Experimental investigation on effective scouring parameters downstream from stepped spillways

Amir Ghaderi, Rasoul Daneshfaraz, Mohammadamin Torabi, John Abraham and Hazi Mohammad Azamathulla

ABSTRACT

Experimental tests were carried out to investigate the effective scouring parameters downstream from stepped spillways with different flow rates and step sizes. The results indicated that the flow regime plays an important role in scour-hole dimensions such that the minimum scouring depth happens in the nappe flow regime. Moreover, step size and tailwater depth are essential parameters for maximum scouring depth. Increasing tailwater depth from 6.31 cm to 8.54 cm and then to 11.82 cm decreases the scouring depth by 18.56% and 11.42%, respectively. These alterations also decrease the scouring length by 31.43% and 16.55%, respectively. By increasing the flow rate, the particle Froude number will increase, and the increased momentum of the flow promotes scouring. In addition, the results show that scouring at the sidewalls is higher than in the middle of the cross-section. Finally, an empirical formula with root mean square error = 0.107 and $R^2 = 0.974$ is proposed to predict the maximum scouring depth downstream from the stepped spillways. Comparisons were made between the proposed formula and experimental results. This comparison demonstrated that the formula can predict souring depth to within 3.86% and 9.31% relative and maximum errors, respectively.

Key words | flow regime, local scour, step height, stepped spillway, tailwater depth

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HIGHLIGHTS

- The flow regime on stepped spillway plays an important role in scour-hole dimensions.
- Step size and tailwater depth are essential parameters for maximum scouring depth.
- The particle's Froude number affects the downstream scouring of the spillway in respect to velocity.
- An empirical formula with good accuracy to predict the maximum scouring depth downstream from the stepped spillways.

NOTATION

The following symbols were used in this study:

$q(Q/B)$	Water discharge per unit width $[L^2T^{-1}]$
B	Width of the flume [L]
h	The step's height [L]
l	The length of step [L]
L_d	The length of the stilling basin [L]
H_s	Height of stepped spillway [L]
d_{smax}	The maximum scouring depth [L]
α	Chute angle [–]
h_c	The critical depth [L]
h_t	The tail water depth [L]
ρ_s	Density of sediments $[ML^{-3}]$
ρ_w	Density of the water $[ML^{-3}]$
μ	Dynamic viscosity of water $[ML^{-1}T^{-1}]$

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Re	The Reynolds number [–]
g	Gravitational acceleration [LT^{-2}]
S	The relative density of sediments [–]
D_{50}	Bed material diameter of which is finer by weight [L]
D_{10}	Grain size for which 10% of material is finer [L]
D_{30}	Grain size for which 30% of material is finer [L]
D_{60}	Grain size for which 60% of material is finer [L]
C_u	Coefficient of uniformity [–]
C_c	Coefficient of curvature [–]
Fr_d	Particle Froude number [–]
σ_g	Geometric standard deviation [–]

INTRODUCTION

Stepped spillways with a basin are one of the best solutions to transfer high-energy water and dissipate water flow energy (Ghaderi *et al.* 2020). Hence, the use of stepped spillways has become increasingly widespread due to low manufacturing costs and high efficiency (Daneshfaraz *et al.* 2016). Some energy will be dissipated by the hydraulic jump and as the flow transitions from supercritical to subcritical in the basin. The remaining energy can cause a scouring hole in the spillway toe, downstream from the structure. Severe scouring can impact structural stability.

Significant research has been conducted on downstream scouring of structures (Kells *et al.* 2001; Verma & Goel 2005; Roshan *et al.* 2010; Tuna & Emiroglu 2011; Xie & Lim 2015; Zahabi *et al.* 2018; Ben Meftah & Mossa 2019; Daneshfaraz *et al.* 2019a, 2019b; Ghaderi & Abbasi 2019; Ghaderi *et al.* 2019; Sadeghfam *et al.* 2019). Tuna & Emiroglu (2013) investigated the effect of step size on scouring downstream from stepped spillways. These results indicate that the step height influences the depth of scouring. By increasing the step height with the same flow chute angle, scouring is shown to decrease. Moreover, scouring depths grow with increasing flow rate and chute angle. Aminpour & Farhoudi (2017) investigated the scouring profile downstream from different stepped spillways. This study yielded important information about appropriate dimensionless parameters. By using a dimensionless scouring profile, geometrical characteristics and the volume of transported sediments can be estimated. Elnikhely (2018) worked on scouring downstream from spillways. They placed blocks in the spillway chute to investigate critical parameters and to decrease downstream scouring. Awad *et al.* (2018) worked on minimizing scouring in contracting stepped spillways. They used 60% of the flume width contraction ratios with a 10% opening area in the breaker. Their results indicated that four rectangular openings is the ideal number of openings and can reduce scouring by ~55%. A 10-degree divergent angle can reduce scouring by ~65%.

Ghaderi *et al.* (2018) added a nanomaterial and silica-fume additive to the downstream moveable bed of a stepped spillway. Their results showed that these additives can decrease the depth and length of a scouring hole by ~41% and ~38%, respectively. Aminpour *et al.* (2018) investigated the time scale of local scouring downstream of stepped spillways. They showed that in certain circumstances, the dimensions of the scour hole increase with increasing particle Froude number. They also observed that an increase in the slope of a spillway causes a reduction in the size of the scour hole. It can be seen, based on the research discussed here, that the governing parameters of scouring have been investigated.

There is a significant need to better understand the physics of the scouring process so that design engineers can predict accurately with a high degree of certainty the magnitude and location of local scour around hydraulic structures. The main purpose of the present research is to understand effective scouring parameters downstream from stepped spillways, which were investigated experimentally for different unit discharges (flow regime), step geometries (step sizes), and tailwater depth.

DIMENSIONAL ANALYSIS

In scouring (Figure 1), the maximum scouring depth can be written as a function of the listed parameters, as shown in Equation (1):

$$d_{smax} = f_1(q,\ H_s,\ h,\ l,\ h_t,\ \alpha,\ d_{50},\ g, \rho_s,\ \rho_w,\ \mu,\ L_d) \quad (1)$$

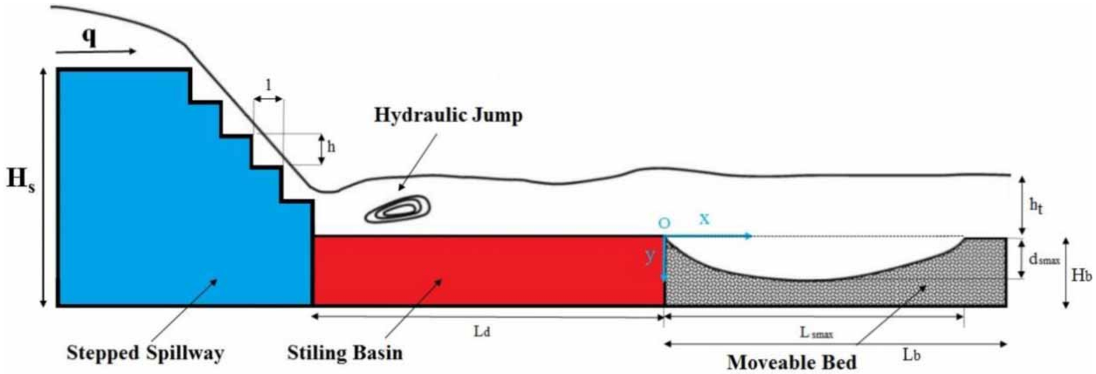

Figure 1 | Schematic scouring of stepped spillway downstream.

where q is the flow rate per unit width, H_s is the height of stepped spillway, h is the step height, l is the length of each step, α is the chute angle of the spillway, h_t is the tail water depth, d_{50} is the sediment particle's dimension, g is gravitational acceleration, ρ_s is the density of sediments, ρ_w is the density of water, μ is dynamic viscosity of water, and L_d is the length of the stilling basin. By combining ρ_s and ρ_w, a parameter Δ can be defined that is related to the interaction between sediments and the water flow. It is defined as:

$$\Delta = \frac{\rho_s}{\rho_w} - 1 = S - 1 \quad (2)$$

Here S is the ratio of sediment to water density (Dey & Raikar 2007). This parameter can be incorporated into the analysis so that:

$$d_{s\max} = f_2(q,\ H_s,\ h,\ h_t,\ l, \alpha,\ d_{50},\ g, \Delta,\ \mu,\ L_d) \quad (3)$$

According to the Buckingham π theorem, the dependent dimensionless parameter is based on independent parameters (Equation (4)). Previous researchers, for instance Hamedi *et al.* (2014), used the same dimensional analysis equation.

$$\frac{d_{s\max}}{h} = f_3\left(Fr_d,\ \frac{H_s}{h},\ \frac{d_{50}}{h},\ \frac{h_t}{h},\ \frac{l}{h},\ \frac{L_d}{h}, \alpha, \mathrm{Re}\right) \quad (4)$$

where Fr_d is particle Froude number $Fr_d = q/(g\Delta d_{50})^{0.5} d_{50}$. The model will not take into account changes in the Reynolds number, chute angle, or still basin length.

$$\frac{d_{s\max}}{h} = f_4\left(Fr_d,\ \frac{H_s}{h},\ \frac{d_{50}}{h},\ \frac{l}{h},\ \frac{h_t}{h}\right) \quad (5)$$

METHODS AND MATERIALS

Experimental facilities

Tests were carried out at the rectangular flume with a 5 m length, a 0.3 m width, and a 0.45 m height. The flume's bed and walls are plexiglass to improve flow visibility and reduce friction. With plexiglass, the influence of sidewall effects is considered to be negligible based upon the findings of Johnson (1996) and Moradinejad *et al.* (2019). The flow in the flume is generated by two pumps with a maximum flow rate of 7.5 L/s connected to two rotameters with ±2% accuracy (see Appendix-A1). To eliminate turbulence in the entrance region, a planar mesh has been added. The moveable bed is 1 m long and 12 cm deep. Three different stepped spillways, with two, three, and four steps of the same height and a 45-degree chuting angle were used. The stepped spillway was fabricated from dense polyethylene. Table 1 lists the geometric and hydraulic conditions of the experiment.

Table 1 | Dimensional and hydraulic experimental parameters

Q(L/s)	α°	h_c(cm)	h_t(cm)	l(cm)	h(cm)	$L_{d(cm)}$	H_s(cm)
3–15	45	2.1–6.3	2.96–12.56	3, 4, 6	3, 4, 6	80	12

To classify the flow regime on the stepped spillway, Equations (6) and (7) were used (Baylar *et al.* 2007). The equations are based on the ratio between the critical depth and the step height.

$$\left(\frac{h}{h_c}\right)_N = 0.57(\tan\alpha)^3 + 1.3 \quad \text{for } 5.7^{\circ} \leq \alpha \leq 55^{\circ} \tag{6}$$

$$\left(\frac{h}{h_c}\right)_S = 1.16(\tan\alpha)^{0.165} \quad \text{for } 5.7^{\circ} \leq \alpha \leq 55^{\circ} \tag{7}$$

where h is the step's height and h_c is the critical depth upstream of the spillway. Figure 2 indicates the flow regimes over stepped spillways.

By decreasing the number of steps and the flow rate, the flow will be in the transitional region and close to the nappe flow regime. By increasing the steps and decreasing the height of the steps, the flow regime will enter the skimming regime. Considering the time needed for reaching a balanced condition within the scouring pit, the duration of the experiment was decided to be 120 min. After this time, the scouring reached a steady state with no further changes in the dimensions of the pit. For the first 20 min, the depth and length of scouring was measured every 2 min. Thereafter, measurements were made every 4 min. To determine the length and depth of the scoured bed, a 3D-laser scanner was used. The 3D scanner used in this research had both a laser and an ultrasonic sensor. These sensors allowed the device to measure distances with an accuracy of 1 mm. To find the longitudinal scouring profile, five points from the mid-section were taken and averaged to eliminate sidewall errors. This technique was adopted from previous studies, such as Torabi & Shafieefar (2015).

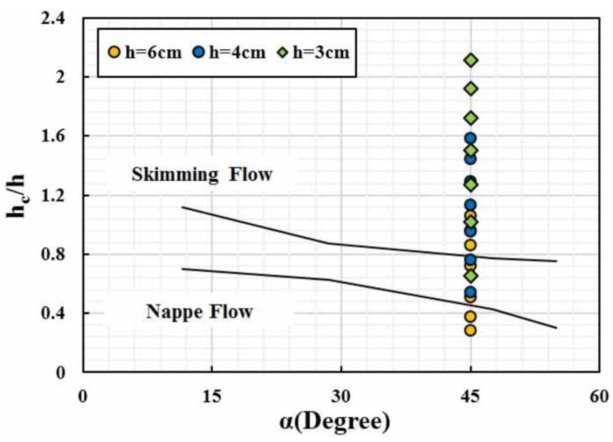

Figure 2 | Flow regime boundaries for stepped spillways.

Bed sedimentation characteristics

Attention was given to the appropriate sediment dimensions (Yalin 1971). According to Raudkivi & Ettema (1983), the minimum dimension of sediment was 0.7 mm to prevent the formation of ripples and to avoid particle adhesion during the scouring process. Uniform particle sizes have a standard deviation ($\sigma_g = (d_{84}/d_{16})^{0.5}$) and a coefficient of uniformity of less than 1/3 and 2, respectively. The scouring depth in non-uniform sediment is less than for the uniform sediment case (Lambe & Whitman 1994; Melville 1997). In this study, the average particle size, with the density, a standard deviation and a coefficient of uniformity and the density were 1.8 mm, 2,400 kg/m^3, 1.26 and 1.56, respectively. With this sediment, scouring takes place without ripple formation. Table 2 lists the sediments characteristics.

Before discussing the results, a comment should be made about the applicability of laboratory-scale experiments to provide accurate information for large-scale flow systems. The use of scaled experiments is helpful in this regard. We are also guided by past success of other researchers in extending laboratory-scale experiments to larger scales (Azmathullah *et al.* 2005; Emiroglu & Tuna 2011; Tuna & Emiroglu. 2011; Tuna & Emiroglu 2013). The use of scaled experiments also motivates the presentation of dimensionless results (as already revealed in the dimensionless governing equations). Of course, in reality it may be that small-scale laboratory experiments are not suitable for scaled investigation in this situation. With this as a possibility, there are some caveats when considering the results. Future work will be performed to ensure validity of small-scale experiments, but such a comprehensive comparison is beyond the scope of the present work.

Table 2 | Sediment properties

Bed particles	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	σ_g	C_u	C_c
	1.3	1.7	2.1	1.26	1.56	0.67

RESULTS AND DISCUSSION

The effect of the number of steps on downstream scouring

According to the Chanson (1994) studies on small experimental canals, the nappe flow regime can dissipate more energy than the skimming regime. This effectively decreases scouring downstream from the structure. Figure 3 shows the scouring hole downstream of the stepped spillway for two, three, and four steps and for different flow rates. In the figure, the flow passes from right to left. The figures correspond to different flow rates and each figure contains various step heights.

For similar flow rates, an increasing number of steps and a decreasing step height increases the scouring. Consequently, scouring in a stepped spillway with fewer large steps is less than scouring in a spillway with more smaller steps. This finding agrees with prior research (Chanson 1994; Ghaderi 2016). A comparison of different flow regimes shows that the nappe flow regime has the least scouring, again in agreement with prior research (Tuna & Emiroglu 2013). Figure 4 shows the

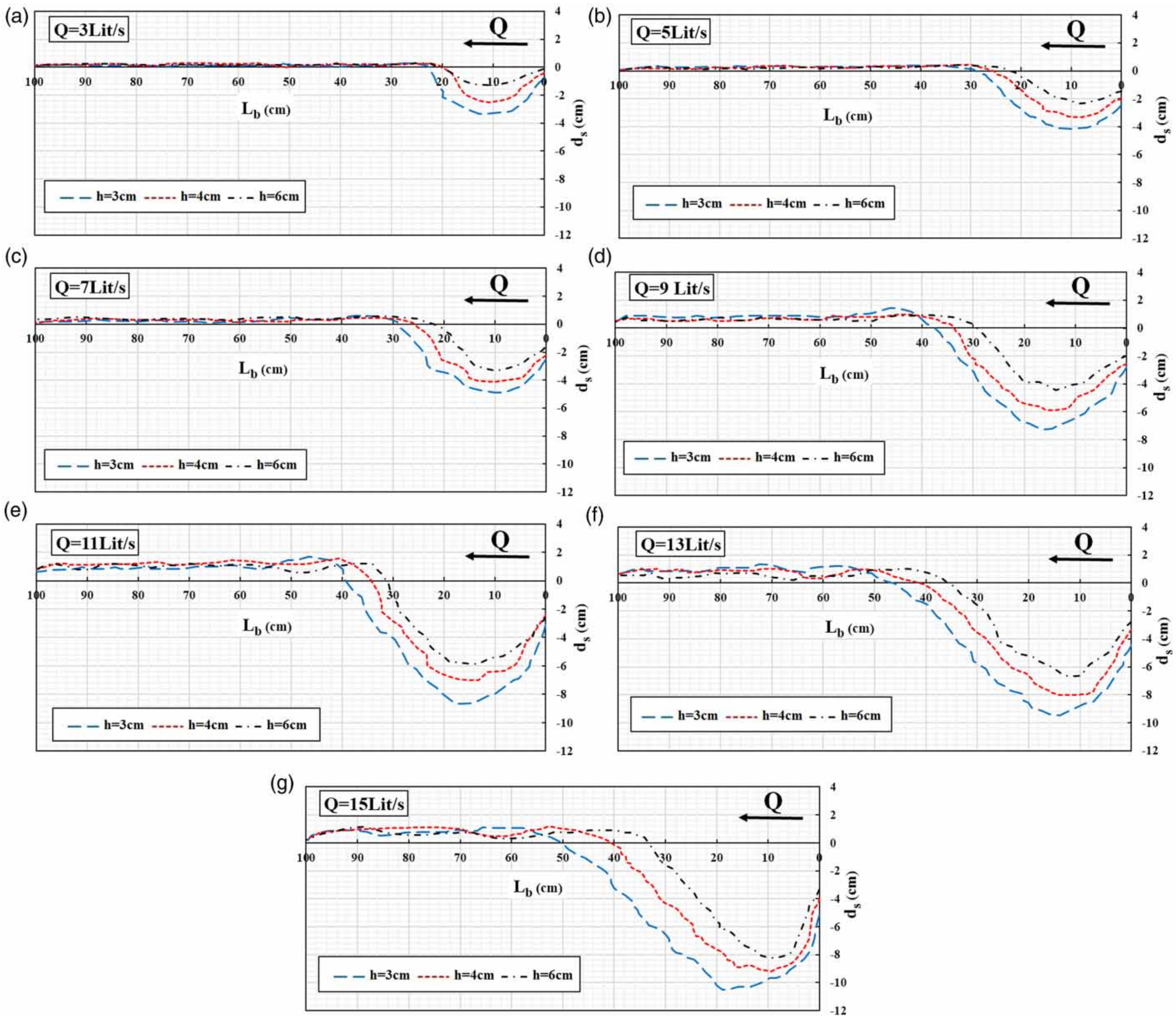

Figure 3 | Longitudinal scouring profiles for different flow rates and step heights: (a) to (g) Q = 3 to 15 L/s.

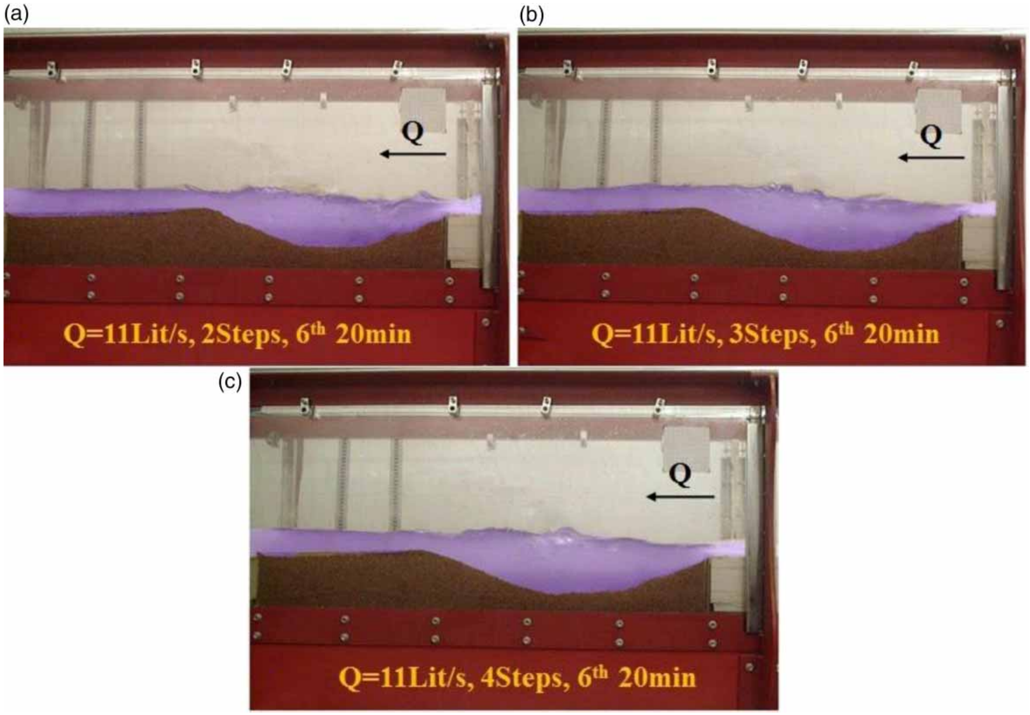

Figure 4 | Longitudinal profile of scouring downstream of a stepped spillway: (a) two steps, (b) three steps, (c) four steps.

scouring profile downstream of the stepped spillway with a constant flow rate of 11 L/s and three different step heights. The photographs were taken in the 6th 20-min segment (the last time period of the 2-h test).

The figure shows that the stepped spillway with two steps decreases the length and depth of scouring downstream of the stepped spillways compared with spillways with three or four steps. The two-step spillway decreases scouring by up to 20.2% compared to the three steps and 48.28% compared to the four steps. The reason for this energy dissipation is the nappe flow regime in two-step spillways. In other research studies, researchers assumed the longitudinal scouring profile existed next to the sidewalls. This assumption is not correct. Scouring near the sidewalls is more extensive than in the middle of the channel. The reason for this phenomenon is the interaction and impact of the transverse flow with sidewalls that transports sediments to the mid-section (see Appendix-A2). By increasing the flow rate, momentum will increase and enhance the length and depth of downstream scouring of the stepped spillway, although the scouring depth in the sidewalls will be more intense.

Tailwater depth effect in downstream scouring

Tailwater depth is one of the important parameters for downstream scouring and its study is important for understanding spillway performance. Based on the Farhoudi & Smith (1985) study, the shape of the scoured bed is independent of the sediment properties and depends instead on the flow regime and flow rate. The most intensive bed scouring takes place with a stepped spillway with four steps of 3 cm height and with skimming flow regime. Figure 5 indicates the longitudinal scouring profile of the above-mentioned spillway with a 13 L/s flow rate.

According to the longitudinal scouring profile shown in Figure 5, with the same hydraulic characteristics and increasing tailwater depth, the size of the scouring hole decreases. By increasing tailwater depth from 6.31 cm to 8.54 cm and then to 11.82 cm, the maximum depths and lengths of the scouring hole will decrease by 18.56% and 12.62% for 8.54 cm and by 31.43% and 16.55% for 11.82 cm, respectively. The results are summarized in Table 3.

The reason for this is the damping effect of the tailwater on the incident flow. This effect reduces energy and decreases

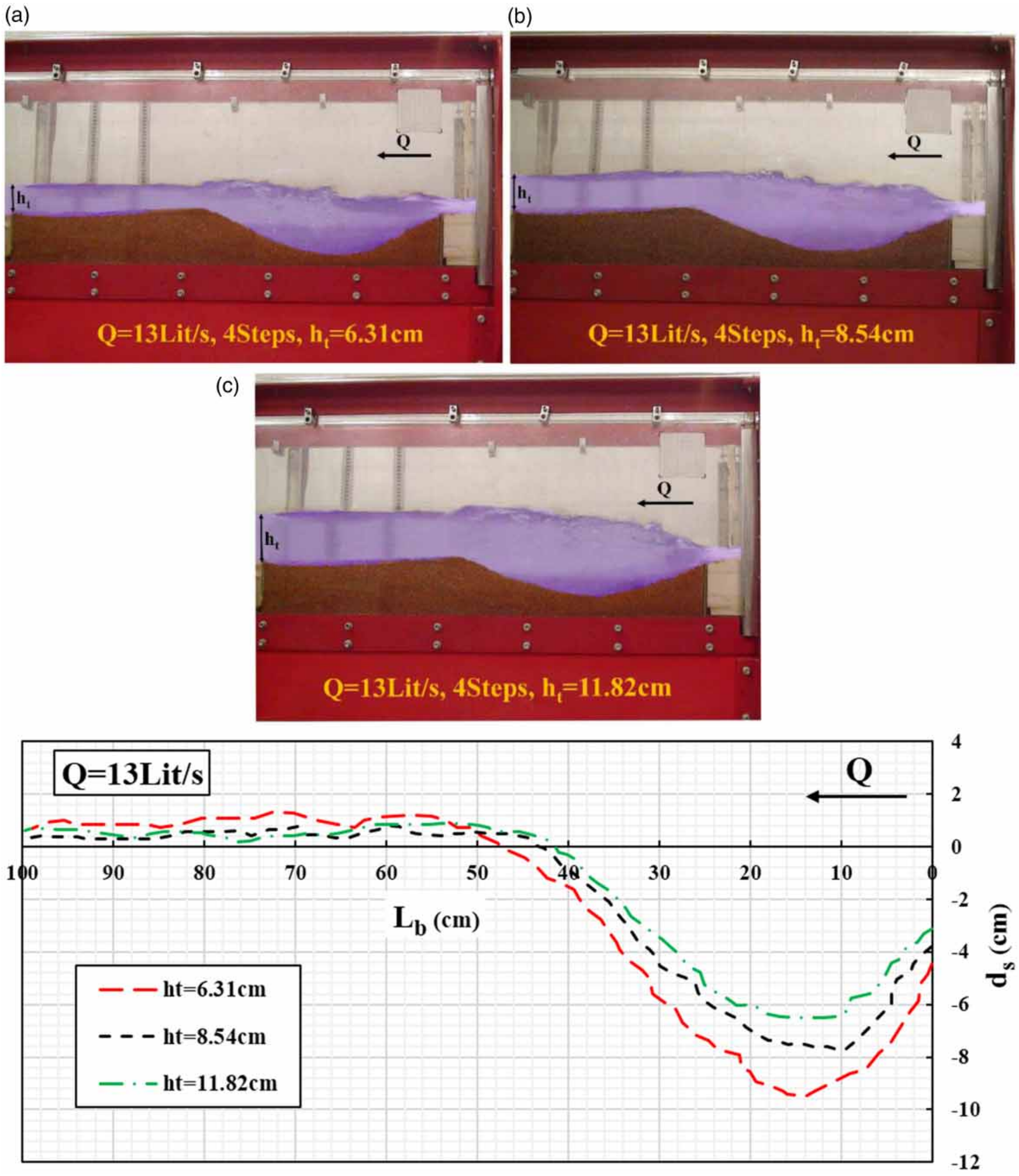

Figure 5 | Longitudinal scouring profile with three different tailwater depths and a 13 L/s flow rate: (a) $h_t = 6.31$ cm; (b) $h_t = 8.54$ cm; (c) $h_t = 11.82$ cm.

scouring (Johnston 1990; Emiroglu & Tuna 2011). The tailwater depth also affects the downstream vortex. Figure 6 shows the impact of two tailwater depths (6.31 cm and 11.82 cm) on the vortex with a 13 L/s flow rate.

By decreasing the flow depth with maintenance of the same flow rate, the velocity and momentum will increase and cause more downstream scouring. With increasing tailwater depth, the intensity and size of the vortex will decrease. Consequently, by increasing the tailwater depth and maintaining the same hydraulic characteristics, the scoured bed (the length and depth of the scouring) will decrease (see Appendix-A3).

The effect of the particle Froude number on scouring

The Froude number of a particle is an important parameter for downstream scouring (Tuna & Emiroglu 2011). In this study, to find the Froude number effect, the velocity at the

Table 3 | Effect of changing tailwater depth on the scour-hole depth and length

Tailwater depth (cm)	Maximum scour depth (cm)	Reduction (%)	Maximum scour length (cm)	Reduction (%)
6.31	9.48	NA	47.19	NA
8.54	7.72	18.56	41.80	11.42
11.82	6.50	31.43	39.38	16.55

end of the still basin upstream of the scour bed was measured. Figure 7 shows the relationship between the Froude number and the downstream scouring depth. It is seen that, in general, smaller but more numerous steps increase the Froude number significantly.

In all tests, the scouring depth increased by increasing the particle's Froude number. The higher the Froude number, the greater the velocity, and consequently larger fluid momentum hitting the bed. The increased momentum increases the vortex intensity and enhances the scouring rate. Scouring rarely took place in models with $Fr_d < 4$. The maximum scouring rate occured for $6 < Fr_d < 9$. This finding is in agreement with previous studies (Tuna & Emiroglu 2011) that also showed that a higher Froude number increases scouring.

Equation (8) allows prediction of the maximum scouring relative depth downstream of the structure. The quality of this fit is quantified by the root mean square error (RMSE) = 0.107 and $R^2 = 0.974$.

$$\frac{d_{s\max}}{h} = -26.34(Fr_d)^{-0.078} - 8.58(\sin(\alpha))^{7.123} - 10.72\left(\frac{b}{h}\right)^{1.07} + 34.42\left(\frac{h_t}{h}\right)^{0.017} + 39.31\left(\frac{d_{50}}{h}\right)^{1.26} \quad (8)$$

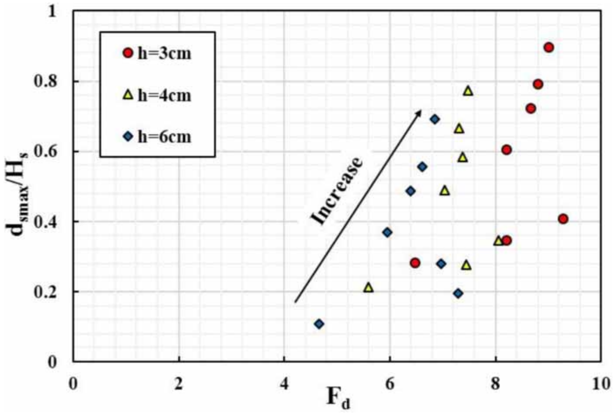

Figure 7 | Particle Froude number effect on the maximum downstream scouring depth.

Equation (8) was developed based on the 70–30% rule for experimental results. In this method, 70% of the data was used to train the coefficients and the remaining 30% was used to test the correlation accuracy. To quantify the accuracy, three statistical indices were used. The RMSE, R^2, and the relative error between the experimental data and the proposed formula. The definitions of these metrics are provided in Table 4.

In Table 4, n is the number of experimental tests, X_{Exp} is the experimental value, and X_{Cal} is the calculated value of the hydraulic parameter. To ensure the accuracy of the proposed experimental data, predicted values were compared with measurements from Emiroglu & Tuna (2011). The comparison shows that the relative and maximum errors were 3.86% and 9.31%, respectively. Figure 8 provides a comparison between the maximum relative depth obtained from experimental data and the predicted formula.

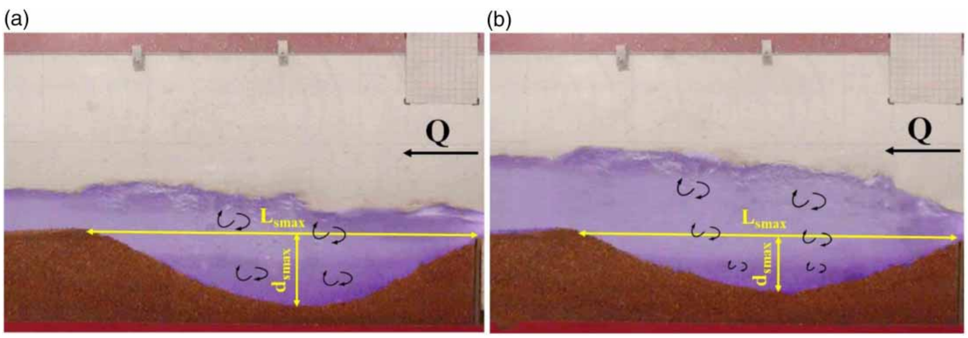

Figure 6 | Vortex inside the scoured hole with two different tailwater depths: (a) $h_t = 6.31$ cm and (b) $h_t = 11.76$ cm.

Table 4 | Statistical indices

Equation	Statistical index
$RMSE = \sqrt{\frac{1}{n}\sum_{1}^{n}(X_{Exp} - X_{Cal})^2}$	Root mean square error
$R^2 = \left(\frac{n\sum X_{Exp}X_{Cal} - (\sum X_{Exp})(\sum X_{Cal})}{\sqrt{n(\sum X_{Exp}^2) - (\sum X_{Exp})^2}\sqrt{n(\sum X_{Cal}^2) - (\sum X_{Cal})^2}}\right)^2$	R-squared
$RE = \frac{\lvert X_{Exp} - X_{Cal}\rvert}{X_{Exp}}$	Relative error

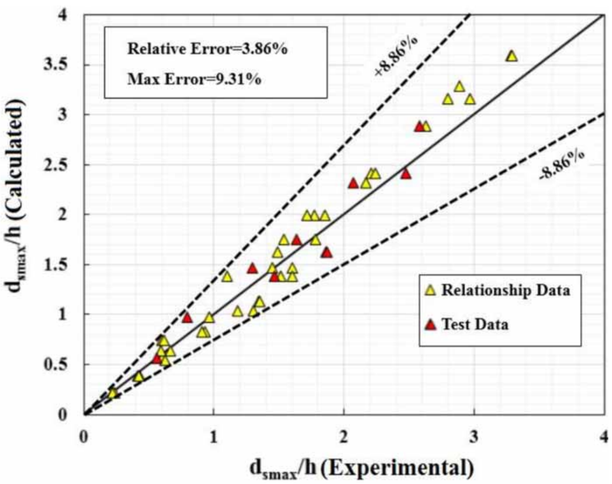

Figure 8 | Comparison between experimental and predicted d_{smax}/h values.

CONCLUSIONS

Scouring is an important issue to consider when designing hydraulic structures. In this research, a scouring phenomenon downstream from the stepped spillway was investigated and the following results were obtained:

- In small canals (the flume), the nappe flow regime can dissipate energy better than the skimming flow.
- The flow regime on a stepped spillway can affect the scouring hole. In this case, nappe flow minimizes scouring.
- The size of the steps is important in the maximum scouring depth. As step height increases, the maximum scouring depth falls.
- The 3D-scoured profile indicates that scouring near the walls is greater than in the middle. The reason for this is the interaction of the cross-sectional flow with the sidewalls that transports sediments to the mid-section.
- Tailwater depth also affects the scouring depth. By decreasing tailwater depth, the bed experiences a larger vortex and a flow with higher momentum.
- By increasing tailwater depth while maintaining the other hydraulic characteristics, the scoured hole will decrease. By increasing the tailwater from 6.31 cm to 8.54 cm, and then to 11.82 cm, the depth and length of the scoured bed decreases. This happens because the water acts like a damper on incident flow, decreasing the scouring rate.
- The particle's Froude number affects the downstream scouring of the spillway in respect to velocity. By increasing the flow rate and the Froude number, flow with higher momentum will impact the bed and cause more scouring.
- Finally, a formula was proposed to investigate the maximum relative scouring depth downstream from the stepped spillway, considering effective parameters. The proposed formula was also used to test the predictions against previous experimental studies (Emiroglu & Tuna 2011), yielding relative and maximum errors of 3.86% and 9.31%.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Aminpour, Y. & Farhoudi, J. 2017 Similarity of local scour profiles downstream of stepped spillways. *International Journal of Civil Engineering* **15** (5), 763–774.

Aminpour, Y., Farhoudi, J., Shayan, H. K. & Roshan, R. 2018 Characteristics and time scale of local scour downstream stepped spillways. *Scientia Iranica* **25** (2), 532–542.

Awad, A. S., Nasr-Allah, T. H., Mohamed, Y. A. & Abdel-Aal, G. M. 2018 Minimizing scour of contraction stepped spillways. *Journal of Engineering Research and Reports* **1** (1), 1–11.

Azmathullah, H. M., Deo, M. C. & Deolalikar, P. B. 2005 Neural networks for estimation of scour downstream of a ski-jump bucket. *Journal of Hydraulic Engineering* **131** (10), 898–908.

Baylar, A., Bagatur, T. & Emiroglu, M. E. 2007 Prediction of oxygen content of nappe, transition, and skimming flow regimes in stepped-channel chutes. *Journal of Environmental Engineering and Science* **6** (2), 201–208.

Ben Meftah, M. & Mossa, M. 2019 New approach to predicting local scour downstream of grade-control structure. *Journal of Hydraulic Engineering* **146** (2), 04019058.

Chanson, H. 1994 Comparison of energy dissipation between nappe and skimming flow regimes on stepped chutes. *Journal of Hydraulic Research* **32** (2), 213–218.

Daneshfaraz, R., Joudi, A. R., Ghahramanzadeh, A. & Ghaderi, A. 2016 Investigation of flow pressure distribution over a stepped spillway. *Advances and Applications in Fluid Mechanics* **19** (4), 811.

Daneshfaraz, R., Sadeghfam, S. & Tahni, A. 2019a Experimental investigation of screen as energy dissipators in the movable-bed channel. *Iranian Journal of Science and Technology, Transactions of Civil Engineering* 1–10. https://doi.org/10.1007/s40996-019-00306-7.

Daneshfaraz, R., Chabokpour, J., Dasineh, M. & Ghaderi, A. 2019b The experimental study of the effects of river mining holes on the bridge piers. *Iranian Journal of Soil and Water Research* **50** (7), 1619–1633.

Dey, S. & Raikar, R. V. 2007 Characteristics of horseshoe vortex in developing scour holes at piers. *Journal of Hydraulic Engineering* **133** (4), 399–413.

Elnikhely, E. A. 2018 Investigation and analysis of scour downstream of a spillway. *Ain Shams Engineering Journal.* **9** (4), 2275–2282.

Emiroglu, M. E. & Tuna, M. C. 2011 The effect of tailwater depth on the local scour downstream of stepped-chutes. *KSCE Journal of Civil Engineering* **15** (5), 907–915.

Farhoudi, J. & Smith, K. V. 1985 Local scour profiles downstream of hydraulic jump. *Journal of Hydraulic Research* **23** (4), 43–58.

Ghaderi, A. 2016 *The Experimental Investigation of the Effect of Labyrinth Weir Geometric Parameters with Energy Dissipater on the Scour of Downstream*. MSc Thesis, University of Maragheh, Maragheh, Iran.

Ghaderi, A. & Abbasi, S. 2019 CFD simulation of local scouring around airfoil-shaped bridge piers with and without collar. *Sādhanā* **44** (10), 216.

Ghaderi, A., Daneshfaraz, R., Zaerkabeh, R. & Ashkan, F. 2018 Experimental investigation of stepped spillways downstream erosion control using microsilica-structured and nano materials. *Amirkabir Journal of Civil Engineering.* doi:10.22060/CEEJ.2018.14919.5781 (in press).

Ghaderi, A., Daneshfaraz, R. & Dasineh, M. 2019 Evaluation and prediction of the scour depth of bridge foundations with HEC-RAS numerical model and empirical equations (Case study: bridge of Simineh Rood Miandoab, Iran). *Engineering Journal* **23** (6), 279–295.

Ghaderi, A., Abbasi, S., Abraham, J. & Azamathulla, H. M. 2020 Efficiency of trapezoidal labyrinth shaped stepped spillways. *Flow Measurement and Instrumentation* **72**, 101711.

Hamedi, A., Mansoori, A., Shamsai, A. & Amirahmadian, S. 2014 Effects of end sill and step slope on stepped spillway energy dissipation. *Journal of Water Science and Research* **6** (1), 1–15.

Johnson, M. 1996 *Discharge Coefficient Scale Effects Analysis for Weirs*. PhD Dissertation, Utah State University, Logan, Utah.

Johnston, A. J. 1990 Scourhole developments in shallow tailwater. *Journal of Hydraulic Research* **28** (3), 341–354.

Kells, J. A., Balachandar, R. & Hagel, K. P. 2001 Effect of grain size on local channel scour below a sluice gate. *Canadian Journal of Civil Engineering* **28** (3), 440–451.

Lambe, T. W. & Whitman, R. V. 1994 Soil mechanics SI version John Wiley & Sons. Chutes. *Journal of Hydraulic Research* **32** (2), 213–218.

Melville, B. W. 1997 Pier and abutment scour: integrated approach. *Journal of Hydraulic Engineering* **23** (2), 125–136.

Moradinejad, A., Saneie, M., Ghaderi, A. & Shahri, S. M. Z. 2019 Experimental study of flow pattern and sediment behavior near the intake structures using the spur dike and skimming wall. *Applied Water Science* **9** (8), 195.

Raudkivi, A. J. & Ettema, R. 1983 Clear-water scour at cylindrical piers. *Journal of Hydraulic Engineering* **109** (3), 338–350.

Roshan, R., Azamathulla, H. M., Marosi, M., Sarkardeh, H. & Ghani, A. A. 2010 Hydraulics of stepped spillways with different number of steps. *ICE Journal of Dams and Reservoirs* **20** (3), 131–136.

Sadeghfam, S., Daneshfaraz, R., Khatibi, R. & Minaei, O. 2019 Experimental studies on scour of supercritical flow jets in upstream of screens and modelling scouring dimensions using artificial intelligence to combine multiple models (AIMM). *Journal of Hydroinformatics* **21** (5), 893–907.

Torabi, M. A. & Shafieefar, M. 2015 An experimental investigation on the stability of foundation of composite vertical breakwaters. *Journal of Marine Science and Application* **14** (2), 175–182.

Tuna, M. & Emiroglu, M. E. 2011 Scour profiles at downstream of cascades. *Scientia Iranica* **18** (3), 338–347.

Tuna, M. C. & Emiroglu, M. E. 2013 Effect of step geometry on local scour downstream of stepped chutes. *Arabian Journal for Science and Engineering* **38** (3), 579–588.

Verma, D. V. S. & Goel, A. 2005 Scour downstream of a sluice gate. *ISH Journal of Hydraulic Engineering* **11** (3), 57–65.

Xie, C. & Lim, S. Y. 2015 Effects of jet flipping on local scour downstream of a sluice gate. *Journal of Hydraulic Engineering* **141** (4), 04014088.

Yalin, M. S. 1971 Theory of hydraulic models. In: *Associated Companies in New York*, Vol. 266. Macmillan, London.

Zahabi, H., Torabi, M., Alamatian, E., Bahiraei, M. & Goodarzi, M. 2018 Effects of geometry and hydraulic characteristics of shallow reservoirs on sediment entrapment. *Water* **10** (12), 1725.

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