercritical flow with the partial hydraulic jump, and the third type is for supercritical flow without a hydraulic jump. The limits of the nappe flow regime on the gabion weir can be calculated in terms of the critical depth of flow (yc) and step height (hs) using the empirical onset of the transition flow regime on the gabion stepped weirs can be obtained in terms of the critical depth of flow and step height using the empirical formulae of both of Wuthrich and Chanson (2015) and Zhang and Chanson (2015) [16, 17] as follows:

$$0.6 < \frac{y_c}{h_s} < 0.9 \tag{1}$$

The onset of the skimming flow on the gabion stepped weirs can be determined using formulae obtained by (Wuthrich and Chanson, 2015, Zhang and Chanson, 2015, Zhang and Chanson, 2014) [16-18] as presented in Table 1.

Formulae obtained by (Zhang and Chanson, 2015; Wüthrich and Chanson, 2014) are as follows [17, 19]:

$$0.3 < \frac{y_c}{h_s} < 0.6 \tag{2}$$

The above formulas for onset limits of the skimming flow on the impervious stepped spillway of the steps covered with the gabion baskets. In the current study, the physical models consisted of the porous body for the whole weir. This provided a reliable formula to estimate the onset limits of the skimming flow regime. The determination of the onset of regimes depends on the visual interpretation, which explains the differences in formulae obtained by different authors.

In summary, several studies have been conducted to investigate flow regimes and the onset limits of the regimes on stepped impervious weirs. This has led to the establishment of relationships to determine the onset limits of flow regimes. However, the flow regimes on gabion weirs have not been studied adequately, especially the through-flow regime. This requires more experimental data with different downstream slopes, a wider range of discharges, and different rockfill properties. Doing so will help us understand flow characteristics and develop empirical formulas for the onset limits of each flow regime. The present study aims to provide a good understanding of the characteristics of flow regimes by studying the different parameters (downstream slope, rockfill materials, and discharge)

Table 1. The onset of the skimming flow on the gabion stepped weirs.

Formula	Author
$\frac{y_c}{h_s} > 0.88$	Zhang and Chanson (2014)
$\frac{y_c}{h_s} > 0.90$	(Wuthrich and Chanson, 2015; Zhang and Chanson, 2015)

that affect flow regimes on gabion stepped weirs. In addition, develop a relationship for estimating the onset limits for each flow regime.

Material and Methods

Experimental Facilities

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 a sluice gate at the downstream end to control tailwater depth and the hydraulic jump position. A flow meter was installed to measure the 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.

Physical Models and Test Program

The gabion baskets of physical models were made of 1.5 mm galvanized wire mesh with square openings of 12.7 mm x 12.7 mm. Two types of rockfill materials were used, crushed stone and rounded gravel. 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. Nine physical models of gabion weirs were studied to investigate the effect of downstream slope on flow regimes. The models have downstream slopes of 1:0.5, 1:0.83, 1:1, 1:1.5, 1:2, 1:2.17, 1:2.5, 1:3, and 1:4 (V:H) tested with crushed stone. Moreover, eight physical models of gabion weirs were utilized in this investigation to study the effect of rockfill materials. The models have four downstream slopes 1:0.5, 1:1, 1:2, and 1:3 (V:H) each tested with two rock fill materials (crushed stone and rounded gravel). According to Pegram et al. (1999) [20] and (Chanson, 2000) [21] models of a 1:20 or larger scale could represent the prototype behavior of stepped weirs. Further, a smaller scale may show significant scale effects. Therefore, the scale 1:10 has been chosen to avoid the scale effect. All models were designed 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). All models tested with ten runs of different discharges ranged between 0.006 and 0.105 m^3/sec/m. Table 2 shows the details of tested physical models.

Definition of Flow Regimes

The determination of limits of flow regimes is a significant aspect in the design of stepped weirs due

Table 2. Details of tested physical models.

Model number	Weir slope V:H	Rock fill materials	Test	
			Effect of the downstream slope	Effect of rockfill materials
N-CS-0.5	1:0.5	Crushed stone	*	
N-CS-0.83	1:0.83	Crushed stone	*	
N-CS-1	1:1	Crushed stone	*	
N-RG-1	1:1	Rounded gravel		*
N-CS-1.5	1:1.5	Crushed stone		*
N-CS-2	1:2	Crushed stone	*	
N-RG-2	1:2	Rounded gravel	*	*
N-CS-2.17	1:2.17	Crushed stone	*	
N-CS-2.5	1:2.5	Crushed stone	*	
N-CS-3	1:3	Crushed stone	*	*
N-RG-3	1:3	Rounded gravel		*
N-CS-4	1:4	Crushed stone	*	*
N-RG-4	1:4	Rounded gravel		*

to differences in the hydraulic performance for each flow regime. Many studies have been carried out to investigate the limits of flow regimes on impervious stepped weirs. However, on gabion stepped weirs, few studies have investigated flow regimes and their limits. The definitions of flow regimes on gabion stepped weirs are as follows:

Through-Flow Regime

When the entire flow is through the porous body of the weir. There is no overflow at the outer edge of the steps. The water seeps into the vertical face of the upstream side of the weir and exits through the vertical face of the first step (lowest step) only.

Transition I Flow Regime

In this regime, the water begins exiting through the vertical face of other steps, which causes the overflow to begin on the horizontal face of lower steps. In this case, the flow is through-flow at the upper steps and overflow at the lower steps.

Nappe Flow Regime

The flow in this regime is over the whole body of the weir. The water flow as a free-falling nappes and jet impact from one step to the next. There is no cavity below the nappe due to water seeping out of the vertical faces of the steps.

Transition II Flow Regime

In this regime, the flow changed from nappe to skimming on the lower steps, while it remains nappe on the upper steps. In other words, it is the nappe flow regime on the upper steps with the skimming flow regime on the lower steps.

Skimming Flow Regime

The water moves down the steps in a consequential flow. Recirculating vortices are restricted between the steps and work as a cushion with no air pockets under the jets. Water, then, skims over the pseudo-bottom formed by the outer edge of steps.

The determination of the onset of regimes usually depends on visual interpretation. Table 3 shows the criteria utilized in this study to determine the flow regimes [11].

Results and Discussion

Experimental Observations

In the current investigation on the gabion stepped weir, five flow regimes were identified. Figure (2) shows the flow regimes in the normal sequence on model N-CS-4 as an example. For small discharges (Drop number<0.0004), a through-flow regime was observed. The water seeped into the vertical face of the upstream side of the weir and exited through the vertical face of the first step (lowest step). In this stage, the whole flow is through the porous media, i.e., through the weir body, as shown in Fig. 1a). In this regime, there is no flow over the crest or the steps of the weir for all downstream slopes. The amount of through-flow depends on the porosity of the rockfill materials and the weir height, length, and slope.

When the flow rate increased, the water started exiting through the vertical face of the second step, and the overflow began at the first step (lowest step). At this discharge, the flow is mixed (i.e., the through-flow at the upper steps and overflow at the first step). This regime will be called a transition I flow regime, as shown in Fig. 1b). With increasing discharge, the overflow will appear on other steps until the whole weir is submerged. Then, the nappe flow regime will begin (Fig. 1c). There is no cavity below the nappe due to water seeping out of the vertical faces of the steps. With the continued increase in discharge, the flow regime changes from the nappe flow to the skimming flow through the transition II regime. In the transition II flow, the regime changes from nappe to skimming on the lower steps, while it is still nappe on the upper steps (Fig. 1d).

At the skimming flow regime, water moves down the steps in a consequential flow with recirculating vortices restricted between the steps working as a cushion (with no air pockets under the jets). The flow passes over the pseudo-bottom formed by the external edge of steps (Fig. 1e). On the steep slopes, interference has been observed between the transition flow regimes

Table 3. Flow regimes criteria.

Flow regime	Regime description
Through flow	No overflow at the outer edge of the 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 skimming over the pseudo-bottom formed by the outer edge of the steps.

that lead to dominating the transition I and II regimes on the nappe flow regime. In slopes 1:0.5 and 1:0.83, the flow regime changed from transition I to transition II directly without observation of a clear nappe flow regime on all steps at the same time. In other words, the through-flow regime on the upper steps with the nappe flow on the lower steps. With increasing discharge, the flow changed to the nappe flow on the upper steps with the skimming flow on the lower steps. However, all the flow regimes were observed

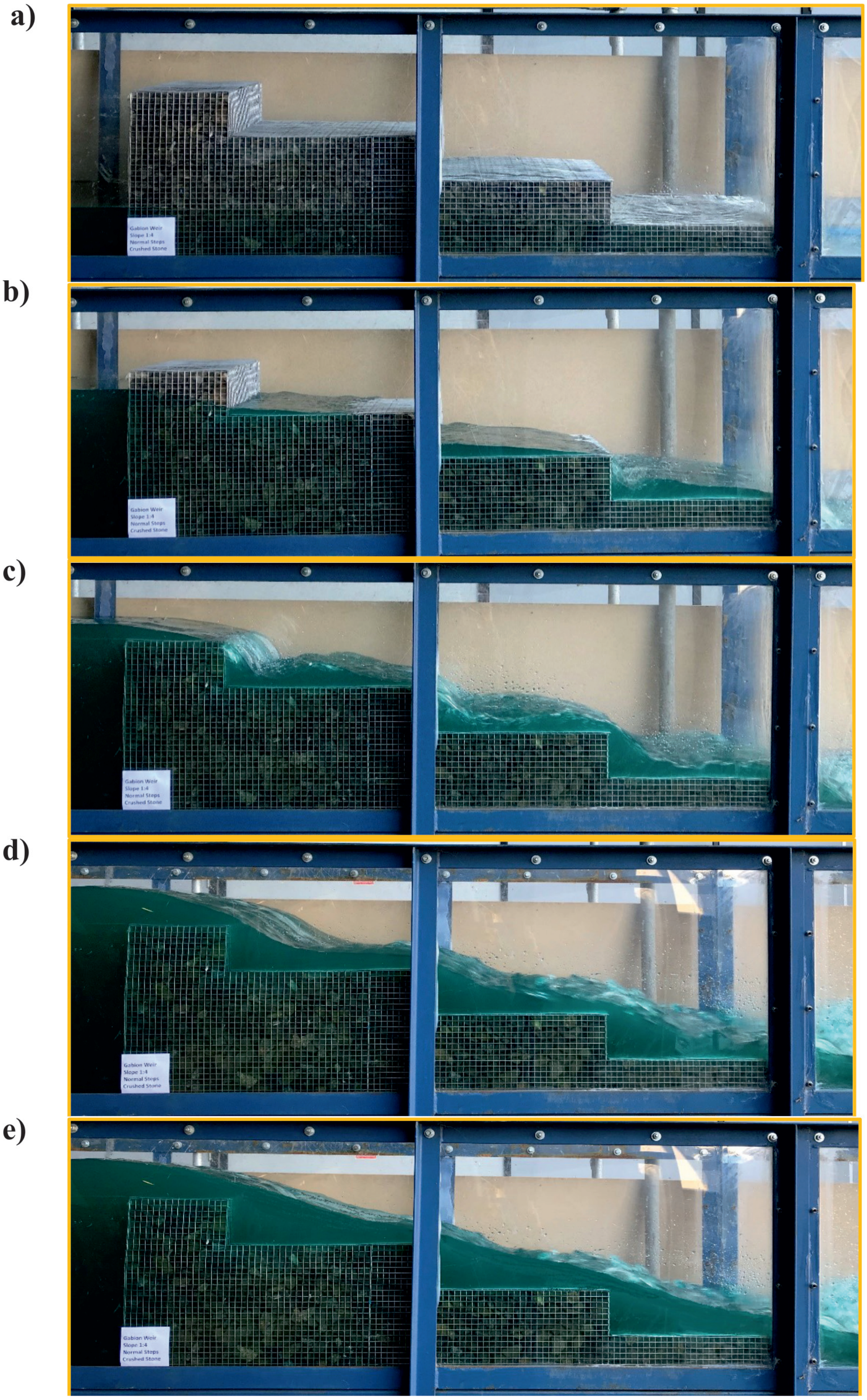

Fig. 1. Observed flow regime on mild slope model (N-CS-4): a) through-flow, b) transition I flow, c) nappe flow, d) transition II flow, and e) skimming flow.

in the normal sequence on the other slopes, especially on mild slope models (slope 1: 3 and 1: 4). Fig. 2 presents a comparison of observed flow regimes between steep and mild downstream slopes.

Effect of Downstream Slope

Essery and Horner (1978) [22] and Peyras et al. (1991) [23] as cited in (André and Schleiss, 2004) [24] stated that the flow regime on stepped spillways depends on the discharge and the downstream spillway slope. Therefore, the parameters that affect the type of flow regimes are the weir geometry, rockfill material properties, and the amount of discharge. In this section, the results of the experimental physical models of the gabion stepped weirs of normal steps with different downstream slopes, two rockfill materials, and a wide range of discharge will be presented. To investigate the flow regimes on normal steps gabion stepped weirs, nine models of different downstream slopes were tested for a range of discharges (Table 2). The models have the same rockfill materials (crushed stone of porosity 0.42). The discharge limits ranged between 0.006 and 0.105 m^3/sec/m. A visual interpretation was used to investigate the flow regimes on each model with a range of used discharges. All types of flow regimes were recognized, especially on the moderate and mild slopes. However, on the steep slopes, as mentioned earlier, the nappe flow regime was not noticed on all steps at the same time. The reason for this behavior might be due to the increasing amount of discharge on the lower steps from the additional flow, which is seeped from the vertical face of the steps. This can change the flow regime from nappe to skimming on the lower steps before starting the nappe flow on the higher steps. The seepage flow from the vertical face of steps was higher on steep slopes than the mild slopes likely due to less internal resistance. Indeed, the path of through-flow is shorter in the steep slopes. That's why the nappe flow regime was not apparent on all steps at the same time at the steep slopes on gabion stepped weirs. Fig. 3 shows the flow regimes for all downstream slopes as

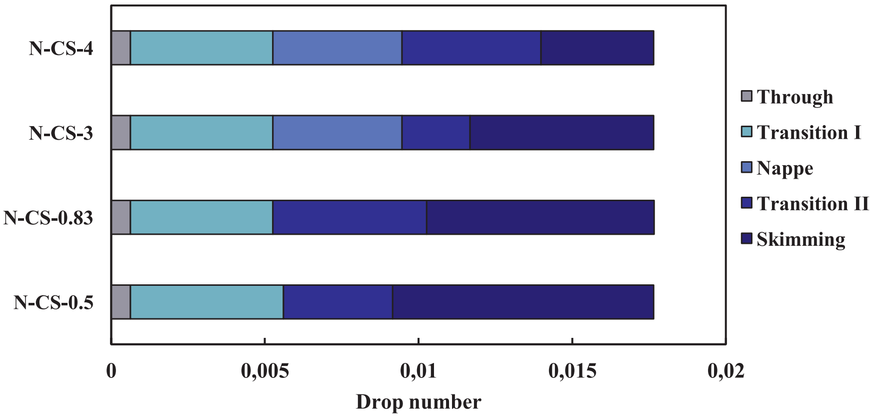

Fig. 2. Comparison of observed flow regimes between steep and mild downstream slopes.

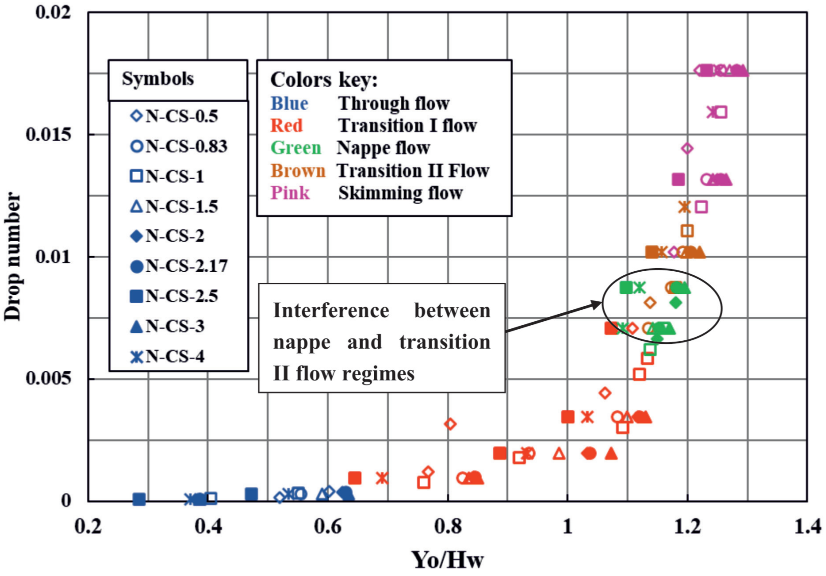

Fig. 3. Flow regimes on normal steps models.

a function of the drop number (discharge) and upstream flow depth ratio (y_0/h_w). In general, it can be recognized for all downstream slopes that the normal sequence of flow regimes with increasing discharge, starting from the through-flow at the low range of discharge to the skimming flow at the higher range of discharge. The flow regime is a function of the upstream depth ratio. At a low upstream depth ratio, the flow is through the porous media. Increasing the upstream depth ratio, the flow regime leads to the transition I flow regime and then overflow (nappe, transition II, and skimming). On the other hand, the upstream depth ratio is a function of the drop number. With an increase in the drop number (discharge), the upstream depth ratio increases. As a result, the flow regime is a function of the drop number. This result can be clearly noticed in Fig. 3, where, with increasing the drop number, the flow regimes changed in a successive pattern. They started with the through-flow regime and ended with the skimming flow regime. The effect of the downstream slope on flow regimes can be divided into two parts. The first part is for the through and transition I flow. At the low (milder) slopes, the length of the weir will be longer. The through-flow path will be longer, as well. In this case, the internal resistance increased, which lead to an increase in the upstream flow depth. As a result of the increasing upstream water depth, the overflow will be started at a lower discharge than that for the high (steep) slopes. The second part is for the overflow regimes. At low slopes, the contact surface between the water and the weir will be longer, and the friction resistance will be greater. The velocity, in this case, will be lower. That's why all the flow regimes were clearly observed in the normal sequence

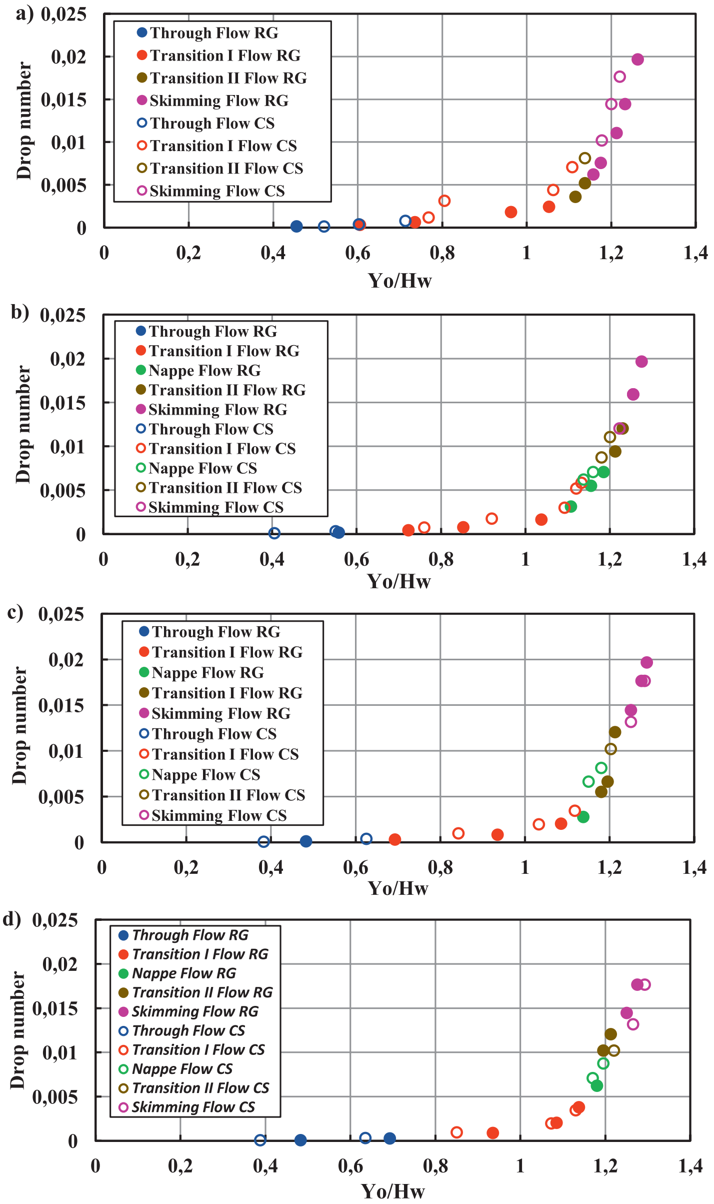

Fig. 4. Comparison of flow regimes between rockfill type: crushed stone (CS) and rounded gravel (RG): a) models N-CS-0.5 and N-RG-0.5, b) models N-CS-1 and N-RG-1, c) models N-CS-2 and N-RG-2, and d) models N-CS-3 and N-RG-3.

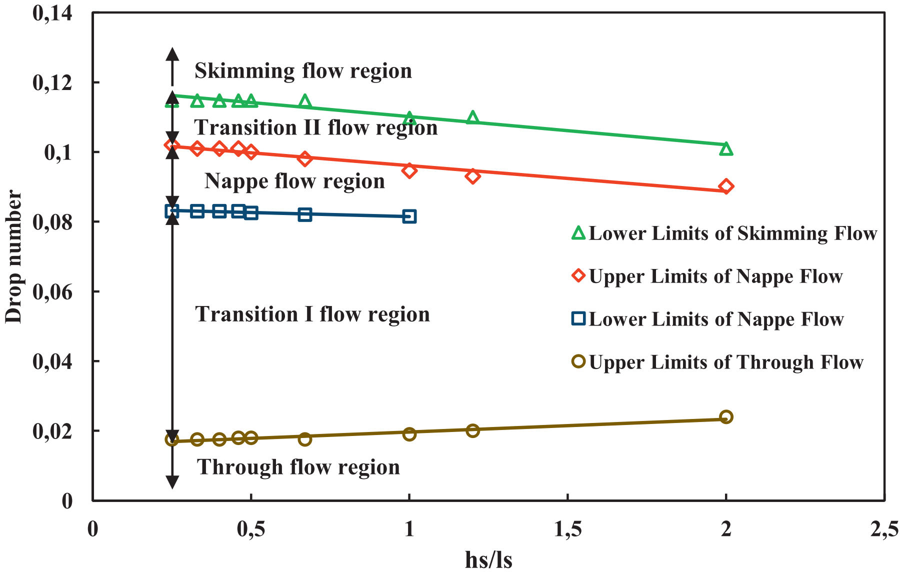

Fig. 5. Flow regimes limits on normal steps models.

on the mild slope models. For the same reason, the interference between transition I and II flow regimes on the steep slopes were noticed, and the nappe flow regime was not seen, as shown in Fig. 3.

Effect of Materials Rockfill

Two types of rockfill materials were used to investigate the effect of particle shape and porosity on flow regimes. Rounded gravel of nominal size (26.5 mm - 13.2 mm) D50 = 16 mm, and angular crushed stone of nominal size (37.5 mm - 13.2 mm) D50 = 23 mm. The average porosity was 0.38 for rounded gravel and 0.42 for crushed stone. Four downstream slopes (1: 0.5, 1: 1, 1: 2, and 1: 3) were used for each rockfill material with a wide range of discharge. Fig. 4 shows a comparison of the flow regimes between crushed stone and rounded gravel for each downstream slope. There is no clear effect of the rockfill materials' shape and porosity on the flow regimes, especially at the high drop numbers (at the overflow regimes). The shape and porosity of the rockfill materials can affect the amount of flow through the porous medium. More angularity means more resistance to the flow, while more porosity means less resistance to the flow. At the low drop numbers (D<0.003), there is a minor effect for filling material on the flow regimes (through-flow and transition I flow regimes). This result agrees with the finding of Jalil et al. (2019) [25]. At a high discharge (D>0.006), the effect of the rockfill materials is not apparent because the amount of through-flow was too small compared with the amount of overflow. Then, the overflow was not affected by the rockfill shape or porosity.

Table 4. The suggested relationships for estimating the flow regimes limits.

Flow regime	Formula	*R*
Upper limit of through-flow	$\sqrt{\frac{q}{\sqrt{g\,H_w^3}}} = 0.016 + 0.0037\left(\frac{h_s}{l_s}\right)$	0.965
Lower limit of nappe flow	$\sqrt{\frac{q}{\sqrt{g\,H_w^3}}} = 0.084 - 0.0023\left(\frac{h_s}{l_s}\right)$	0.951
Upper limit of nappe flow	$\sqrt{\frac{q}{\sqrt{g\,H_w^3}}} = 0.103 - 0.0073\left(\frac{h_s}{l_s}\right)$	0.971
Lower limit of skimming flow	$\sqrt{\frac{q}{\sqrt{g\,H_w^3}}} = 0.118 - 0.0081\left(\frac{h_s}{l_s}\right)$	0.970

Flow Regime Limits

Fig. 5 presents the limits of flow regimes on gabion stepped weirs (normal steps) as a relationship between the square root of the drop number and the downstream slope. The upper limits of the through-flow regime have a positive relationship. Indeed, as the downstream slope increases (steepens), the weir becomes shorter, has less internal friction resistance, and has more flow through the weir body. For the overflow regimes limits, the relation has a negative trend. The reason for this behaviour is likely due to the surface friction resistance that increased as the downstream slope decreased (milder). The flow velocity, consequently, also decreased. Using experimental data presented in Fig. 5, relationships were suggested for estimating the flow regimes limits on the gabion stepped weirs (normal steps) as shown in Table 4. Most studies such as (Zhang and Chanson, 2014; Wuthrich and Chanson 2015; Zhang and Chanson, 2015) used y_c/h_s to obtain the flow regime limits instead of the drop number [17, 18, 19]. This could be correct on the gabion spillways. However, on the gabion weirs, it might be inaccurate as the calculation of critical depth depends on the total discharge. Meanwhile, in the porous media, the flow has two components: through flow and overflow. The amount of through-flow is not negligible, especially at low and moderate discharge. The suggested limits were obtained for the normal step gabion weirs of 0.42 porosity with downstream slopes ranging from 0.25 to 2.0 ($14.03° \leq \alpha \leq 63.43°$) and drop numbers ranging from 0.0003 to 0.0132. It is recommended for the above ranges only, and the validity of these limits outside the ranges is questionable. There is no available information outside of the ranges.

Conclusions

The current study investigated the flow regimes on gabion stepped weir for different downstream slopes and rockfill materials experimentally. Nine normal steps models were tested, each with ten runs of different discharges to investigate the effect of downstream slopes on flow regimes. The downstream slopes ranged between 1:0.5 to 1:4 V:H. Results show that all flow regimes have been observed in the normal sequence on most downstream slope models. However, for the steeper slope models (1:0.5, 1:0.83), the nappe flow regime is not observed clearly on all steps at the same time. This is due to interference between the nappe and transition II flow regimes. Moreover, based on the experimental data, four relationships were suggested to estimate the flow regime limits in terms of the square root of the drop number and the downstream slope. The coefficient of correlation (R) of the developed equations ranged between 0.95 to 0.97. Furthermore, two types of rockfill materials (rounded gravel of 0.38 porosity and crushed stone of 0.42 porosity) were utilized to study the effect of the rockfill materials on flow regimes. The results indicated that the shape and size of the rockfill materials have a minor effect on flow regimes at a low discharge only. This was when most of the flow was through the porous media. At a high rate of flow, when the flow was an overflow, the effect of rockfill materials is insignificant.

Acknowledgments

The authors would like to thank all the staff of the Digital Manufacturing and Civil Laboratories at Deakin University for their assistance and support. The first author would like to acknowledge the full scholarship support provided by the Ministry of Higher Education and Scientific Research of Iraq, Lulea University of Technology-Sweden, and Al-Mustaqbal University College-Iraq.

Conflict of Interest

The authors declare no conflict of interest.

References

1. PAGLIARA S., PALERMO M. Rock grade control structures and stepped gabion weirs: Scour analysis and flow features. Acta Geophysica, **61**, 126, **2013**.
2. PAGLIARA S., PALERMO M. Protected stilling basins downstream of low-head river training structures: energy dissipation. 36th IAHR World Congress, **2015**.
3. SALMASI F., ABRAHAM J. Discussion of 'Hydrodynamics of rectangular broad-crested Porous Weirs' by Akbar Safarzadeh and Seyed Hossein Mohajeri. Journal of Irrigation and Drainage Engineering, **144** (10), 04018028, **2020**.
4. FATHI-MOGHADDAM, SADRABADI M.T., RAHMANSHAHI M. Numerical simulation of the hydraulic performance of triangular and trapezoidal gabion weirs in free flow condition. Flow Measurement and Instrumentation, **62**, 93, **2018**.
5. MORADI M., MOGHADAM M.F., DAVOUDI L. Experimental investigation of submerged flow over porous embankment weirs with up and downstream slopes. Irrigation Sciences and Engineering, **43**, 187, **2020**.
6. SALMASI F., SABAHI N., ABRAHAM J. Discharge coefficients for rectangular broad-crested gabion weirs: experimental study. Journal of Irrigation and Drainage Engineering, **147** (3), 04021001, **2021**.
7. FELDER S. Air-water flow properties on stepped spillways for embankment dams: Aeration, energy dissipation and turbulence on uniform, non-uniform and pooled stepped chutes, **2013**.
8. WÜTHRICH D., CHANSON H. Air entrainment and energy dissipation on gabion stepped weirs. 5th IAHR International Symposium on Hydraulic Structures, **2014a**.
9. WÜTHRICH D., CHANSON H. Hydraulics, air entrainment, and energy dissipation on a Gabion stepped weir. Journal of hydraulic engineering, **140**, **2014b**.

10. SAQIB N.U., AKBAR M., PAN H., OU G., MOHSIN M., ALI A., AMIN A. Numerical Analysis of Pressure Profiles and Energy Dissipation across Stepped Spillways Having Curved Risers. Applied Sciences, **12**, 448, **2022**.
11. ALABAS M.A., AL-AMERI R., CHUA L., DAS S. Investigation of flow regimes and energy dissipation in gabion stepped weirs. IAHRAPD 2018: Multi-perspective water for sustainable development: Proceedings of the 21st Congress of International Association for Hydro-Environment Engineering and Research (IAHR), Asia Pacific Division (APD), in conjuction with 6th Regional Conference on Natural Disaster (RCND), Department of Civil and Environmental Engineering, Faculty of Engineering, 319, **2018**.
12. RAJAEI S.H., KHODASHENAS S.R., ESMAILI K. Comparative evaluation of energy dissipation over short, stepped gabion and rigid spillways. Journal of Hydraulic Research, **2019**.
13. KHATIBI R., SALMASI F., GHORBANI M.A., ASADI H. Modelling energy dissipation over stepped-gabion weirs by artificial intelligence. Water resources management, **28**, 1807, **2014**.
14. ZHANG G., CHANSON H. Hydraulics of the developing flow region of stepped spillways. I: Physical modeling and boundary layer development. Journal of Hydraulic Engineering, **142**, 04016015, **2016**.
15. REEVE D.E., ZUHAIRA A.A., KARUNARATHNA H. Computational investigation of hydraulic performance variation with geometry in gabion stepped spillways. Water Science and Engineering, **12**, 62, **2019**.
16. WUTHRICH D., CHANSON H. Aeration performances of a gabion stepped weir with and without capping. Environmental Fluid Mechanics, **15**, 711, **2015**.
17. ZHANG G., CHANSON H. Free-surface and seepage bubbly flows on a gabion stepped spillway weir: experimental observations. Arthur Mynett, Proceedings of the 36th IAHR World Congress: Deltas of the Future and What Happens Upstream. 36th IAHR World Congress, 6624, **2015**.
18. ZHANG G., CHANSON H. Step cavity and gabion aeration on a gabion stepped spillway. ISHS 2014-Hydraulic Structures and Society-Engineering Challenges and Extremes: Proceedings of the 5th IAHR International Symposium on Hydraulic Structures, The University of Queensland, 1, **2014**.
19. WUTHRICH D., CHANSON H. Aeration and energy dissipation over stepped gabion spillways: A physical study. AUSTRALIA: School of Civil Engineering, The University of Queensland, **2014**.
20. PEGRAM G.G., OFFICER A.K., MOTTRAM S.R. Hydraulics of skimming flow on modeled stepped spillways. Journal of hydraulic engineering, **125**, 500, **1999**.
21. CHANSON H. Hydraulics of stepped spillways: Current status. Journal of Hydraulic Engineering, **126**, 636, **2000**.
22. ESSERY I.T.S., HORNER M.W. The hydraulic design of stepped spillways. 2 ed.: Construction Industry Research and Information Association, **1978**.
23. PEYRAS L., ROYET P., DEGOUTTE G. Ecoulement et dissipation sur les déversoirs en gradins de gabions. La Houille Blanche, 37, **1991**.
24. ANDRÉ S., SCHLEISS A. High velocity aerated flows on stepped chutes with macro-roughness elements. EPFL-LCH, **2004**.
25. JALIL S.A., SARHAN S.A., HUSSEIN B.S., QASIM J.M. Effect of Gravel Size and Weir Height on Flow Properties of Gabions. Journal of University of Babylon for Engineering Sciences, **27**, 214, **2019**.