Characterizations of flow over stepped spillways with steps having transverse slopes

A S Ali¹ and O S Q Yousif¹,²

¹Irrigation Engineering Department, University of Sulaimani, Sulaimani-Kirkuk Main Road, Iraq-Kurdistan Region, Al- Sulaimaniyah, Iraq

E-mail: omed.qadir@univsul.edu.iq

Abstract. The top and downstream face of the embankment dams must be protected from overtopping damages happen due to extreme floods. This can be achieved by providing one of the overtopping protection systems. The most common overtopping protection systems are those which have stepped fashion. This type of protection systems consists of a series of continues steps mostly made of concrete. In this study, the effects of the transverse slope of steps on flow properties over the overtopping protection systems were explored experimentally. Steps with transverse slopes are those which have inclinations from one spillway wall towards the other spillway wall in a zigzag way. To achieve the goals of the study, three physical models, stepped spillways, were made of wood and tested in a prismatic flume. The width, depth, and length of the wooden models were 0.6 m, 0.96 m and 1.92 m respectively. Sixteen steps (with three different transverse slopes ranging from zero to 5.7°) were cut into the surface of the models from the crest to the toe. The models were then tested under various flow rates ranging from 0.003 to 0.05 m³/s. The results showed that the models with steps having transverse slope had higher energy dissipation capability compared to the model with steps having zero transverse slopes (flat steps); up to 14% higher. In addition, for the models with steps having the transverse slope, the onset of the skimming flow occurred at higher ratios of critical depth (y_c) to step height (h_s); greater than 1.37. However, the distances of the inception points from the first step brink (inception point locations) were reduced by half, on average, for the model with steps having a transverse slope of 5.7°.

1. Introduction

During normal flood events, the excessive water in the reservoirs is normally discharged over spillways. However, during extreme events, due to inadequate spillway capacity at some existing dams flood overtopping may occur over the dam body. Recently, the spillway capacities of some old dams were re-evaluated worldwide. It was found that the revised flood capacities were higher than the original (designed) capacities of the spillways [1-4]. If the revised floods occur, the probability of overtopping of these old dams will be very high. For embankments dams, overtopping is typically not allowed to occur; the overtopping might erode the downstream face of the dam endangering the safety of the dam or causing catastrophic failure. Accordingly, rehabilitation for these dams are needed.

One of the most effective methods for dam rehabilitation is overtopping protection system [3-6]. The overtopping protection systems are typically using for covering the top of the dam and its downstream face. They are very effective for increasing flood discharge capacity at the old dams in order to discharging extreme floods safely. Accordingly, several overtopping protection systems have been invented such as paving, reinforced earth, stepped overlapping concrete blocks, stepped gabions
and roller compacted concrete, [1, 3, 5, 7-15]. However, the most common and effective overtopping protection systems are those which have stepped fashion [3, 4, 15-17]. Besides erosion protection, the stepped protection systems have several other advantages such as construction economy (less financial expenditure and shorter construction time by using RCC concrete); reduction of cavitation risks; flow aeration; and significant energy dissipation due to steps which in turn may lead to a remarkable reduction in dimensions of energy dissipater structures at the toe of the spillway [1, 17-31]. The stepped overtopping consists of a series of continues steps constructed on the downstream slope from the crest to the toe.

In order to enhance the energy dissipation of flows over steps overlaid on the embankments, several step shapes and configurations have been studied but steps with transverse slopes [1, 3-5, 9, 11, 14, 16-21]. Steps with transverse slopes have slopes from one abutment, or spillway wall, towards the other abutment, other spillway wall in a zigzag way. This paper explores the effects of transverse slopes of steps of stepped spillways on the properties of flows over the stepped spillways.

2. Experimental setup and procedure

The tests were conducted in a rectangular Scoret-walled (10 mm thickness) flume in the Hydraulics laboratory of the College of Engineering at the University of Sulaimani. The flume was 8 m long and 0.605 m wide having two depths; the first 2.5 meter length of the flume has 1.35 m depth while the rest of the flume, 5.5 m long, has 0.70 m depth. Water flow was supplied from a large feeding basin leading to a steel reservoir (a stilling tank) upstream of the flume.

Three physical models were made of wood (Medium-density fibreboard - MDF) for the purposes of the present study. Each model consisted of a broad crested weir (0.605 m wide, 0.60 m long, with upstream sharped corner) followed by sixteen steps. The ratio of step height to step length was 1V:2H (h = 0.06 m, l = 0.12 m); the slope (θ) of the stepped spillway section was 26.6°. Two of the three stepped spillways were equipped with a combination of flat and not-flat steps. The not-flat steps are those which have transverse slopes. Steps with transverse slopes means the steps that have inclination from one abutment, or spillway wall, towards the other abutment, other spillway wall in a zigzag way. Sketches of the stepped models used in the present study are provided in Figure 1. For the first model, M1 configuration, all sixteen steps were kept flat as a reference model. For the other two models, M2 and M3 configurations, different transverse slopes were given to twelve steps after the first step. Since the dam crests cannot have transverse slope, the first step was kept flat. The last three steps were also kept flat in order to reduce the effects of skewing jumps that produce at the toe. For the M2 and M3 configurations, the step height changes across the flume; from 0.06 m to zero for M3 configurations, or from 0.06 m to 0.03 m for M2 configurations (see Table 1).

![Figure 1](image-url)
Table 1. Summary of configurations used in the experimental work.

| Step Configuration | Step Height, m | Transvers slope, α, degree | Discharge per unit width, (q_w) m^2/s |
|--------------------|----------------|---------------------------|--------------------------------------|
| M1 - 16 flat steps with h = 0.06 m | 0.06 0.06 0.06 | 0.006-0.075 |
| M2 - 12 steps with transverse slope with average h = 0.045 m, 3 flat steps with h = 0.06 m | 0.03 0.045 0.06 2.84 | 0.006-0.075 |
| M3 - 12 steps with transverse slope with average h = 0.03 m, 3 flat steps with h = 0.06 m | 0.00 0.03 0.06 5.66 | 0.006-0.075 |

The length of wooden stepped models were 2.52 m with Scoret-sidewalls followed by a horizontal Scoret-invert flume ending in a downstream large steel tank, from where the water was pumped to the upstream feeding basin. The pump supplied a constant water discharges up to 0.05 m^3/s (0.83 m^2/s). The discharges were measured using ultrasonic flow meter positioned in the inlet pipe; 0.00025 to 0.065 m^3/s. The schematic diagram of the flume and the other facilities, such as: storage tank, recirculation tank, pump, ultrasonic flow meter, point gauges and valves is shown in Figure 2.

Water flow depths upstream the broad crested models and downstream the hydraulic jumps were measured using pointer gauges with 1 mm accuracy. The first, upstream, point gauge was located 0.6 m upstream the models. The second point gauge, located downstream the hydraulic jumps, was used to measure the sequent depths of the hydraulic jumps. The depth of water downstream the models, after creating hydraulic jumps, was controlled by placing wooden sills at the end of the flume. The locations of the hydraulic jumps were kept close to the toe of the models as much as possible (20 cm away from the last step).

Figure 2. Schematic diagram of the experimental setup.

3. Result analysis
For each test, data points were collected along with 6 to 8 hours of visual observations. More than 250 individual data (discharges, water depths at three locations, inception point locations, and hydraulic jump lengths) were documented along with taking photographs and recordings on videotapes.

3.1. Flow characterizations
For the flows over stepped spillways, the flow patterns and regimes can be differentiated by visual observations [2, 22-25]. For the present study, at small discharges, the flows over the stepped models
were of nappe flow type. The nappe flow is a type of flow that characterized by a series of free-falling jets flowing over the steps; the water falling from upper step hitting the tread of the lower step with or without forming a hydraulic jump [22]. From Figure 3, for M1 configuration, the nappe flow regime was observed for \( y_c/h < 0.63 \), where \( y_c \) is the critical depth of flow and \( h \) is the step height. The critical depth for flow over a spillway in a rectangular channel can be calculated from \( y_c = (q_w^2/g)^{1/3} \), where \( q_w \) is the water discharge per unit width and \( g \) is the gravity acceleration. For M2 configuration, the nappe flow regime was prevailed for \( y_c/h < 0.98 \) (see Figure 4), while, for M3 configuration, the nappe flow regime was prevailed for \( y_c/h < 1.1 \).

Figure 3. Flow patterns for configuration M1, nappe flow, \( y_c/h = 0.63 \).

Figure 4. Flow patterns for configuration M2, \( y_c/h = 0.98 \).
At large discharges, on the other hand, skimming flows occurred. In the skimming flow, the water flows like a thick layer over a pseudo-bottom (invert) formed by the step edges [22]. In addition, the undulations of the water surface in the skimming flow are not reflecting the underlying step pattern [26]. For M1 configuration, the skimming flow regime was observed for \( y_c/h \geq 0.87 \) (Figure 5). The results were in agreement with the literature [23, 24]; Rajaratnam (1990) [23] found that the skimming flow occurs for ratios \( y_c/h \) greater than 0.8. However, for the models with steps having transverse slopes, M2 and M3 configurations, the skimming flow regime was observed for larger \( y_c/h \) obtained in the literature. For M2 configuration, the skimming flow regime was occurred for \( y_c/h > 1.2 \). While for M3 configuration, the skimming flow was not observed even for \( y_c/h = 1.37 \) (Figure 6); the maximum discharge used in this study.

According to the literature [23, 25], for stepped spillways with \( \theta = 26.6^\circ \), the skimming flow typically occurs when the steps under the flowing water are totally submerged. In addition, in the skimming flows, water recirculation with vortices patterns are typically formed in the interior of the

---

**Figure 5.** Flow patterns for configuration M1, onset of skimming flow, \( y_c/h = 0.87 \).

**Figure 6.** Flow patterns for configuration M3, \( y_c/h = 1.37 \).
steps. For the M2 and M3 configurations, for \( y_c/h > 1.2 \), water ponded in the interior portion of all steps beneath the free-falling jets. However, at some discharges, transition states occur when the flow jets hit the steps partially (near the end of the step) and the steps under flowing water are partially full. The requirements of skimming flow regime was met for \( Q_w > 0.036 \, \text{m}^3/\text{s} \). At some intermediate discharges, a chaotic behaviour with strong splashing was observed. This type of flow is classified as transition flow [2].

In general, the flow conditions along the spillways with steps having transverse slopes (M2 and M3 configurations) were very turbulent. The free surfaces were very irregular with having many cross waves. This, in turn, led to thicker flows to be formed on M2 and M3 configurations. Therefore, for the same flow rates, bulking of the flow along the M1 appeared to be less than for the M2 and M3 models; the air-water mixing of the flowing water for the M2 and M3 configurations was stronger compared to the flowing water over the M1 model (see Figure 7). This may due to strong interaction among the flow, the recirculating vortices inside the steps and free surface which, in turn, this led to entrain a large amount of air into the mainstream flow.

![Figure 7. Flow patterns for the three configurations, \( y_c/h \approx 1.37 \).](image)

3.2. Location of inception points

For all configurations, the aerated flow has typically occurred very near to the crest at low discharges. However, as discharge increased, the aerated flow occurred after the upper few steps and steadily increased with discharge increasing. For the non-aerated regions, the surface of the flow was clear and glassy; non-aerated flow. However, significant aeration then occurred after those few steps where the step cavities-induced turbulence (turbulent boundary layer) reached the surface of the flowing water. The place of reaching the turbulent boundary layer and free surface is referred to the point of inception [22, 27]. Beyond the point of inception, the air started to entrain and penetrate throughout the bulked depth of flow. However, before the points of inception, the air entrainment is typically attributed to the turbulence formed by the sidewalls and the surface longitudinal vortices [28].

For the three models studied in this research, the locations of the inception point were identified and measured as the longitudinal distance from the edge of the first step to the beginning of the free-surface aeration. The points of inception were distinguished as the locations at which the flowing water transformed from a clear, glassy appearance to an air-entrained, foamy appearance on the surface of flowing water. In order to quantify the effects of transverse slopes of the steps on the locations of inception points, the experimental results are displayed in a dimensionless structure in Figure 8 utilizing dimensionless terms, \( L_i/(h \cos \theta) \) as a function of a dimensionless discharge \( y_c/h \), where \( L_i \) is the longitudinal distance estimated from the edge of the first step to the separation line between aerated and non-aerated regions, \( \theta \) is the angle between a line passes through the edges of the steps and the horizontal, and \( h \) is step height. The relationships were constructed for \( y_c/h \geq 0.8 \).
From the results, the lengths of the non-aerated region were greater for M1 configuration compared to the corresponding ones for the M2 and M3 configurations. From Figure 8, for similar \( y_c/h \), the values of \( L_i \) for M2 configuration reduced to one third (on average), 33\%, of the values of \( L_i \) for M1 configuration, while for M3 configuration, the values of \( L_i \) reduced to about half (on average); 48\%. This is attributed to the effects of the transverse slopes of the steps. The transverse slopes of the steps in a zigzag way formed a non-uniform velocity distribution condition across the flume and cross waves. In addition, the sidewalls formed waves that slightly raised the water surface next to the walls from which the waves could fall or roll into the primary stream. Accordingly, this led to creating an extremely turbulent, highly irregular free surface full of cross waves. This, in turn, led to decreasing the distance of the frothy appearance of the flowing water, at the free surface, from the edge of the first step; decreasing the values of \( L_i \).

3.3. Energy dissipation
In general, energy dissipation of flow over stepped spillways can be estimated as the proportion of energy losses over the stepped spillway, \( \Delta H \), to the total head available on the crest of the stepped spillway. The \( \Delta H \) over the stepped spillway, equals the difference between the total head (maximum head) available on the crest of the stepped spillways, \( H_{\text{max}} \), and the residual head remained at the toe of the stepped spillway, \( H_{\text{res}} \). The maximum head available on the crest of an ungated spillway can be obtained from; \( H_{\text{max}} = H_{\text{dam}} + 1.5y_c \), where \( H_{\text{dam}} \) is the dam height and \( y_c \) is critical depth of water flowing over the stepped spillway. The \( H_{\text{res}} \) can be expressed as [29]: \( H_{\text{res}} = 1.5y_c + \alpha \left( q_w^2/2gy_w^2 \right) \), where \( y_w \) is clear water depth, \( q_w \) is discharge per unit length and \( \alpha \) is energy correction coefficient. The energy correction coefficient ranges from 1.01 to 1.13 [20, 30]. In the present study, the average value was taken; \( \alpha = 1.07 \). The \( H_{\text{res}} \), also called the residual energy or the energy remained at the toe of the spillways, is important for designing the energy dissipation structure downstream of a spillway. The kinetic part of the \( H_{\text{res}} \) is typically dissipated at the toe of the spillway by a hydraulic jump in a structure called stilling basin.

In order to quantify the energy dissipation on the stepped models, the relationships for the data obtained in this study were constructed using dimensionless terms, \( \Delta H/ H_{\text{max}} \) as a function of a dimensionless discharge \( y_c/h \) as shown in Figures 9 and 10. Although, for M2 and M3 configurations, the step height changes across the flume, the step height of 0.06 m (\( h = 0.06 \) m) was considered in constructing all relationships in this study.

From Figure 9, for the three stepped models, results show that the energy dissipated due to the
steps depends primarily on the $y_c/h$ ratios; the amount of energy dissipated on the stepped models decrease as $y_c/h$ ratio increases. In addition, from the comparison of the results, as expected, a higher energy dissipation was observed for the models with steps having transverse slopes during all discharges, for $0.25 < y_c/h < 1.4$. From Figure 10, for all discharges, the energy dissipation for M2 configuration was higher than the energy dissipation M1 configuration by 7%. While for M1 and M3 configurations, the percentage differences of energy dissipation between M1 and M3 configurations ranges from 6 to 14% with an average value of 11%.

![Figure 9](image1.png)

**Figure 9.** Comparison of energy dissipation, $\Delta H/H_{\text{max}}$, as a function of $y_c/h$ for different step configuration, $\theta = 26.6^\circ$.

![Figure 10](image2.png)

**Figure 10.** Relative energy loss and relative critical flow depth for different step configurations, $\theta = 26.6^\circ$.

The above findings can be explained as follows; most of the flows occurred on the models with steps having transverse slopes were nappe flows. In the nappe flow regime, the water is moving down from the upper steps to the lower ones as a sequence of free-falling jets. The kinetic energy in the nappe flow regime is typically dissipated by hitting, mixing and breaking up of the flow jets on the steps and the formation of a partially or fully formed hydraulic jump on the steps [22, 31].
M3 configurations, the transverse slopes of the steps enhance jet hitting, breaking up and mixing; the slopes of the step increase the step height and forms lateral flows. In other words, the transverse slopes of the steps create wakes which in turn can create larger flow resistance. This, accordingly, causes higher energy dissipation of the flows over the models with steps having transverse slopes compared to the models with flat slopes.

4. Conclusions
In this experimental study, the characterizations of flow over stepped spillways with steps having transverse slopes were investigated experimentally. The focus of the study was on the energy dissipation performances of a stepped spillway having longitudinal slope (θ) of 26.6°, a typical slope for embankment dams. On a stepped spillway with flat steps, three types of flow regime may occur; nappe flow, transition and skimming flow. However, on the stepped spillway with steps having transverse slopes, only two types of flow may occur; nappe flow and transition flow. The transverse slopes of the steps reduces the distances of the inception points from the first step brink (inception point locations); for the model with steps having transverse slope of 5.7º the distances of the inception points from the first step brink were reduced by 48%. In addition, for the models with steps having transverse slope, the onset of the skimming flow occurred at higher ratios of critical depth (yc) to step height (h); greater than 1.37. Furthermore, the energy dissipation calculations showed that the rate of energy dissipation increases with the transverse slope of the steps. For a given transverse slope of the steps, however, the rate of energy dissipation decreases with increasing discharges. The largest energy dissipation occurred on the spillway with steps having the maximum transverse slope (5.7º). However, for higher discharges, the energy dissipation rate is slightly lower.

Acknowledgments
The authors are very grateful to the College of Engineering at the University of Sulaimani for allowing us to use the experimental facility in the Hydraulic laboratory. The partial financial support from Mr. Shaswar Abdulwahid Qadir is quite appreciated. Special thanks to Mr. Goran Jalal for providing help during the tests.

References
[1] Frizzell K H 1992 Hydraulics of stepped spillways for RCC dams and dam rehabilitations Roller Compacted Concrete III, ASCE pp 423-39
[2] Chanson H and Felder S 2010 Energy dissipation on embankment dam stepped spillways, overflow stepped weirs and masonry stepped spillways Proc. of 17th Congress of IAHR Asia and Pacific Division, IAHR-APD B Melville, G DE Costa and T Swann eds. (Auckland, New Zealand)
[3] Chanson H 2015 Embankment overtopping protection systems Acta Geotechnica 10 305-18
[4] Hepler T, Crookston B and Crowder J 2018 Successful overtopping protection projects in the Eastern US Protections 2018 3rd International Conference on Protection against Overtopping (Grange-over-Sands, UK)
[5] ASCE Task Committee 1994 Alternatives for Overtopping Protection of Dams (New York: ASCE) p 139
[6] FEMA 2014 Technical manual: overtopping protection for dams Report P-1015 (Washington D.C.)
[7] Clopper P E 1991 Protecting embankment dams with concrete block systems Hydro Review 10 (CD-ROM)
[8] Osvalt N R 1992 Overtopping protection alternatives for dams Hydraulic Engineering: Saving a Threatened Resource—In Search of Solutions ASCE pp 1210-5
[9] Frizzell K H 1997 Protecting embankment dams with concrete stepped overlays Hydro Review 16 36-45
[10] Frizzell K H and Ruff J F 1995 Embankment overtopping protection-concrete blocks or riprap
Water Resources Engineering ASCE pp 1021-5
[11] Frizzell K H, Matos J and Pinheiro A N 2000 Design of concrete stepped overlay protection for embankment dams Proceedings of the International Workshop on Hydraulics of Stepped Spillways H E Minor and W H Hager, A A Balkema, Rotterdam eds. (Zurich) pp 179-86
[12] Manso P D A and Schleiss A J 2002 Stability of concrete macro-roughness linings for overflow protection of earth embankment dams Can. J. Civil Eng CSCE 29 762-76
[13] Chanson H and Gonzalez C A 2004 Recent advances in stepped spillway design: Air–water flow on stepped chutes, embankment dam stepped spillway and other considerations Fluvial, Environmental and Coastal Developments in Hydraulic Engineering 91-108
[14] Gonzalez C A and Chanson H 2007 Hydraulic design of stepped spillways and downstream energy dissipators for embankment dams Dam Eng. 17 223-44
[15] Chanson H and Felder S 2010 Energy dissipation on embankment dam stepped spillways, overflow stepped weirs and masonry stepped spillways Proc. of 17th Congress of IAHR Asia and Pacific Division, IAHR-APD B Melville, G De Costa, and T Swann eds. (Auckland, New Zealand)
[16] Gonzalez C A and Chanson H 2006 Air entrainment and energy dissipation on embankment spillways International Symposium on Hydraulic Structures (Ciudad Guayana, Venezuela)
[17] Felder S 2013 Air-water flow properties on stepped spillways for embankment dams: Aeration, energy dissipation and turbulence on uniform, non-uniform and pooled stepped chutes (Brisbane, Australia: The University of Queensland)
[18] Toombes L and Chanson H 2005 Air-water mass transfer on a stepped waterway J. Environ. Eng. ASCE 131 1377-86
[19] Hunt S L and Kadavy K C 2011 Inception point relationship for flat-sloped stepped spillways J. Hydraulic Eng. ACES 137 262-6
[20] Hunt S L and Kadavy K C 2010 Energy dissipation on flat-sloped stepped spillways: Part 1. Upstream of the inception point Transactions of the ASCE 103-9
[21] Hunt S L and Kadavy K C 2010 Energy dissipation on flat-sloped stepped spillways: Part 2. Downstream of the inception point Transactions of the ASABE 53 111-8
[22] Chanson H 1993 Stepped spillway flows and air entrainment Can. J. Civil Eng. CSCE 20 422-35
[23] Rajaratnam N 1990 Skimming flow in stepped spillways J. Hydraulic Eng. ASCE 116 587-91
[24] Chanson H 2001 Hydraulic design of stepped spillways and downstream energy dissipators Dam Eng. 11 205-42.
[25] Ohtsu I, Yasuda Y and Takahashi M 2004 Flow characteristics of skimming flows in stepped channels J. Hydraulic Eng. ASCE 130 860-9
[26] Pegram G G S, Andrew K O and Samuel R M 1999 Hydraulics of skimming flow on modeled stepped spillways J. Hydraulic Eng. ASCE 125 500-10
[27] Bindo M, Gautier J and Lacroix F 1993 Stepped spillway of M’Bali dam Int. Water Power Dam Constr. 45 35-6
[28] Chamani M R 1999 Characteristics of skimming flows over stepped spillways J. Hydraulic Eng. ASCE 125 361-8
[29] Boes R M and Hager W H 2003 Hydraulic design of stepped spillways J. Hydraulic Eng. ASCE 129 671-9
[30] Boes R M 1999 Physical model study on two - phase cascade flow Proc. 28th IAHR Congress, Graz, Austria, Session SI.International Association for Hydro - Environment Engineering and Research (CD-ROM)
[31] Felder S and Chanson H 2011 Energy dissipation down a stepped spillway with nonuniform step heights J. Hydraulic Eng. ASCE 137 1543-8