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Characteristics and time scale of local scour downstream stepped spillways

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KEYWORDS
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Stilling basin;
Hydraulic jump.

Abstract. Stepped spillways are employed to reduce excess energy encountered with exiting flow from high hydraulic structures. Study of local scour evolution downstream of stepped spillways wilt, therefore, provide the required information to reap the benefits made from these structures to minimize the scour hole dimensions. This paper provides the results of 67 experiments downstream of some stepped spillways subjected to different Froude numbers, basin lengths, tail-water depths, sediment sizes, and two different sloped spillways. The experiments were continued for 6, 8, 12, and 24 hours from which 824 profiles and 85000 data points were recorded and analyzed. The results show that, in certain circumstances, the dimensions of scour hole increase in accordance with particle Froude number. It was also observed that an increase in the slope of spillway would result in reduction in the geometries of scour hole. Under certain conditions, as the tail-water increases, the depth of scour hole increases and elongates the hole. The relations of duration of scour evolution downstream of stepped spillway are presented in this paper. Finally, it was observed that the stepped spillway would considerably decrease the dimensions of scour hole compared with ogee spillways, reflecting the excess energy downstream loss of stepped spillway.

1. Introduction

Local scour develops downstream of hydraulic structures due to insufficient energy loss and formation of eddy currents encountered with the flow coming out of such structures [1-5]. Stepped spillways, which have recently attracted design engineer's attention, are one of the most effective structures in reducing the excess energy of flow, which would result in the reduction of local scour dimensions compared with ordinary spillways. Most of past studies on local scour were concentrated on downstream of chutes, Ogee spillways, and culverts. Few studies have focused on this downstream phenomenon of stepped spillways. Due to interesting features of stepped spillways in reduction of inflow energy and, consequently, in local scour dimensions, it would be important to study the evolution of local scour downstream of such structures.

Stepped spillways would dissipate the excess energy of water flowing over the spillway by means of steps. As a result, hydraulic jump downstream of these spillways would consist of less energy than that formed downstream of other spillways. Therefore, it is anticipated that the outgoing flow from these structures would be less capable of eroding the sediments from their immediate downstream.

In 1967, Breusers [6] experimentally studied the

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Table 1. Definition of experimental parameters.

Parameters	Range of parameters	
	Model I	**Model II**
Flow discharge, Q (lit/s)	7.4-29.9	31.5-89
Sediment size, D_{50} (mm)	0.58, 1.11, 1.78	1.11, 1.78
Height of steps of spillway, h_s (cm)	3	4
Width of steps of spillway, l_s (cm)	5	10
Length of stilling basin, L_B (cm)	10, 37, 55, 74, 110	120
Height of stepped spillway, H_d (cm)	45	60
Width of the flume, B (cm)	41	90
Depth of tail-water, y_{tw} (cm)	8-18.4	11.6-21.7
Number of experiments	55	12

time evolution of local scour downstream of hydraulic structures and proposed a power equation to estimate the time scale for the phenomenon as follows:

$$\frac{y_{\max}}{d_0} = \left(\frac{t}{t_0}\right)^{\alpha}, \tag{1}$$

where $y_{\max}$ is maximum depth of scour hole at time t, d_0 is the depth of scour hole at a certain time of t_0, and α is a parameter dependent on the type of structure and flow conditions. In 1985, Farhoudi and Smith [7] widely studied local scour evolution downstream of an ogee spillway and reported an equation similar to that of Breusers [6] for time scale of scour hole where α was estimated equal to 0.19. Ali and Lim [8] reported the effect of tail-water depth on dimensions of scour hole and suggested a limit for tail-water depth affecting the maximum scour depth. Lim [9] studied the effect of canal width on the evolution of local scour downstream of sluice gate, and found that if the ratio of canal width to the opening of gate is larger than 10, the variation of canal width would have no influence on the dimensions of scour hole. Balachandar et al. [10] considered the influence of particle sizes on the dynamics of local scour profiles downstream of sluice gate. Tuna and Emiroglu [11,12] investigated scour profiles downstream of stepped spillways for three types of different flow regimes. Results showed that the type of flow regime formed on stepped spillway has very important effect on maximum scour depth, such that, in a nappe flow regime, the maximum scour depth was less than that of skimming flow regime. Emiroglu and Tuna [13] investigated the effects of tail water depth on local scour downstream of stepped spillways. They concluded that scour hole dimensions will increase with an increase in tail water depth.

This paper highlights the result of an experimental study on local scour downstream of a stepped spillway in which the influences of various parameters, such as flow conditions, spillway geometries, time length, and energy downstream loss of the structure, were considered.

2. Experimental layouts and procedures

The experiments were conducted using two separate flumes where three different sizes of sand were subjected to different flow conditions downstream of stepped spillways with different layouts, whose dimensions are described in Table 1. The characteristics of experimental layouts are presented in Figure 1(a). The schematic sketch of the experimental layout is shown in Figure 1(b), where a stepped spillway was operated with a stilling pool of varying lengths. The size distribution of the used sediments is shown in Figure 2. The incoming flow was measured by means of either a magnetic flow meter or a pre-calibrated sharp crested rectangular weir. The water level was recorded by means of a point gage with accuracy of ±0.1 mm. The dimensions of scour hole were recorded using a precise leveled digital camera. The recorded pictures, like Figure 3, were then retrieved to take advantage of Grapher7 from which the profiles of scour hole were recorded.

3. Analysis of experimental data

3.1. Parameters influencing local scour downstream of stepped spillway

To analyze the experimental data, it is of utmost importance to identify and define the effective parameters of the phenomenon, which can be summarized as follows:

$$\begin{aligned} F(\text{Scour}) &= f(y_m, x_m, x_s) \to f(y_m, x_m, x_s) \\ &= f(\rho, \mu, D_{50}, \rho_s, \sigma_g, C_u, \phi, FS, h_s, l_s, \\ &\quad L_B, H_d, q, y_{tw}, g, t), \end{aligned} \tag{2}$$

where y_m and x_s are maximum depth and length of

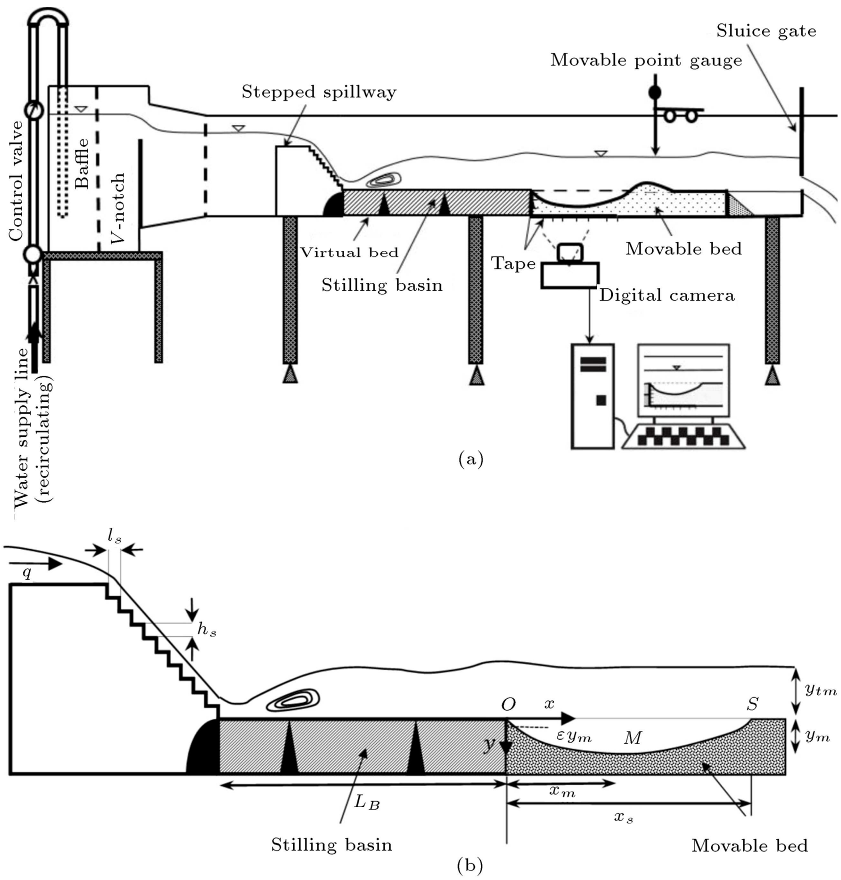

Figure 1. Experimental layout and effective parameters.

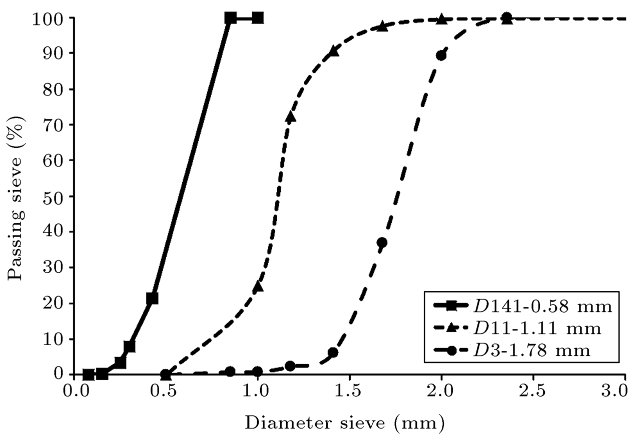

Figure 2. Size distribution of used sediments.

scour hole, respectively, x_m is the longitudinal position of maximum depth from stilling basin, ρ and μ are mass density and dynamic viscosity of water, respectively, D_{50} is the size of sediment in which 50 percent of sediments are finer than ρ_s which is mass density of sediments, σ_g is geometric standard deviation of sediments, C_u is uniformity coefficient of sediments, ϕ is angle of repose, FS is shape factor of sediments, h_s and l_s are the height and length of steps, respectively, L_B is the length of stilling basin, H_d is the height of spillway, q is the discharge intensity, y_{tw} is tail-water depth, g is acceleration due to gravity, and t is the time.

Since the selected sediments were assumed to be granular and also had a uniform distribution, C_u, σ_g and FS could be relaxed. On the other hand, the angle of repose could be assumed constant as 35 degrees. Furthermore, the number of steps on the spillway was fixed to 15; therefore, the effect of h_s could be compensated by using H_d. Consequently, Eq. (2) could be summarized as follows:

$$F(\rho, \mu, \rho_s, D_{50}, h_s, l_s, L_B, q, y_{tw}, g, t, y_m, x_m, x_s) = 0. \tag{3}$$

Taking benefits of Buckingham theorem, Eq. (3) could be written in a non-dimensional form as follows:

$$f\left(\frac{h_s}{l_s}, \frac{L_B}{D_{50}}, \frac{y_{tw}}{D_{50}}, \frac{t}{t_0}, \mathrm{R_e}, \mathrm{Fr}_D, \frac{y_m}{D_{50}}, \frac{x_m}{D_{50}}, \frac{x_s}{D_{50}}\right) = 0. \tag{4}$$

Since during the experiments Re $>$ 4000, the effect of Reynolds number could be overlooked. It should be clarified that $t_0 = \frac{h_s^2}{\sqrt{g(S_s-1)D_{50}^3}}$ and $\mathrm{Fr}_D = \frac{q}{\sqrt{g(S_s-1)D_{50}^3}}$ (particle Froude number) were defined where $S_s = \frac{\rho_s}{\rho}$. Taking a note of these clarifications, Eq. (4), thereafter, will be the base of data analysis.

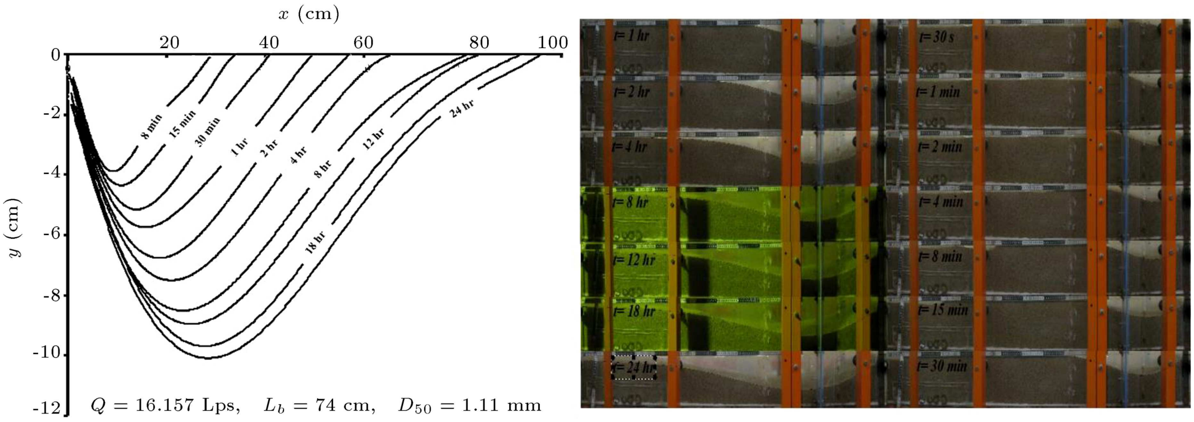

Figure 3. Sample pictures and retrieved scour hole profiles.

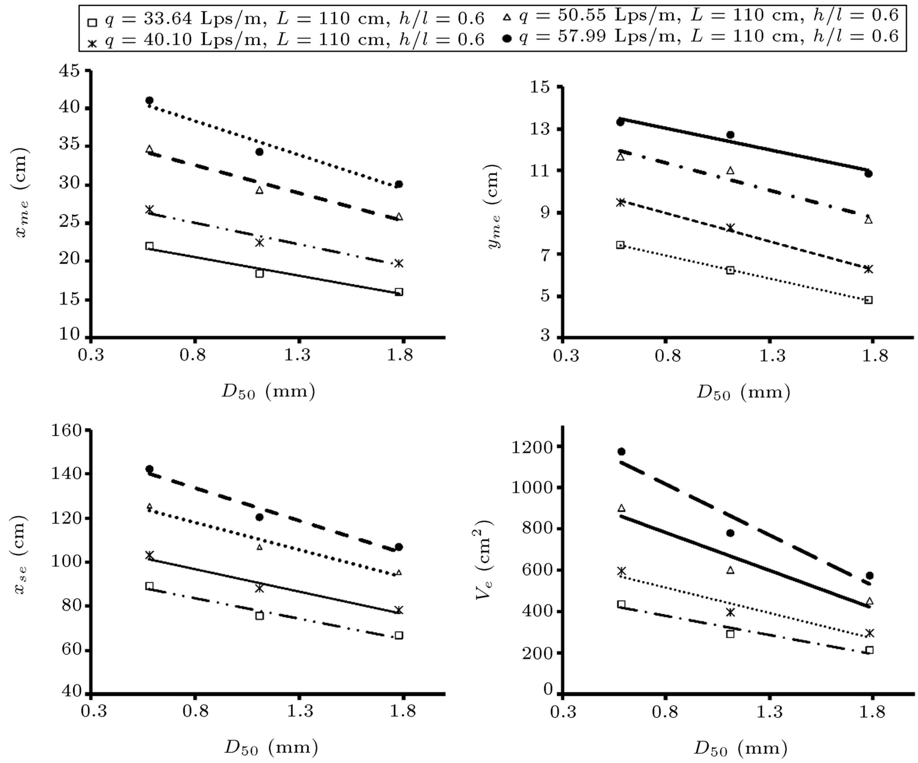

Figure 4. The effect of sediment size on the dimensions of scour hole.

3.2. The influence of various parameters on dimensions of scour hole

3.2.1. Effects of sediment size

Figure 4 shows the effect of sediment sizes on the geometries of scour hole. It is clear from the figure that the dimensions of scour hole show an adverse trend with sediment sizes. This is because of direct proportionality of shear stress with sediment size. Therefore, it is expected that the scour hole achieve smaller dimensions with larger sediments.

3.2.2. Effects of the length of stilling basin

Figure 5 depicts the effects of the length of stilling basin on the geometries of scour hole. It was observed that an increase in the length of the stilling basin would inversely affect the dimensions of scour hole. This could be related to the higher energy losses inside the longer stilling basins. It means that as the stilling basin becomes longer, the amount of energy transported to downstream of structure decreases, which leaves less potential to erode the bed materials.

3.2.3. The influence of sediment Froude number on dimensions of scour hole

Figure 6 shows the impacts of Froude number on the geometries of scour hole downstream of stepped spillways. It was observed that Fr_D directly af-

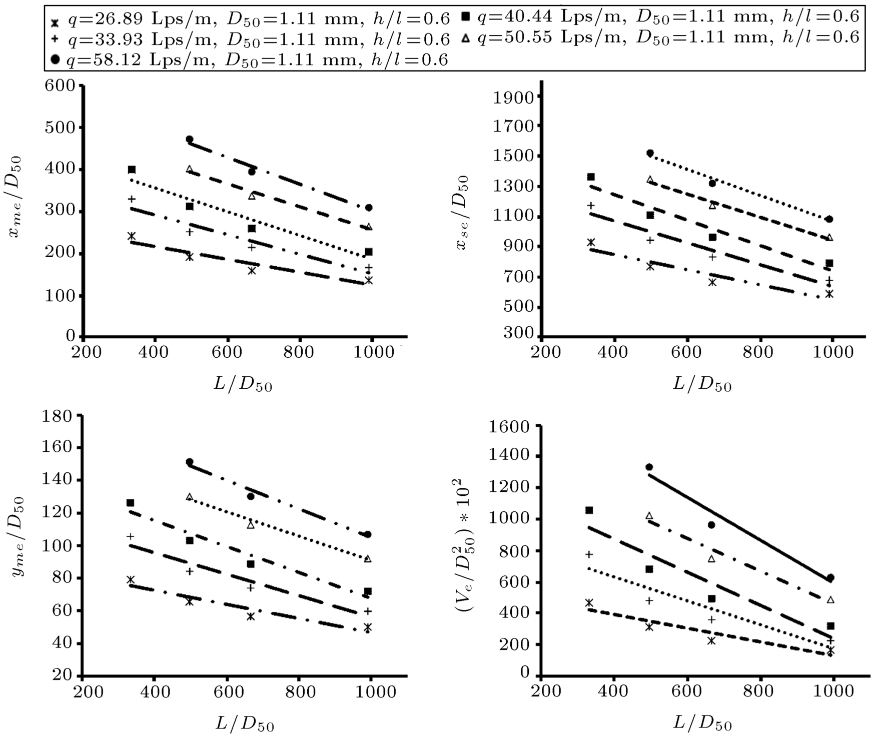

Figure 5. Impacts created by the length of stilling basins on the dimensions of scour hole.

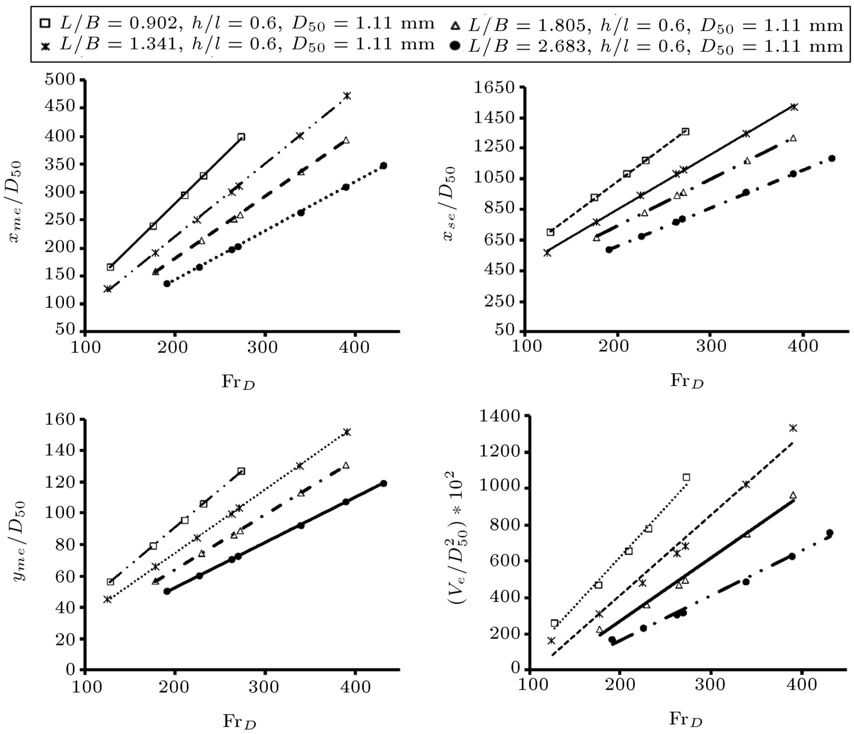

Figure 6. Influence of Froude number on dimensions of scour hole.

fects the dimensions of scour hole. This is because of inherent influence of flow discharge embedded in Fr_D, which affects the energy loss in stilling basin as well as the shear stress acting on the bed.

3.2.4. *The influence of spillway slope on dimensions of scour hole*

The influences of spillway slope on dimensions of scour hole are depicted in Figure 7, showing that as the slope increases (higher spillway), the geometries of scour

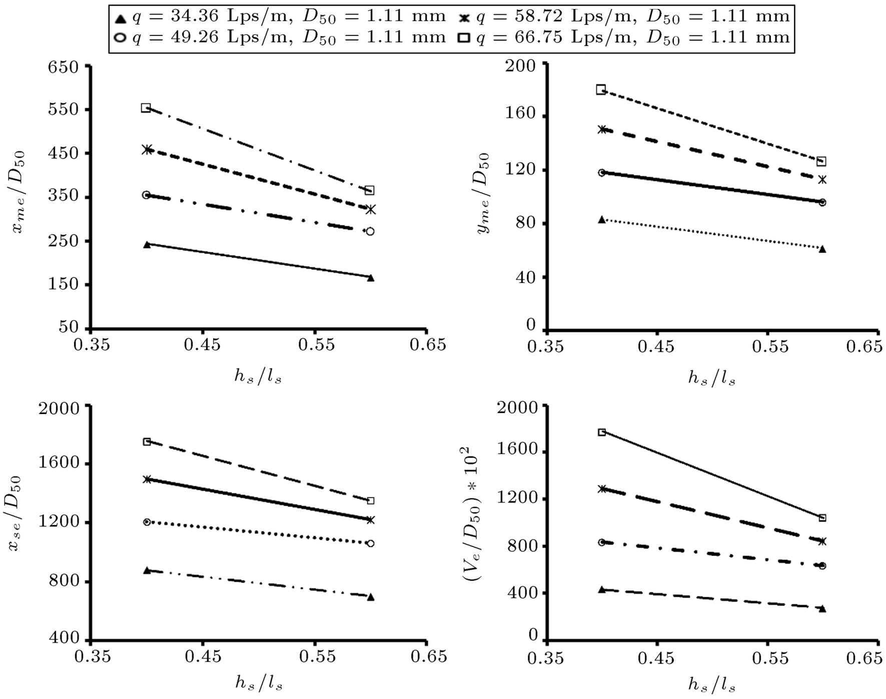

Figure 7. Influence of steps slope on dimensions of scour hole.

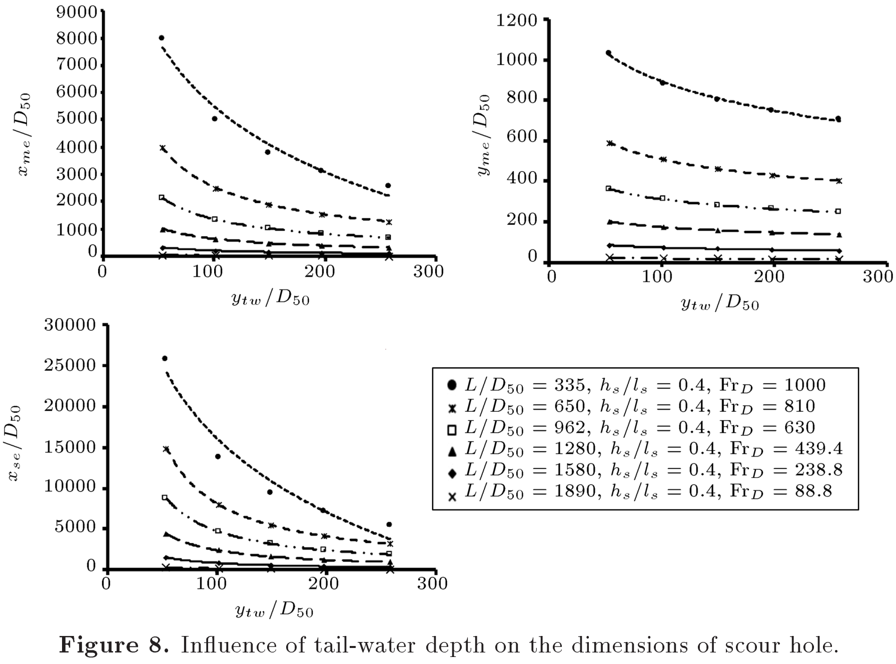

Figure 8. Influence of tail-water depth on the dimensions of scour hole.

hole at its maximum stage decrease. This could be attributed to larger energy losses with higher spillways as reported by Chanson [14]. Figure 7 shows the effect of steps slope on scour geometry and, consequently, the effect of spillway slope.

3.2.5. *Influence of tail-water depth on the dimensions of scour hole*

The experimental observations recorded from the effects of tail-water depth variation scour hole characteristics are demonstrated in Figure 8, showing an indirect role in the development of scour hole dimensions. This would be related to the decrease in flow velocity with deeper tail-water, resulting in lower energy available for eroding the flow bed.

3.3. *Time Scale of scour hole downstream of stepped spillway*

As previously mentioned, Breusers [6] expressed the time scale of scour evolution by an exponential equa-

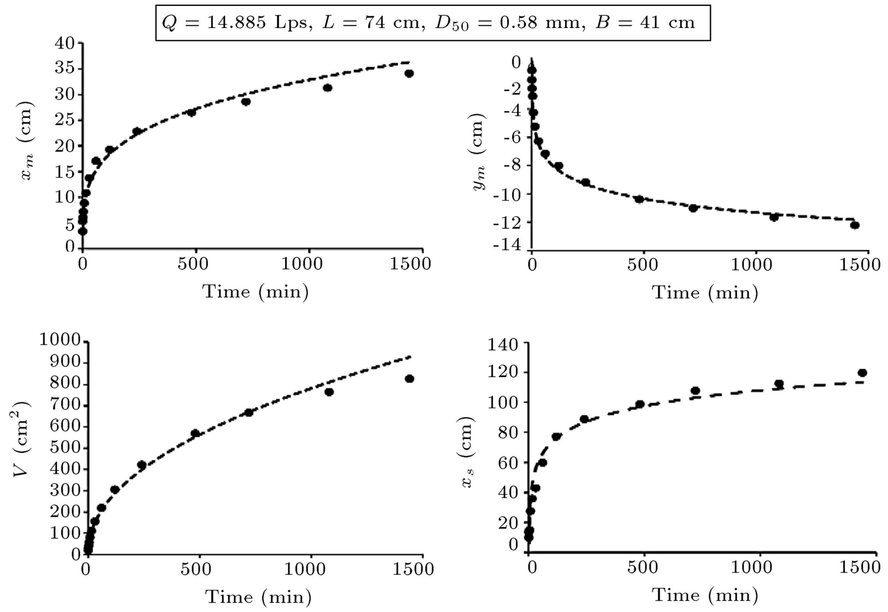

Figure 9. Changes of scour hole and the volume of sediment transported by time.

tion, later addressed by many researchers. His proposed equation was employed for scour development downstream of stepped spillways with stilling basin and revised according to experimental results. Figure 9 depicts the ultimate maximum scour depth (y_m), distance from maximum scour depth to the end of stilling basin (x_m), length of scour hole (x_s), and transported sediment volume from the hole (V) with time. According to the figures, the upstream section of scour hole will reach its equilibrium stage sooner than the downstream section of hole. Due to the experimental restrictions, the time interval for equilibrium was selected as 24 hours. However, some longer periods would be required for the satisfaction of relative equilibrium state. In equilibrium stage, the position of maximum depth of scour hole almost stands stable. However, due to inverse eddies action, the sediment moves towards the upstream face of the hole, changing the configuration of scour hole. Accordingly, the dynamic equilibrium of bed cannot be reached even in longer time intervals. Balachandar et al. [10] referred to this fact according to their experiments at 96 hours. Therefore, it would be wise to use the term "semi-equilibrium stage" instead of "equilibrium stage".

In order to investigate the possibility of similarity between maximum scour geometry and time, Breusers [6] proposed the following equation:

$$\frac{y_{\max}}{d_0} = k\left(\frac{t}{T}\right)^{\alpha}, \tag{5}$$

where $y_{\max}$ is the maximum depth of scour hole after time t, T is the time when water depth reaches d_0, which is a length parameter related to the structure dimension referred to as characteristic depth, k and α were calculated according to experimental results. Figure 10(a) shows the variation of $\frac{y_{\max}}{d_0}$ with time ratio $\frac{t}{T}$ which would facilitate to determine k and α values for experimental data. In this research, characteristic depth, d_0, is considered twice the steps height ($d_0 =$

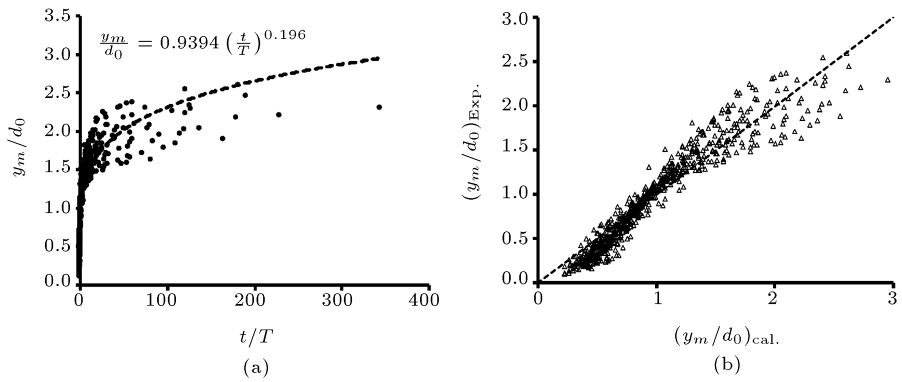

Figure 10. (a) Determining factor k and α based on laboratory data. (b) Evaluating the accuracy of Eq. (5).

Table 2. A comparison between k and α values for different hydraulic structures reported by previous researchers.

Structural type	Researcher	k	α
River entries without hydraulic jump formation	Breuser (1967) [6]	1.00	0.38
Ogee spillway without end sill	Farhoudi and Smith (1982) [16]	1.00	0.19
Ogee spillway with the end sill	Oliveto and et al (2011) [17]	0.92	0.20
Ogee spillway	Dargahi (2003) [18]	1.00	$\alpha = -0.17 \ln\left(\frac{h_0}{h_d}\right) + 0.04$
Sluice gate with horizontal stilling basin	Farhoudi and Shayan (2014) [19]	0.99	0.32
Stepped spillway	Present work	0.94	0.196

Table 3. Range of effective parameters in Farhoudi and Smith (1980) [15].

Spillway height (cm)	Discharge range (lit/s)	Length of stilling basin (cm)	Sediment particle size distribution (mm)	Profile of ogee spillway
Small (10)	8.3-25	41.5	Sand (0.15, 0.25, 0.52, 0.85) Bakelite (0.25, 0.52)	$y = -0.1806x^{1.872}$
Medium (20)	23.3-70	83		
Large (40)	66-198	166		

$2h_s$). In each experiment, T values were interpolated between maximum depths of scour with time when a magnitude of $2h_s$ is reached. The values of k and α were determined as 0.9394 and 0.196, respectively, from Figure 10. The following equation was used to calculate T values:

$$\frac{T}{t_0} = 2258.62 \left(\frac{l_s}{D_{50}}\right)^{-2.0955} \left(\frac{h_s}{D_{50}}\right)^{2.796} \left(\frac{L_B}{D_{50}}\right)^{3.931} (\mathrm{Fr}_D)^{-5.0532}. \quad (6)$$

Figure 10(b) was also used to evaluate the accuracy of Eq. (5). Table 2 shows k and α values downstream of various hydraulic structures obtained by various researchers. It is observed that after a while, scour depth downstream of stepped spillways is less than that of ogee spillways and gate valves. In other words, because of further energy dissipation through stepped spillways, the time needed for achieving special scour depth is much longer than ordinary spillways. A reduction in k and α values is expected as the flow characteristics tend towards the nappe flow condition.

3.4. Role of stepped spillways in reducing the scour hole geometries compared with ogee spillways

One of the advantages of stepped spillways compared with ogee spillways is its high-energy dissipation, which would end with smaller dimensions of scour hole downstream of these structures. To clarify this prediction, Farhoudi's data [15] for scour evolution downstream of ogee spillways were used. The study was conducted on three ogee spillways with different heights. Table 3 shows the structure details and ranges of different parameters in brief.

These researchers studied the process of scour development and counter effects of hydraulic jump under high, low, and balanced tail-water depths. In order to compare the effects of stepped spillways with ogee spillways on the development of scour hole, 20 series of Farhoudi's data [15] from experiments under balanced tail water were selected. For each series of experiments, maximum scour hole depth (y_m), distance of maximum scour hole depth from end of stilling basin (x_m), and scour hole length (x_s) were determined for equilibrium conditions. The relationship between particle Froude number and relative scour hole dimensions was then calculated, depicted in Figure 11 for both structures. Figure 11 shows that, in a certain flow condition and specific range of particle Froude number, the relative depth of scour ($\frac{y_m}{D_{50}}$) in stepped spillway is less than that of ogee spillway. This observation explains that with the higher energy dissipation caused by stepped spillway, the scour hole dimensions will be considerably less than those observed with ogee spillways.

Chanson [14] proposed the following relationship for calculating energy dissipation by stepped spillway in nappe flow condition:

$$\frac{\Delta H}{H_{\max}} = 1 - \left(\frac{\left(\frac{f_e}{8 \sin\theta}\right)^{\left(\frac{1}{3}\right)} \cos\theta + \frac{1}{2}\left(\frac{f_e}{8 \sin\theta}\right)^{\left(\frac{-2}{3}\right)}}{\frac{3}{2} + \frac{H_{\mathrm{dam}}}{y_c}} \right), \quad (7)$$

where ΔH is the value of energy dissipation by stepped

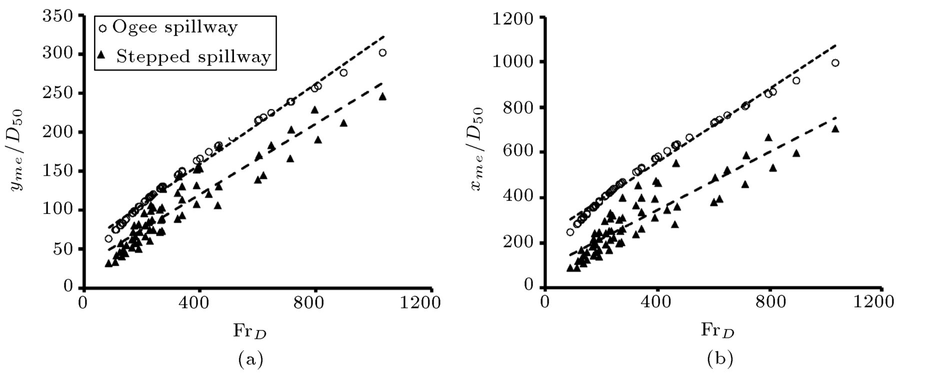

Figure 11. The relationship between particle Froude number and relative scour hole dimensions for ogee spillway .

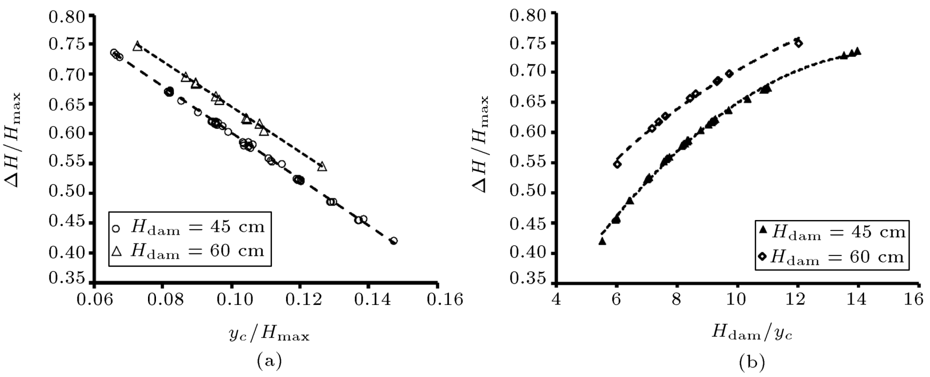

Figure 12. (a) The relationship between the rates of relative energy dissipation with critical depth. (b) The relationship between the rates of relative energy dissipation with Spillway height.

spillway. In addition, H_{dam} is the spillway height, $H_{\max}$ is the total energy height upstream of spillway, which can be calculated from $H_{\max} = H_{\mathrm{dam}} + y_0$, ($y_0$ is water head on spillway crest), f_e is the friction factor for water-air flows which is 0.2 for stepped spillway and 0.03 for ogee spillway, respectively, θ is the angle of spillway slope, and y_c is the critical depth of flow. The relative energy loss for experimental data was calculated using Chanson equation and plotted in Figure 12. It could be observed from Figure 12(a) that, in a spillway of a specific height, an increase in flow discharge would significantly reduce the energy loss. On the other hand, Figure 12(b) shows that, under specific discharge, as the height of spillway increases, the energy dissipation decreases, confirming the achievement of Chanson [14]. It could be concluded that the existence of steps in stepped spillways will cause higher energy loss of 42.06 to 74.82 compared with ogee spillways.

In Figure 13, the relationship between relative energy loss of stepped spillway, scour hole geometry and volume of transported sediments of size $D_{50} = 1.11$ mm to downstream of a stilling basin of 110 cm length is shown. According to this figure, as the energy loss by stepped spillway decreases, the dimensions of scour hole as well as the volume of transported sediments out of the hole significantly increase.

4. Conclusion

From wide ranges of experiments downstream of some stepped spillways subjected to different Froude numbers, basin lengths, tail-water depths, sediment sizes, and different sloped spillways, the following remarks could be concluded. With certain length of stilling basin, relative tail water and particle Froude number, the scour hole geometry will decrease with sediment size. On the other hand, with fixed sediment sizes, slope of stepped spillway, relative tail water and particles Froude number, the geometry of scour hole will decrease as the length of stilling basin increases. An increase in particles Froude number with constant values of other parameters would tend to an increase in the dimensions of scour hole. As the slope of stepped spillway increases, the geometries of scour hole decrease. Under constant conditions, an increase in tail-water depth would end with deeper scour hole having a longer longitudinal length. An exponential equation would predict the time scale of scour evolution downstream of stepped spillway.

It was concluded that the energy dissipation of stepped spillways under specific condition is higher than that of ogee spillways. This would result in smaller dimensions of scour hole and longer time required to reach the semi-equilibrium stage, i.e. down-

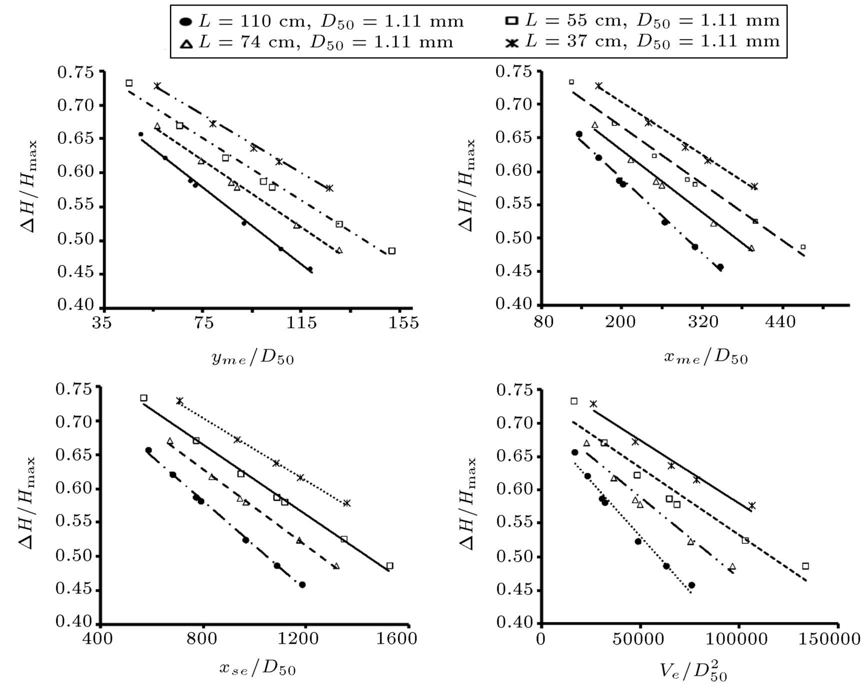

Figure 13. The relationship between the relative energy dissipation by stepped spillway and dimensions of scour hole.

stream of these structures compared with that of ogee spillways being the same.

Nomenclature

B	Width of the flume (cm)
C_u	Uniformity coefficient of sediments
D_{50}	Sediment size (cm)
Fr_D	Particle Froude number
FS	Shape factor of sediments
H_d	Height of stepped spillway (cm)
$H_{\max}$	Total energy height upstream of spillway
L	Length of stilling basin (cm)
Q	Flow discharge (lit/s)
T	Time required the scour depth reaches d_0
V	Volume of transmitted Sediments from hole
f_e	Friction factor
y_m	Maximum depth of scour hole (cm)
x_m	Position of maximum depth from stilling basin (cm)
x_s	Maximum length of scour hole (cm)
q	Discharge intensity $\left(\frac{\text{lit/s}}{\text{m}}\right)$
$y_{\max}$	Maximum depth of scour hole at time t
d_0	Depth of scour hole at a certain time t_0
y_0	Water head on spillway crest
h	Height of steps of spillway (cm)
g	Acceleration due to gravity (m/s^2)
t	Time
y_{tw}	Depth of tail-water (cm)
α	A parameter depending on the type of structure and flow conditions
l	Width of steps of spillway (cm)
y_c	Critical depth of flow
σ_g	Geometric standard deviation of sediments
θ	Angle of Spillway slope
ΔH	Height of energy dissipation by stepped spillway
ρ	Mass density of water (kg/m^3)
ρ_s	Mass density of sediments (kg/m^3)
ϕ	Angle of repose
μ	Dynamic viscosity of water $\left(\frac{\text{N-s}}{\text{m}^2}\right)$

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