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Assessment of submerged floor water jets to minimize the scour downstream from a stepped spillway

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Abstract: Because of hydraulic jump, the scour downstream a stepped spillway is the most confusing issue that endangers the overall stability of the spillway. In this paper, thirty-six exploratory runs are described to explore the impact of utilizing submerged water jets fixed in the stilling basin of a stepped spillway on the downstream scour measurements under various flow conditions. A smooth apron where the water jets are disabled is incorporated to characterize the impact of adjustments studied. Trials are performed utilizing different upstream discharges, jets arrangements, and tailwater depths. The results are analyzed and graphically presented. The experimental data are contrasted to a scour formulae developed by other specialists. Outcomes indicated that by utilizing submerged floor water jets, the maximum scour depth is decreased between 14.3 and 36.0%. Additionally, the maximum scour length is reduced by 9.7 to 42.3%. Finally, involving regression analysis, simple formulas are developed to estimate different scour parameters.

Keywords: floor jets, flume, jet rows, stepped spillway, scour depth, scour length

INTRODUCTION

Water levels in waterways are controlled by hydraulic structures including spillways as one of most commonly utilized solutions [OLIVETTO, COMUNIELLO 2009]. Water flows over the spillway crest and falls down developing high velocities to create hydraulic jump that causes erosion of alluvial beds. To mitigate it, different energy dissipation methods have been applied. For example, baffle blocks have been utilized and studied by BRADLEY and PETERKA [1957], PETERKA [1978], VISCHER and HAGER [1995], EL-MASRY and SARHAN [2000], EL-GAMAL [2001], EL-MASRY [2001a, b], HELAL [2004] and ABDELHALEEM [2013]. The researchers suggested utilizing a single line of blocks in a vertical position opposing the upstream flow. They are installed in the range of 40 and 55% of floor width. ABDEL SAMAD *et al.* [2012] run a test model to describe the impact of a half circle ledge on the scour geometry downstream of a pipe culvert. ABDELHALEEM *et al.* [2012] and ALI *et al.* [2014] focused their experiments on the impact of corrugated beds on the downstream characteristics of local scour.

While focusing on stepped spillways, the researchers used their principle function of a guiding structure and also a water energy dissipater. The dissipation is caused by the scattering of water energy along the steps of the spillway. This improves the exhibition of the downstream stilling basin and limits its length which has a direct effect on the construction cost. QIAN *et al.* [2009], TABBARA *et al.* [2005], HEIDARI and GHASSEMI [2014], and ARJENAKI and SANAYEI [2020] analytically examined the impact of a stepped weir on scattering energy. The outcomes demonstrated that the introduction of steps increased the energy scattering by 15%. FELDER and CHANSON [2011] presumed that graded step heights did not have an important effect on the energy dissipation. SHAHHEYDARI *et al.* [2015] inferred that the energy scattering is diminished by the increase of the relative discharges, whereas CHATILA and JURDI [2004] showed that the number of steps is the dominant factor determining kinetic energy.

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While examining of the local scour downstream the stepped spillway, numerous examinations were performed. Habib *et al.* [2016], Hussein *et al.* [2009], Aminpour and Farhoudi [2017] and Aminpour *et al.* [2018] experimentally tested the capability of a stepped spillway to decrease the downstream scour and collated it with a single inclined spillway. They concluded that the use of a spillway significantly decreasing the scour depth. Emiroglu and Tuna [2011] experimentally investigated the impact of the tailwater depth on the scour downstream stepped chutes. They found that the lower tailwater depth produced deeper scour.

Various strategies are utilized to control the scour downstream spillways. Elnikhely [2018] considered the impact of cylinder blocks fixed on the back slope of the spillway on the geometry of scour downstream of a spillway. Amir *et al.* [2016] controlled the scour downstream of a stepped spillway by utilizing Nano materials. Olivetto and Comuniello [2009] and Eghlidi *et al.* [2020] demonstrated that positive inclination of a stilling basin reduced the downstream scour depth. Nozzles fixed in the stilling basin to create water jets produced a hydraulic jump which dispersed, and consequently reduced the local scour. El-Azab [2014] demonstrated that the floor water jets decreased the maximum scour depth from 50 to 90%, as well as reduced the scour length from 42 to 85%, as contrasted with the case of a floor with no water jets. amin [2015] showed the viability of double line water jets on improving the hydraulics and limiting the scour downstream of over-fall weirs. Elsaeed *et al.* [2020a, b] characterized the ideal arrangement for floor water jets to reduce the scour depth downstream of a Fayoum type weir. Helal *et al.* [2020] systematically demonstrated that bed water jets improved submerged hydraulic jumps by 85.4% and reduced submerged jump lengths by 59%, as compared to a floor without jets.

Most of the previous studies are based on the estimation of hydraulics and local scour downstream of ogee spillways; few examinations have been made to anticipate the bed morphology downstream of a stepped spillway. Likewise, the procedure of using floor water jets is not broadly applied to limit the downstream scour. This accentuates the need for additional investigations in this respect. Therefore, the current investigation focuses on the establishment of 5 lines of floor water jets fitted in a rigid stilling basin downstream of a stepped spillway to limit the local scour under various flow conditions.

MATERIALS AND METHODS

DIMENSIONAL ANALYSIS

A schematic diagram of a stepped spillway and five lines of floor water jets are presented in Figure 1. Variables affected the downstream bed morphology with and without the floor water jets are as follows: flume width (B); tailwater depth (y_t); basin length (L_b); step height of a spillway (S_h); step width of a spillway (S_w); number of spillway steps (N); distance from the spillway toe to the center of a water jet line (L_j); orifice diameter (O_d); distance between jets in the flow direction (D_{jx}); distance between jets across the flume width (D_{jy}); mean longitudinal velocity component in each section (V); upstream water depth (y_{up}); initial water depth at the hydraulic jump (y_1); sequent depth at the hydraulic jump (y_2); time to reach the maximum scour (t); median particle diameter (d_{50}); gravitational acceleration (g); soil particle density (ρ_s); maximum scour depth (d_s); water density of the flow (ρ); flume bed slope (S_o); dynamic viscosity of water (μ); discharge over a spillway (Q_{sw}); discharge from floor jets (Q_j); and the total discharge at the tail of the channel (Q_t) where $Q_t = Q_{sw} + Q_j$.

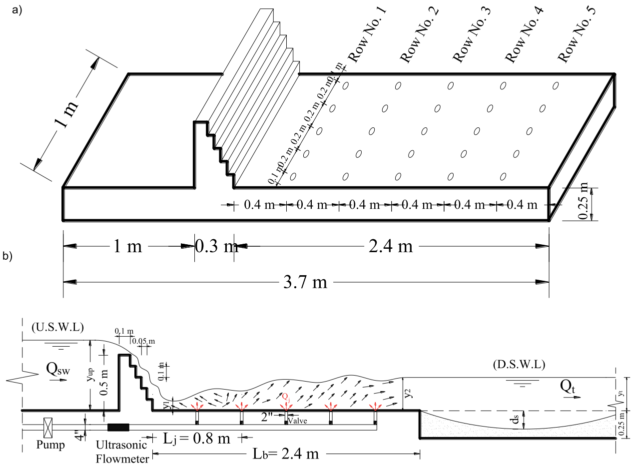

Fig. 1. Schematic diagram: a) stepped spillway model, b) flow pattern; U.S.W.L. = upstream water level, D.S.W.L. = downstream water level, L_b = basin length, L_j = distance from the spillway toe to the center of a water jet line, d_s = maximum scour depth, Q_{sw} = discharge over a spillway, Q_t = total discharge at the tail of the channel, y_{up} = upstream water depth, y_1 = initial water depth at the hydraulic jump, y_2 = sequent depth at the hydraulic jump; source: own elaboration based on El-Azab [2014], and Amin [2015]

For a given problem, the variables that affect the bed profile downstream of a stepped spillway with and without floor water jets can be expressed in the following functional form:

$$\phi\begin{pmatrix} B,\ y_t,\ S_h, S_w,\ N,\ L_b,\ L_j, O_d, D_{jx}, D_{jy}, V, y_{up}, y_1, y_2, \\ t, d_{50},\ d_s,\ L_s, g, \rho_s,\ \rho,\ \mu, S_o,\ Q_{sw}, Q_j,\ Q_t \end{pmatrix} \quad (1)$$

In this study, B, S_h, S_w, N, L_b, O_d, D_{jx}, D_{jy}, d_{50}, ρ_s, and S_o, are kept constant; so they are removed from Equation (1). The run time duration is fixed to be six hours when the quasi-equilibrium state is found.

Based on dimensional analysis using the Buckingham's theorem, the following dimensionless groups can be obtained to describe the phenomenon [Helal *et al.* 2020]:

$$f\left(\frac{Q_j}{Q_t}, \frac{L_j}{L_b},\ \mathrm{Fr} = \frac{V}{\sqrt{g y_t}}, \mathrm{Re} = \frac{\rho Q_{sw}}{B\mu}, \frac{y_1}{y_t}, \frac{y_2}{y_t}, \frac{y_{up}}{y_t}, \frac{d_s}{y_t}, \frac{L_s}{y_t}\right) = 0 \quad (2)$$

where: Fr = Froude number calculated at the section where y is measured; Re = Reynolds number at the weir; influence of the viscosity is of secondary significance in estimating the scour parameters and ρ is constant, hence Re can be neglected. Moreover, y_{up} can be presented in terms of Q_{sw}. Additionally, y_1 and y_2 is a function in Fr.

The Froude number may be expressed in terms of the kinetic flow factor; $\lambda^{-1} = \frac{1}{\mathrm{Fr}^2}$, hence Equation (2) is summarized to:

$$\frac{d_s}{y_t} = f\left(\frac{Q_j}{Q_t}, \frac{L_j}{L_b},\ \lambda^{-1}\right) \quad (3)$$

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$$\frac{L_s}{y_t} = f\left(\frac{Q_j}{Q_t}, \frac{L_j}{L_b}, \lambda^{-1}\right) \tag{4}$$

EXPERIMENTAL SETUP AND INSTRUMENTATION

Tests have been carried out in a hydraulics lab at the National Water Research Center of the Hydraulics Research Institute, Egypt. Experiments are carried out in a flume which is 26.0 m long, 1.0 m wide and 1.2 m deep. The flume side walls are made of glass on the two sides to permit visual examinations in addition to video recording and photographic capturing.

One pump of 300 $dm^3 \cdot s^{-1}$ maximum capacity is used to provide the flow into the flume by the suction of water from upstream sump of 3 m in height, width and length. The flume is equipped with a tilted tailgate for adjusting the tailwater depth. The stepped spillway model is made of timber 0.5 m height, 0.1 m crest width, and 0.3 m base width. The upstream face of the model is vertical; however, the downstream face comprised of 4 steps 0.1 m height and 0.05 m width each (Fig. 1). The stepped spillway model is fixed on a rigid stilling basin of 2.4 m downstream length, which begins from the model toe. The stilling basin is fitted with 25 nozzles in 5 lines over the flume width and 5 sections longitudinally in the flow direction. The spacing is shown in Figure 1. Every 5 nozzles over the stilling basin width are fed by nozzles pipeline of 2 inches (5 cm) in diameter laid in the stilling basin and stretched out over the flume width underneath the nozzles. A control valve is fitted at the inlet of every nozzle pipeline to control the discharge. The maximum nozzle pipeline discharge is 4 $dm^3 \cdot s^{-1}$ to permit 0.8 $dm^3 \cdot s^{-1}$ flow from each nozzle when the control valve is fully opened. A subsidence 14 m length, 4 inches (10.16 cm) diameter pipeline is installed parallel to the flume floor to convey the discharge to the nozzle pipelines by pumping water from the downstream sump. One and a quarter cubic meter of bed material of d_{50} = 0.423 mm are fitted in its area which has width of 1.0 m equivalent to the flume width, 5.0 m in length, and 0.25 m in depth.

During the exploratory setup, some challenges have been found predominantly concerning the system of floor water jets including nozzle diameter and the related flow discharge, in addition to the fed pipelines diameter. Numerous preliminary tests have been completed, including a computational software model (ANSYS), to determine the nozzle diameter before the installation in the exploratory model. The nozzle diameter is selected to produce an effective height for the water jet. The impact of floor jets as energy dissipaters is valueless on account of low jets heights. However, expanding the water jet height makes the jets to act as a vertical thin inflexible obstruction to penetrate the flow. Thus, the flow has to pass around, and accordingly the jets lose their importance. Henceforth, after considering the tested discharges over the spillway and the tailwater depths, the effective water jet height for all tests in the current study is the 9 mm nozzle fixed on 2 inches (5 cm) nozzles pipeline. It should be emphasized that the major considerable scale effect during the experiments is the head loss for the feeding system. The head loss in the nozzles pipeline might be ignored because of its short length of 1.2 m.

Measuring devices included 2 ultrasonic flowmeters of an accuracy ±1% are utilized for flow measurements of the primary pipe that provided water to the flume and the subsidence pipe that fed of the nozzles pipeline. A point gauge with accuracy to the closest millimeter is utilized for measurements of bed and water levels at various points. The measurements are double checked by a leveling device.

EXPERIMENTAL APPROACH

In this study, thirty-six exploratory tests have been implemented utilizing 3 discharges over the spillway, 3 scenarios for jet arrangements, and 3 tailwater depths (Tab. 1). The runs are divided into four sets for each arrangement of the experimental work. Additionally, 3 values of total discharges are utilized (Q_t = 120, 150, and 180 $dm^3 \cdot s^{-1}$). For all sets, every spillway discharge is tested with 3 depths for tailwater (y_t = 20, 25, and 30 cm). The set (A) is viewed as the base case, where the floor water jets are disabled. The results of set (A) are contrasted with different cases of comparable flow conditions to assess the effectiveness of floor water jets in limiting the downstream scour. As regards sets B, C, and D, the floor water jets are useful given that 3/5 lines are activated regardless their arrangement to provide steady jet discharge (Q_j = 12 $dm^3 \cdot s^{-1}$). The operation of floor water jets can be divided into three situations: initiated jet rows are the first three (i.e. No. 1, 2, and 3), or the middle three (i.e. No. 2, 3, and 4), or the last three jet lines (i.e. No. 3, 4, and 5; see Fig. 1).

To explain the configurations of bed material after each run, a planned mesh comprises of 105 measuring points distributed in 5 lines crossing 13 segments at consistent 0.25 m longitudinal and transverse spacing. The measurements have been performed downstream of the stilling basin to cover the total length of bed material.

EXPERIMENTAL PROCEDURE

After the flume is filled with bed material and precisely leveled at its place in the model, the tailgate is totally closed, and the downstream feeding gradually begins until its depth becomes higher than the downstream water depth. Simultaneously, the upstream feeding continues until it reaches the spillway crest. Henceforth, the control valves on desired nozzle pipelines rows gradually open according to the jet operation scenario. The tailgate is tilted gradually until required downstream water depth is balanced and afterward, the primary pump is activated until the tested spillway discharge is reached. Subsequently, the run time duration is begun; six hours are chosen as a constant time for all runs, where the quasi-equilibrium state is reached and no changes in the geometry of the scour hole are accounted for. The pumps are turned off and the run is stopped. The flume is drained slowly not to disturb the bed material. The bed profile is recorded at various locations of the designed mesh. All previous steps are repeated for each run.

RESULTS AND DISCUSSIONS

GENERAL INFORMATION

Outcomes of the experiment are analyzed and graphically presented to explore the geometry of the scour hole in terms of its depth and length. Results are compared with the case when no jet activated to illustrate the effectiveness of jets installation in addition to their arrangement. Also, the analysis is focused on the

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Table 1. Flow conditions for the tested model

Set No.	Test No.	Q_t	Q_j	y_t (cm)	Activated jet row			
		dm^3·s^{-1}			number	L_j (m)	L_j/L_b	$\Sigma Q_j/Q_t$
A	1	120	0	20	no jets			
	2			25				
	3			30				
	4	150		20				
	5			25				
	6			30				
	7	180		20				
	8			25				
	9			30				
B	10	120	12	20	1, 2, 3	0.4, 0.8, 1.2	0.166	0.100
	11				2, 3, 4	0.8, 1.2, 1.6	0.333	
	12				3, 4, 5	1.2, 1.6, 2.0	0.500	
	13			25	1, 2, 3	0.4, 0.8, 1.2	0.166	
	14				2, 3, 4	0.8, 1.2, 1.6	0.333	
	15				3, 4, 5	1.2, 1.6, 2.0	0.500	
	16			30	1, 2, 3	0.4, 0.8, 1.2	0.166	
	17				2, 3, 4	0.8, 1.2, 1.6	0.333	
	18				3, 4, 5	1.2, 1.6, 2.0	0.500	
C	19	150		20	1, 2, 3	0.4, 0.8, 1.2	0.166	0.080
	20				2, 3, 4	0.8, 1.2, 1.6	0.333	
	21				3, 4, 5	1.2, 1.6, 2.0	0.500	
	22			25	1, 2, 3	0.4, 0.8, 1.2	0.166	
	23				2, 3, 4	0.8, 1.2, 1.6	0.333	
	24				3, 4, 5	1.2, 1.6, 2.0	0.500	
	25			30	1, 2, 3	0.4, 0.8, 1.2	0.166	
	26				2, 3, 4	0.8, 1.2, 1.6	0.333	
	27				3, 4, 5	1.2, 1.6, 2.0	0.500	
D	28	180		20	1, 2, 3	0.4, 0.8, 1.2	0.166	0.067
	29				2, 3, 4	0.8, 1.2, 1.6	0.333	
	30				3, 4, 5	1.2, 1.6, 2.0	0.500	
	31			25	1, 2, 3	0.4, 0.8, 1.2	0.166	
	32				2, 3, 4	0.8, 1.2, 1.6	0.333	
	33				3, 4, 5	1.2, 1.6, 2.0	0.500	
	34			30	1, 2, 3	0.4, 0.8, 1.2	0.166	
	35				2, 3, 4	0.8, 1.2, 1.6	0.333	
	36				3, 4, 5	1.2, 1.6, 2.0	0.500	

Explanations: Q_j = the discharge from floor jets, y_t = tailwater depth, other as in Fig. 1.
Source: own elaboration.

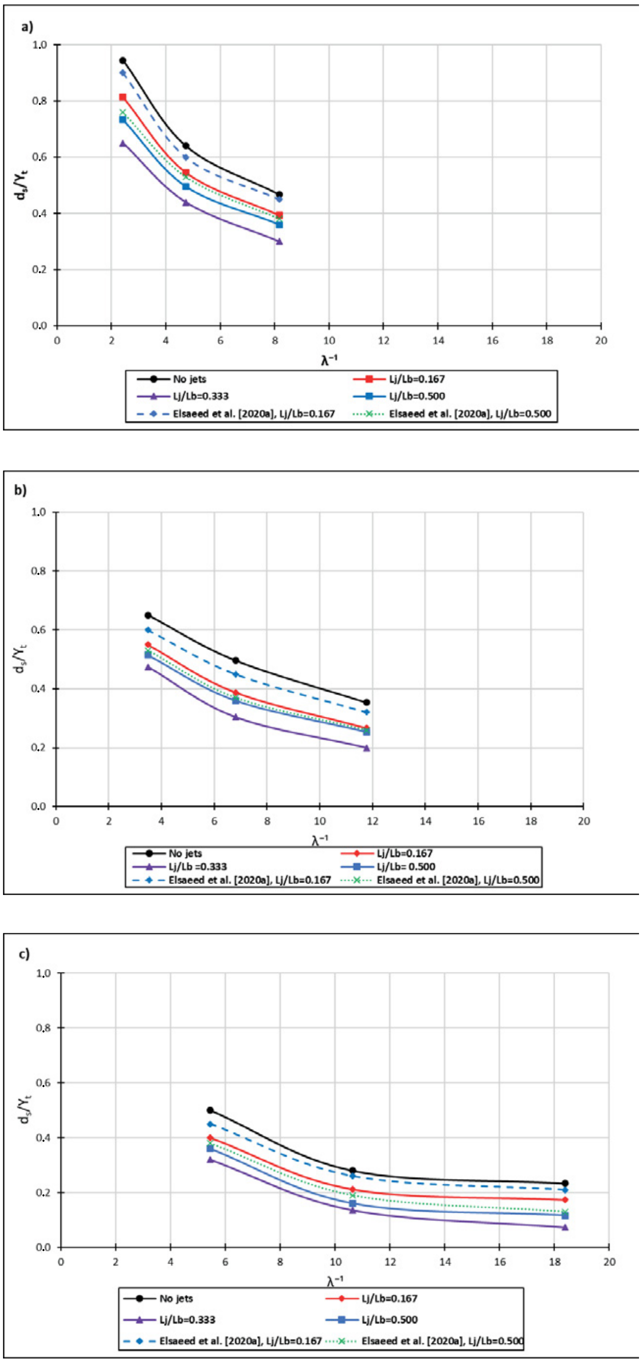

Fig. 2. Relation between relative scour depth d_s/y_t and kinetic flow factor λ^{-1} for: a) $\Sigma Q_j/Q_t$ = 0.067, b) $\Sigma Q_j/Q_t$ = 0.080, c) $\Sigma Q_j/Q_t$ = 0.100; Q_j = discharge from floor jets, Q_t = total discharge at the tail of the channel, L_j = distance from the spillway toe to the center of water jet line, L_b = basin length; source: own study

comparison between the geometry of the scour hole downstream of the stepped spillway in the current research contrasted with the Fayoum type weir presented by Elsaeed *et al.* [2020b] for similar flow conditions. Finally, empirical equations are developed using data available to predict the scour geometry.

THE SCOUR DEPTH

Figure 2 is plotted to characterize the relation between the kinetic flow factor λ^{-1} and relative scour depth d_s/y_t under different flow conditions and jets operation scenarios. Regardless the presence of jets, the figure indicates that the scour depth decreases by the increase in the kinetic flow factor. For the cases where the jets are switched on, it is remarked that by the increase of $\Sigma Q_j/Q_t$ the limits of λ^{-1} are increased to cover more extensive range and the plots are shifted towards higher values for λ^{-1}. Additionally, for constant λ^{-1}, d_s/y_t decreases by the increase of $\Sigma Q_j/Q_t$. This is explained by increasing the total discharge within a constant cross section area which leads to corresponding increment in velocity. The latter is associated with the Froude number. Hence, the scour depth is increased as it is considered a functional parameter in the flow velocity. The figure additionally demonstrates the effective-

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ness of jet installation regardless their arrangement to minimize the scour depth. As the case jets are deactivated showed the maximum scour depth for any kinetic flow factor.

Table 2 summarizes the reduction of the maximum scour depth in experiments with activated jets under different scenarios compared to the case of jets switched off. Moreover, results from the table are used to characterize the optimum arrangement of jets concerning the scour depth under different flow conditions. The table shows that the efficiency of jets to decrease the scour depth increases with the increase in $\Sigma Q_j/Q_t$. While emphasizing findings in Figure 2 and Table 2, it is exhibited that for any value of $\Sigma Q_j/Q_t$, the maximum decrease in the scour depth is accounted for by activating the middle three rows of jets (i.e. L_j/L_b = 0.333). This is explained by the location of the hydraulic jump. According to unpublished measurements and visual observations of hydraulic jump parameters during the experimental runs, it has been noticed that the majority of tests have the hydraulic jump located between L_j = 0.8 m and L_j =1.6 m. Therefore, by activating the middle three rows the upward jets flow strikes the hydraulic jump to scatter most of its energy. Henceforth, the flow velocity is decreased prompting significant reduction in the scour depth.

Table 2. Maximum scour depth reduction compared to the case of deactivated jets

L_j/L_b	Reduction (%) at $\Sigma Q_j/Q_t$		
	0.067	**0.080**	**0.100**
0.167	14.29	15.38	24.00
0.333	26.15	32.21	36.00
0.500	20.00	22.75	28.00

Explanations: L_j, L_b, Q_j, Q_t as in Fig. 2.
Source: own study.

To confirm the previous comments, Figure 3 is plotted to illustrate the relation between λ^{-1} and d_s/y_t for constant L_j/L_b = 0.333 and varying $\Sigma Q_j/Q_t$. L_j/L_b = 0.333 is used according to the outcomes of Figure 2 and Table 2 as the optimum jets arrangement. The figure indicates that the presence of floor water jets show high performance in decreasing the scour depth for $\Sigma Q_j/Q_t$ = 0.1 contrasted with other cases considered. That confirms results included in Figure 2.

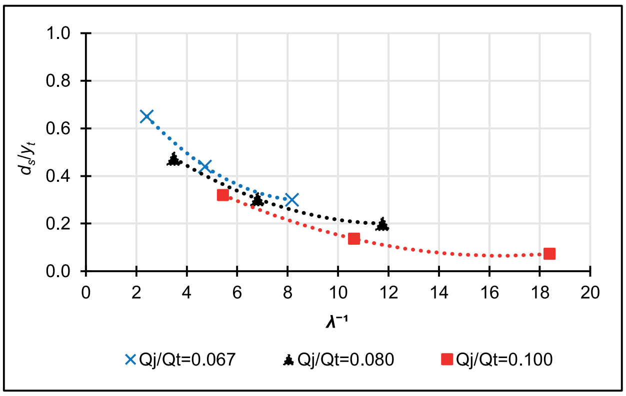

Fig. 3. Relation between relative scour depth d_s/y_t and kinetic flow factor λ^{-1} for L_j/L_b = 0.333; L_j, L_b, Q_j, Q_t as in Fig. 2; source: own study

To check the ability of a stepped spillway to limit the scour depth compared to the Fayoum type weir under the same flow condition, results of the current investigation are compared with Elsaeed *et al.* [2020b] and the outcomes are shown in Table 3. It should be emphasized that Elsaeed *et al.* [2020b] completed their exploratory work only for L_j/L_b = 0.167 and 0.5. Combining the results in Figure 2 and Table 3, it is concluded that the stepped spillway decreases the scour depth from 4.76 to 24.00% compared with findings of Elsaeed *et al.* [2020b]. Therefore, the flow losses a considerable in terms of its energy through the crash with spillway steps. The conclusions are in line with Hussein *et al.* [2009], Habib *et al.* [2016], and Aminpour and Farhoudi [2017].

Table 3. Maximum scour depth reduction for Fayoum type weir

L_j/L_b	Reduction (%) at $\Sigma Q_j/Q_t$		
	0.067	**0.080**	**0.100**
0.167	4.76	7.69	10.00
0.500	18.46	19.58	24.00

Explanations: L_j, L_b, Q_j, Q_t as in Fig. 2.
Source: own study and Elsaeed *et al.* [2020b].

THE SCOUR LENGTH

To explore the influence of bottom floor jets on the scour length, Figures 4 and 5 are introduced. The figures show the relation between the kinetic flow factor λ^{-1} and relative scour length L_s/y_t for various flow conditions and jet operation scenarios. The figures illustrate that the jets presence, notwithstanding their arrangements, decrease the relative scour length compared with the case of disabled jets. Comparative patterns can be seen for the relative scour depth d_s/y_t. The increase of the kinetic flow factor λ^{-1} prompts the decrease in the relative scour length L_s/y_t. These remarks are made for similar hydraulic reasons as discussed in the subsection "The scour depth".

Combining the outcomes of Figure 4 and Table 4, it can be seen that the minimum reduction in the scour length compared with the case of deactivated jets is 9.68% for $\Sigma Q_j/Q_t$ = 0.067 at L_j/L_b = 0.167. While the maximum reduction is 42.31% which is noticed for $\Sigma Q_j/Q_t$ = 0.1 at L_j/L_b = 0.333. Considering the conclusions of the subsection "The scour depth", the ideal performance of jets to diminish the scour geometry can be achieved by activating the middle three rows of jets (L_j/L_b = 0.333).

Results shown in Figure 4 and Table 5 confirm the ability of a stepped spillway to decrease the scour length compared to the Fayoum type weir under comparable flow conditions. The maximum reduction in the scour length contrasts with the case when jets are switched on at L_j/L_b = 0.500 are 23.07% and 30.77% for the Fayoum type weir and stepped spillway, individually. The superior performance of the stepped spillway in decreasing the scour geometry is due to the existence of steps and their significant importance in dissipating the flow energy.

Figure 5 is plotted to describe the effect of $\Sigma Q_j/Q_t$ for the optimum scenario of jets arrangement (L_j/L_b = 0.333). The figure demonstrates that for $\Sigma Q_j/Q_t$ = 0.067, the maximum and

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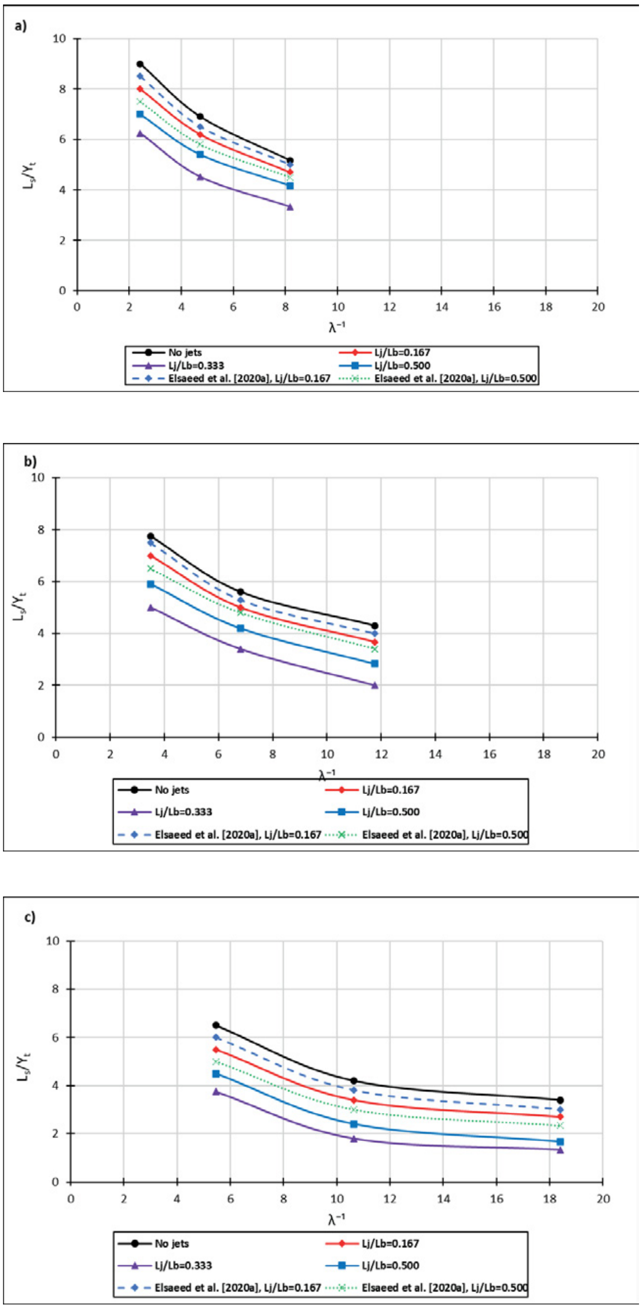

Fig. 4. Relation between relative scour length L_s/y_t and kinetic flow factor λ^{-1} for: a) $\Sigma Q_j/Q_t$ = 0.067, b) $\Sigma Q_j/Q_t$ =0.080, c) $\Sigma Q_j/Q_t$ = 0.100; L_j, L_b, Q_j, Q_t as in Fig. 2; source: own study

Table 4. Maximum scour length reduction compared with the case of deactivated jets

L_j/L_b	Reduction (%) at $\Sigma Q_j/Q_t$		
	0.067	0.080	0.100
0.167	9.68	11.11	15.38
0.333	30.56	35.48	42.31
0.500	22.22	23.87	30.77

Explanations: L_j, L_b, Q_j, Q_t as in Fig. 2.
Source: own study.

Table 5. Maximum scour length reduction for the Fayoum type weir

L_j/L_b	Reduction (%) at $\Sigma Q_j/Q_t$		
	0.067	0.080	0.100
0.167	3.23	5.56	7.69
0.500	16.13	16.67	23.07

Explanations: L_j, L_b, Q_j, Q_t as in Fig. 2.
Source: own study and Elsaeed *et al.* [2020b].

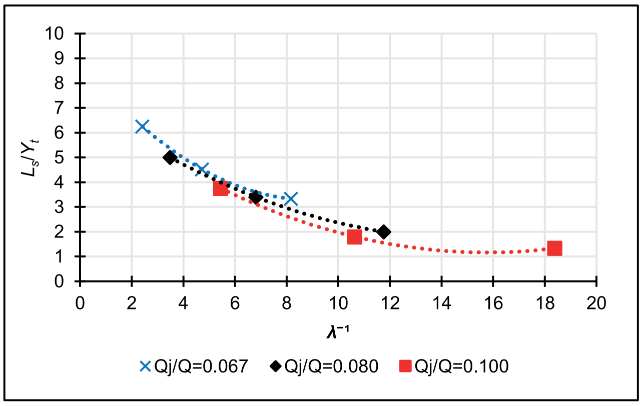

Fig. 5. Relation between relative scour length L_s/y_t and kinetic flow factor λ^{-1} for L_j/L_b = 0.333; L_j, L_b, Q_j, Q_t as in Fig. 2; source: own study

minimum L_s/y_t are 6.25 and 3.33, respectively. However, these values decrease by 40.0 and 60.1% in the case of $\Sigma Q_j/Q_t$ = 0.10, to be 3.75 and 1.33 as maximum and minimum L_s/y_t, respectively. Therefore, the efficiency of jets to decrease the scour length increases by the decrease in the total discharge where the jets discharge is constant in all experiments.

The experimental results are used for the different dimensionless variables to develop empirical formulae to calculate the scour depth and length. With the assistance of the nonlinear regression analysis, the accompanying observational formulas are inferred:

$$\frac{d_s}{y_t} = \exp\left[-0.115\left(\frac{L_j}{L_b}\right) - 11.526\left(\frac{\sum Q_j}{Q_t}\right) - 0.309\ \lambda^{-1} + 0.813\right], R^2 = 0937 \quad (5)$$

$$\frac{L_s}{y_t} = \exp\left[-0.383\left(\frac{L_j}{L_b}\right) - 8.849\left(\frac{\sum Q_j}{Q_t}\right) - 5.883\ \lambda^{-1} + 2.659\right], R^2 = 0.891 \quad (6)$$

The inferred formulas are valid for the following conditions: $0.166 \leq \frac{L_j}{L_b} \leq 0.500$; $0.067 \leq \frac{\sum Q_j}{Q_t} \leq 0.5$; $2.42 \leq \lambda^{-1} \leq 18.39$. The overall pattern of inferred formulas is in line with the results of El-Azab [2014] and Elsaeed *et al.* [2020b]. Equations (5) and (6) confirm that the scour geometry downstream of a stepped spillway with submerged floor water jets decreases by the increase of all referenced parameters. Moreover, the relative discharge $\Sigma Q_j/Q_t$ is the dominant variable that affects the scour geometry. However, the arrangement of activated jets L_j/L_b shows the least influence.

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CONCLUSIONS

The experimental study to evaluate the performance of submerged floor water jets to minimize the scour downstream of a stepped spillway has led to the following conclusions:
1. use of floor water jets shows good performance in minimizing the scour geometry;
2. stepped spillway decreases the scour geometry compared to the Fayoum type weir under comparable flow conditions and jet operation scenarios;
3. scour geometry decreases by the increase in the kinetic flow factor;
4. efficiency of jets to decrease the scour geometry increases as $\Sigma Q_j/Q_t$ increases;
5. using submerged floor water jets, the maximum scour depth decreases between 14.3 and 36.0%. Additionally, the maximum scour length is diminished between 9.7 and 42.3%;
6. to minimize the scour geometry, it is recommended to activate only the three middle rows of jets (i.e. L_j/L_b= 0.333);
7. the scour geometrical parameters are highly sensitive to the total discharge; however, the kinetic flow factor is found to have secondary importance.

NOTATIONS

B	=	flume width (m)
d_s	=	maximum scour depth (m)
d_{50}	=	mean particle diameter (m)
D_{jx}	=	distance between jets in the flow direction (m)
D_y	=	distance between jets across the flume width (m)
g	=	gravitational acceleration (m·s^{-2})
L_b	=	basin length (m)
L_j	=	distance from the spillway toe to the center of water jet line (m)
L_s	=	maximum scour length (m)
N	=	number of spillway steps (–)
O_d	=	orifice diameter (m)
Q_{sw}	=	discharge over spillway (dm^3·s^{-1})
Q_j	=	discharge from floor jets (dm^3·s^{-1})
Q_t	=	total discharge at the tail of the channel (dm^3·s^{-1})
S_h	=	spillway step height (m)
S_w	=	spillway step width (m)
t	=	time duration to reach the maximum scour (h)
V	=	mean flow velocity (m·s^{-1})
y_1	=	initial water depth at the hydraulic jump (cm)
y_2	=	sequent depth at the hydraulic jump (cm)
y_t	=	tailwater depth (cm)
y_{up}	=	upstream water depth (cm)
ρ	=	water density of the flow (kg·m^{-3})
ρ_s	=	soil particle density (kg·m^{-3})
μ	=	dynamic viscosity of water (kg·m^{-1}·s^{-1})
S_o	=	flume bed slope (–)
Fr	=	Froude number (–)
Re	=	Reynolds number (–)
λ^{-1}	=	kinetic flow factor (–)

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