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Laboratory Investigation of Stilling Basin Slope Effect on Bed Scour at Downstream of Stepped Spillway: Physical Modeling of Javeh RCC Dam

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Abstract
Stepped spillway and stilling basin are one of the most important energy dissipation structures. Eventhough, most of energy dissipated by these structures, but in skimming flow, the upstream flow motion is nonaerated and the residual energy capable to destroyed structures during floods. In this study, effect of stilling basin slope on bed scour, downstream of Javeh dam was investigating. Experiments performed in hydraulic structures laboratory of the University of Kerman with six different discharges (5, 7, 13, 17, 25 and 30 l/s.m) and five various stilling basin slope (0.02, 0.01, 0, −0.01 and −0.02). The parameters such as maximum scour depth (d_s), flow velocity (in three point), water depth on upstream and downstream of stepped spillway and stilling basin, the distance of the maximum scour depth to sill (L_s) and the gheometery of scour hole measured. Result shown that when stilling basin slopes was 0.02, the average of maximum relative scour depth, 47% Increased and in −0.02, 52.2% Decreased. In addition, the distance of maximum scour depth until stilling basin increased by increasing and decreased by decreasing the stilling basin slope.

Keywords Stilling basin · The energy dissipation structures · The maximum depth of scour · Scour hole

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1 Introduction

Scour is a natural phenomenon caused by the erosive action of flowing stream on alluvial beds (Hoffmans and Pilarczyk 1995). Scour hole that created in downstream of hydraulic structures because of insufficient energy depreciation (Shafaei Bejestan 2006).

Historical records indicate that stepped spillways have been used for thousands of years (Chanson 1995, 2001). Stepped spillways are one of the energy depreciation structur that in these years considered by designer engineers and reaserchers because of the technical advances in construction of the roller compacted concrete dams (RCC) (Qian et al. 2009), relatively low cost, quick construction and also high energy depreciation (Chanson 2002). In addition, stepped spillways contribute to the stability of the dam (Chatila and Jurdi 2004). The steps act as macroroughness elements, contributing to enhanced energy dissipation and significant aeration (Rajaratnam 1990). In stepped spillway the variation flow, steps, shaft angle, etc. can be effective in developing the scour hole at the downstream. For this reason, in downstream of stepped spillway they construct a stilling basin with less length (Dey and Sarkar 2007). Three basic air entrainment mechanisms are described in stepped spillway (Skimming flow regime, transition flow regime and nappe flow regime) that the maximum scour depth occur in skimming flow (Tuna and Emiroglu 2011a, b).

The study of scour downstream of hydraulic structures such as large dams, stilling basins, diversion works, underflow gates, and culverts constitutes an important field of research due to its frequent occurrence in engineering applications. Scouring hole at downstream is the main problem encountered with using spillways.

If the scour profile gets dimensionless perfectly the scour hole will be similar as geomrtry and independent of time and sediment particle size (Farhoudi and Smith 1985). Nonuniform stepped design might be a practical alternative that the experiment showed the rate of energy dissipation was about the same for uniform and nonuniform stepped configurations. However, the observations suggested some flow instabilities for smaller flow rates (Felder and Chanson, 2012). In MATLAB, genetic algorithm was used to optimize that the results showed stepped spillway leading to increased energy dissipation and reduce energy dissipation in downstream and for constant flow rate, independent of the optimum height of the stairs and decreases with increasing steppe spillway slop (Shoja et al. 2013). The cross profile of scour hole is not symmetric and the maximum scour depth will be happening on the sideways (Tuna and Emiroglu 2011a, b; Aminpour et al. 2014a). The scoure hole depended to steps geometry, sediment particle size, flow discharge, shaft angle and the tailwater depth (Tuna and Emiroglu 2013). In similar hydraulic condition whit, increase the D50 the scour hole will be decrease (Rafiei et al. 2014). The geometry of scour hole depended to step spillway slope, stilling basin length and the Froude number (Aminpour et al. 2014a, b). On a stepped spillway, the steps act as macroroughness elements, contributing to enhanced turbulence. With typical design flow conditions, the water skims down the stepped chute, and the upstream flow motion is nonaerated (Zhang and Chanson 2015, 2016a, b).

From the published literature it can be observed that most of the proposed formulae for predicting maximum scour depth at downstream of hydraulic structures are empirical and the physical models are still the main tool used to study what ultimately happens at the downstream hydraulic structures (Dey and Sarkar 2007). Most experiments were conducted on stepped spillways with uniform flat steps to quantify the energy dissipation and to provide some design guidelines (Matos 2000; Chanson 1995, 2001). However, this study is about the effect of stilling basin slope on scour hole of downstream of stepped spillway. The purpose of this reasearch is to decrease the maximum scour depth with the minimum cost or an eternal way.

2 Physical Modeling, Experimental Facility and Instrumentation

2.1 Presentation Outline

Experiments conducted in the laboratory of hydraulic structures University of Kerman on physical model of Javeh RCC dam. It is the largest dam that built in the country until now and has Concreting record in the month (Fig. 1).

In laboratory, Javeh RCC dam built with 1:40 scale (Novak and Cabelka 1981) that include storage tank, stepped spillway and stilling basin. At the end of these structures, placed a flume as a sedimentary bed and the sidewalls of all structure were made of transparent glass to monitor the flow (Fig. 2).

3 Experimental Flume and Instrumentation

The experimental work conducted in a stepped spillway with a re-circulating flow system with six discharge and five stilling basin slope (Table 1). The longitudinal slope of the flume, the sill and the tailwater kept constant during the experiments. The stepped spillway has 61 steps with 0.025 m lenth, 0.03 m high and 0.04 m wide. The stilling basin straightly set after stepped spillway with 1.33 m lenth, 0.04 m wide and there was a sill with 0.09 m high. Moreover, at the end of these structures there was a channel with 3 m lenth and 0.5 m wide. In addition, at the of the down stream channel, a relief structure (control gate) was placed to kept constent the tailwater level. A schematic diagram of the experimental set-up given in Fig. 3.

Water, pumped to the storage tank and then stilling tank, from which water entered the stepped spillway, stilling basin and after passing through the sill, it encounters sedimentary bed and created the scour hole. In each experiment was measured the velocity and water level in 3 poin that shown in Fig. 3 as a number, the geometry of scour hole, the maximum scour depth and the lenth between the maximum scour hole and the sill.

As seen in Fig. 3, at the end of channel, a relief structure (control gate) placed in order to adjust tailwater level. The control gate high (h_g) was 0.02 m. As a result, tailwater depth (h_t)

Fig. 1 Javeh RCC dam

Fig. 2 The physical model of Javeh RCC dam built on hydraulic structures laboratory of Kerman University

changed between 10.5 and 14.5 cm. In the downstream pool, a material with 1.51 mm thickness of non-cohesive bed material used. A sieve analysis carried out to determine the grain size distribution for each material of sand, the results of which shown in Fig. 4. From this, the median grain size (d_{50}) and coefficient of uniformity C_u (Eq. 1) obtained. The degree of uniformity of the particle size distribution of a sediment sample is defined by the value of geometric standard deviation σ_g (Eq. 2) which is less than 1.4 for uniform sediments (Dey and Sarkar 2007).

$$C_u = \frac{d_{85} - d_{16}}{d_{50}} \tag{1}$$

$$\sigma_g = \left[\frac{d_{84}}{d_{16}}\right]^{0.05} \tag{2}$$

3.1 Velocity and Energy Dissipation

Water jet velocity in four point (that shown in Fig. 3) obtained by Streamflo Velocity Meter that it has the ability to measure velocities as low as 5.0 cm/s. Froud number and velocity distribution graph obtained. Velocity distribution graph at the end of the stilling basin in $Fr_d = 1.5$ shown in Fig. 5.

It can be clearly seen that the changes of stilling basin's slope are the cause of deformation of the velocity distribution chart. Overall, the changes of velocity are lower than the basic experiment's velocity until the middle of chart and after that in positive slope, velocity was increased and in negative slope, velocity was decreased.

Table 1 Laboratory variable of the developing flow region on stepped spillways

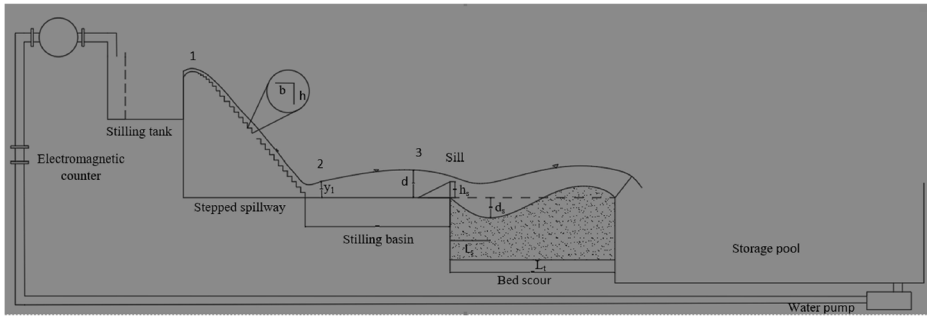| Stilling basin slope (S_o)	−0.02	−0.01	0	0.01	0.02	
Discharge (q, l/s.m)	5	7	13	17	25	30

Fig. 3 A schematic diagram of the structures

The present investigation focused on the skimming flow regime, which is typical of most design flow conditions for modern gravity dam-stepped spillways. To calculate the relative energy dissipation (Ohtsu et al. 2004) presented a method:

$$\frac{\Delta E}{E_{max}} = \frac{E_{max} - E_{res}}{E_{max}} = 1 - \frac{E_{res}}{H_{dam} + 1.5 y_c} = 1 - \frac{E_{res}}{y_c} \times \left(\frac{H_{dam}}{y_c} + 1.5 \right)^{-1} \quad (3)$$

Here ΔE = Head of energy loss between top and end sections of stepped spillway ($\Delta E = E_{max} - E_{res}$), E_{max} = Total energy head at top of stepped channel ($E_{max} = H_{dam} + 1.5 y_c$), E_{res} = Residual energy head, H_{dam} = Total drop height, y_c = Critical depth ($y_c = \sqrt[3]{q^2/g}$).

$$\frac{E_{res}}{y_c} = 1.5 \left[\left(\frac{E_{res}}{y_c} \right)_U - 1.5 \right] \left(1 - \left(1 - \frac{H_{dam}}{H_e} \right)^m \right)$$
$$m = -\frac{\theta}{25} + 4 \ (\theta \text{ in degree}) \quad (4)$$
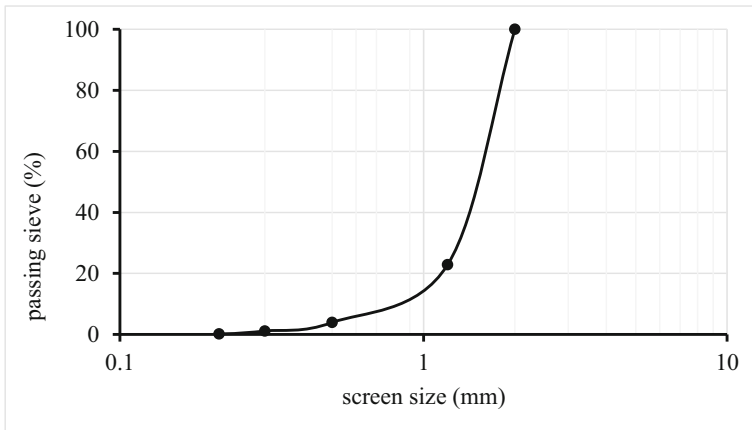

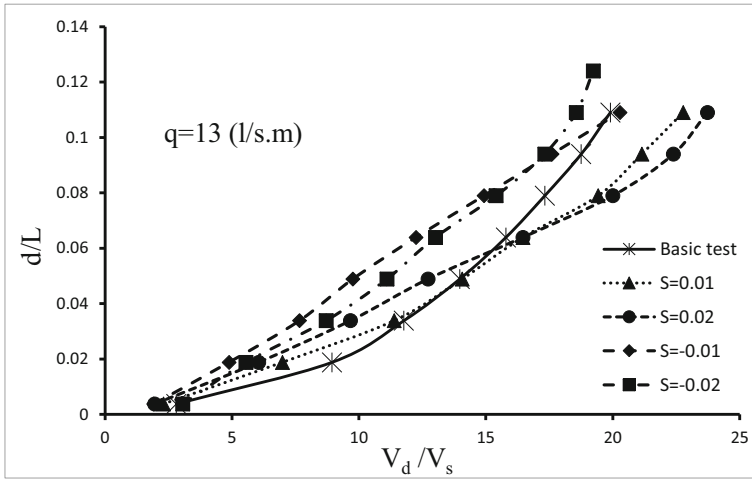**Fig. 4** Grain size distribution curves

Fig. 5 Variation of relative velocity as a function of V_d/V_s in the model for different slope of stilling basin

$$\left(\frac{E_{res}}{y_c}\right)_U = \frac{y_w}{y_c} + \frac{1}{2}\left(\frac{y_c}{y_w}\right)^2 = \left(\frac{f}{8\sin\theta}\right)^{1/3} + \frac{1}{2}\left(\frac{f}{8\sin\theta}\right)^{-2/3} \tag{5}$$

$$f = f_{\max} - A\left(0.5 - \frac{h}{y_c}\right)^2 \text{ For } 0.1 \leq h/y_c \leq 0.5$$

And

$$f = f_{\max} \quad 0.1 \leq h/y_c \leq (h/y_c)_h$$

Where

$$A = -1.7 \times 10^{-3}\theta^2 + 6.4 \times 10^{-2}\theta - 1.5 \times 10^{-1}$$
$$f_{\max} = -4.2 \times 10^{-4}\theta^2 + 1.6 \times 10^{-2}\theta + 3.2 \times 10^{-2} \tag{6a}$$
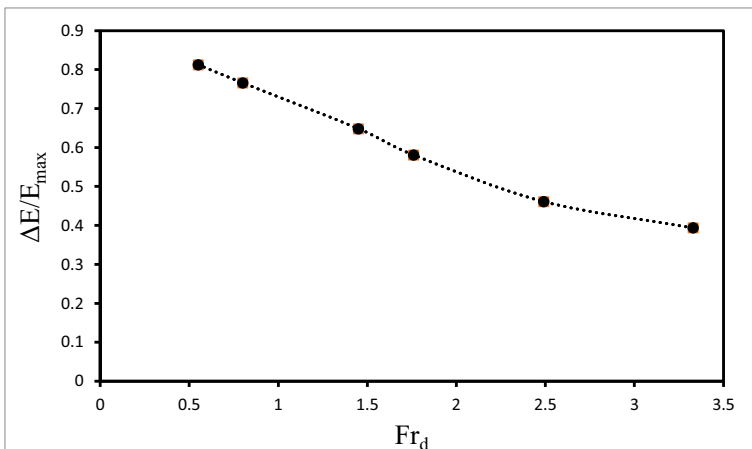$$5.7^o \leq \theta \leq 19^o$$

Fig. 6 Energy dissiplin of stepped spillway from material's Froude number for different slope of stilling basin
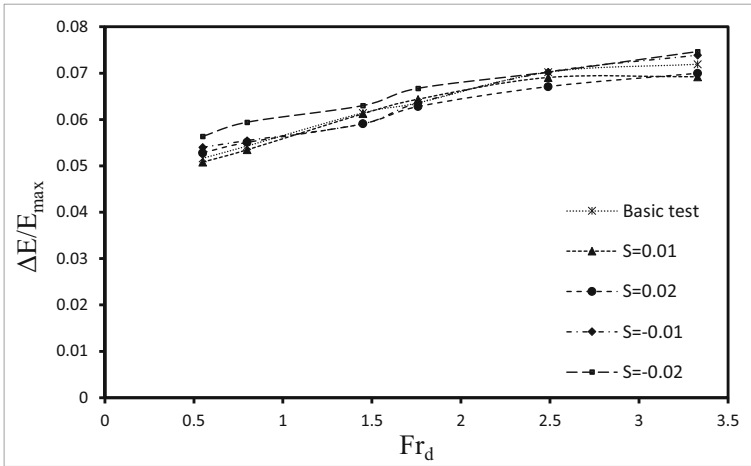
Fig. 7 Energy discipline of stilling basin (ΔE) for different material's Froude numbers (Fr_d) and five different stilling basin slope (S)

$$f = f_{max} - A\left(0.5 - \frac{h}{y_c}\right)^2 \text{ For } 0.1 \leq h/y_c \leq 0.5$$

And

$$f = f_{max} \quad 0.1 \leq h/y_c \leq (h/y_c)_h$$

Where

$$A = 0.452$$
$$f_{max} = 2.32 \times 10^{-5}\theta^2 - 2.75 \times 10^{-3}\theta + 2.31 \times 10^{-1} \quad (6b)$$
$$19^o \leq \theta \leq 55^o$$

Here H_e = Drop height required to form quasi-uniform flow, h = Step height, f = Friction factor, f_{max} = Friction factor for $S/y_c.0.5$.
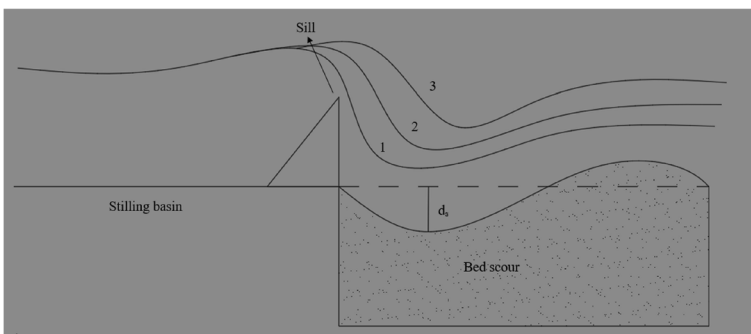

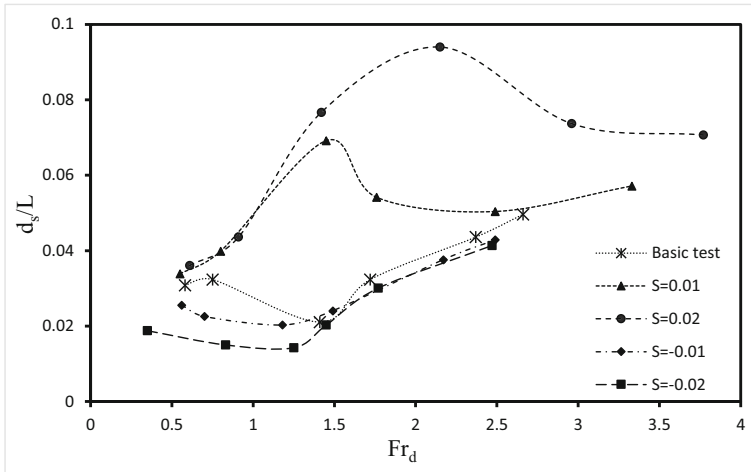**Fig. 8** The angle of jets when it collision to the bed scour

Fig. 9 The maximum scour depth (d_s) for different material's Froude numbers (Fr_d) and five different stilling basin slope (S)

For stilling basin, the energy dissipation calculated by below eqaution

$$\Delta E = \frac{(y_2 - y_1)^3}{4 y_1 y_2} \tag{7}$$

The result for both energy dissiplin of stepped spillway and stilling basin shown on Figs. 6 and 7 relatively.

According to the Fig. 6. In stepped spillway, energy dissiplin decreased by increasing the material's Froude number. This is happened because when discharge increased the regim flow become to skimming and the contact whit stepped decreased. Therefore, the energy dissiplin increased. It means stepped spillway dissiplin energy on high discharge less than the lower discharge.

Figure 7 shown, in stilling basin energy dissiplin decreased by increasing material's Froude number.

3.2 Discussion: Scour Geometry

The flows over and through hydraulic structures often occur in the form of jets. In general, a jet lifts the sediment particles and transports those particles downstream of

Fig. 10 Longitudinal sections of scouring a. -0.02 and b. 0.02 slope of stilling basin
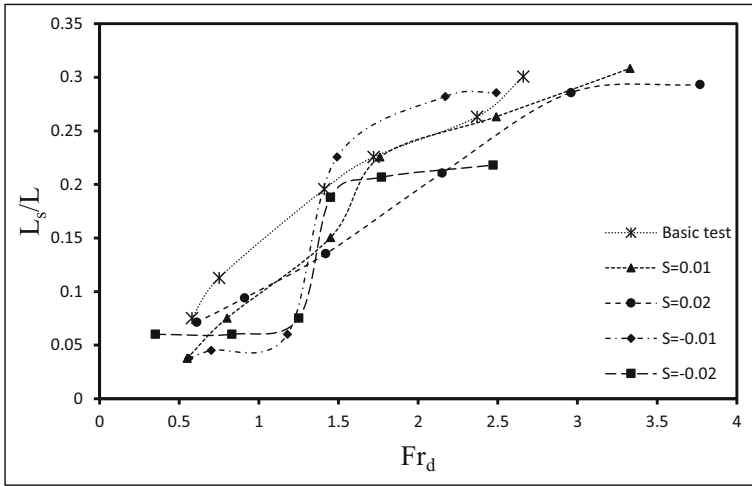
Fig. 11 The changes of maximum depth distance to sill (L_s) for different material's Froude numbers (Fr_d) and five different stilling basin slope (S)

the impacted area. The jet impact area is transformed into an energy dissipator and ascour hole is formed.

When scour hole created, it affected by two factor (the jet and the Froude number). The maximum of scour depth increase with increasing Froude number. Also the angle of jets when it collision to the bed scour has a considerable effect on it that it shown in Fig. 8.

Figure 8 shown that there are three kind of jets flow angle that it depended to the flow discharge. If the angle of jets flow is too close to the $90°$ (the second type of jet flow) the maximum of scour depth will be created.
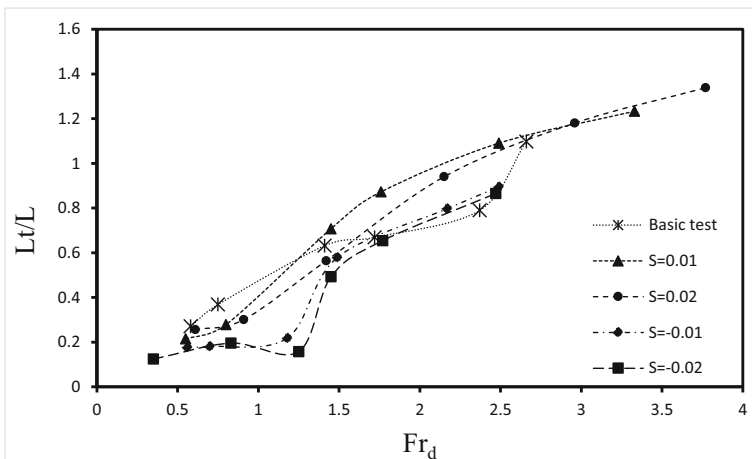

Fig. 12 The changes of scour distance (L_t) to sill for different material's Froude numbers (Fr_d) and five different stilling basin slope (S)

The maximum of scour hole from material's Froude number in five diferent stilling basin slope shown on Fig. 9. In addition, the chenges of maximum depth distance (L_s) and scour distance (L_t) to sill shown in Figs. 11 and 12 reletevely.

It can cleasly to seen that the scour depth is fluctuate on each stilling basin slope. The maximum scour depth preceded by a drop and followd by a decline; it is not necessarily just having a slight rise with rising the material's Froude number. This occurred when the angle of flow jet closing to the 90º.

The minimum and maximum scour depths occure on −0.02 and 0.02 slopes of stilling basin reletevly. Observation shows whit increasing stilling basin slope, the flow jet above the sill became too huge, water flow whit high energy collision with bed, it scouring the material and scour hole becomes deeper. Alternatively, when stilling basin slope decreased it might had flow jet or anything. Thus, the geometery of scour hole becomes smaller. In addition, the relative maximum scour depth and the
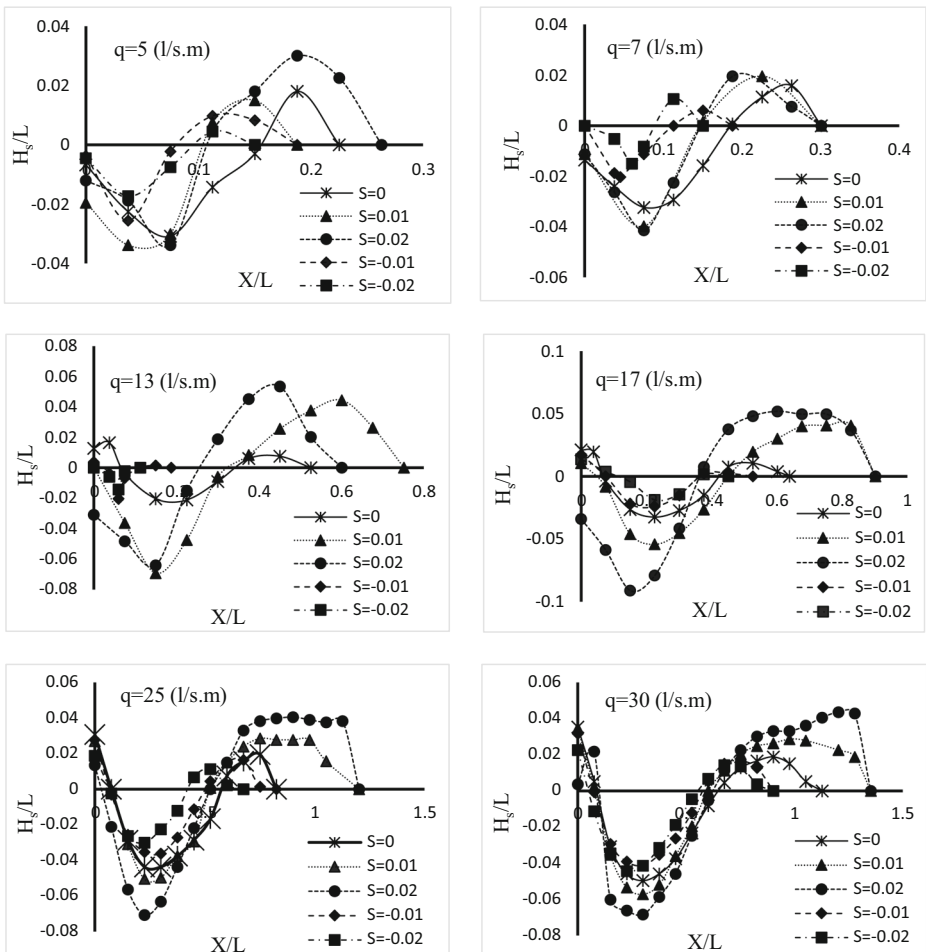

Fig. 13 Longitudinal sections of the relative scour depth in different discharge (q) and stilling basin slope (S)

average scour depth in a certain Froude number increased by increasing the slope of stiiling basin.

Figure 10 shows longitudinal sections of the maximum and minimum scour depth in both slope − 0.02 and 0.02.

According to the Figs. 11 and 12 maximum depth distance and scour distance to sill increased by increasing the material's Froude number in each stilling basin slope. If the material's Froude number does not change it increased by increasing stiiling basin slope.

Longitudinal sections of the relative scour depth in six discharge and five stilling basin slope shown on Fig. 13 and it describes only the distances of scour hole increased by increasing the discharge in each slope. The scour depth not only depended to the discharge, the flow jet affect on it eighter. Even though the maximum scoure depth is on the q = 17 (l/s.m), but the most chenges of scour depth happened on q = 13 (l/s.m). For this reason, the chenges of topography and contour line are brought on this discharge for five slope of stilling basin.

Figure 14 shown the scour hole immediatly created after the sill and it taking some time to scour hole formed and the maximum scour depth get constant (about 3 h).
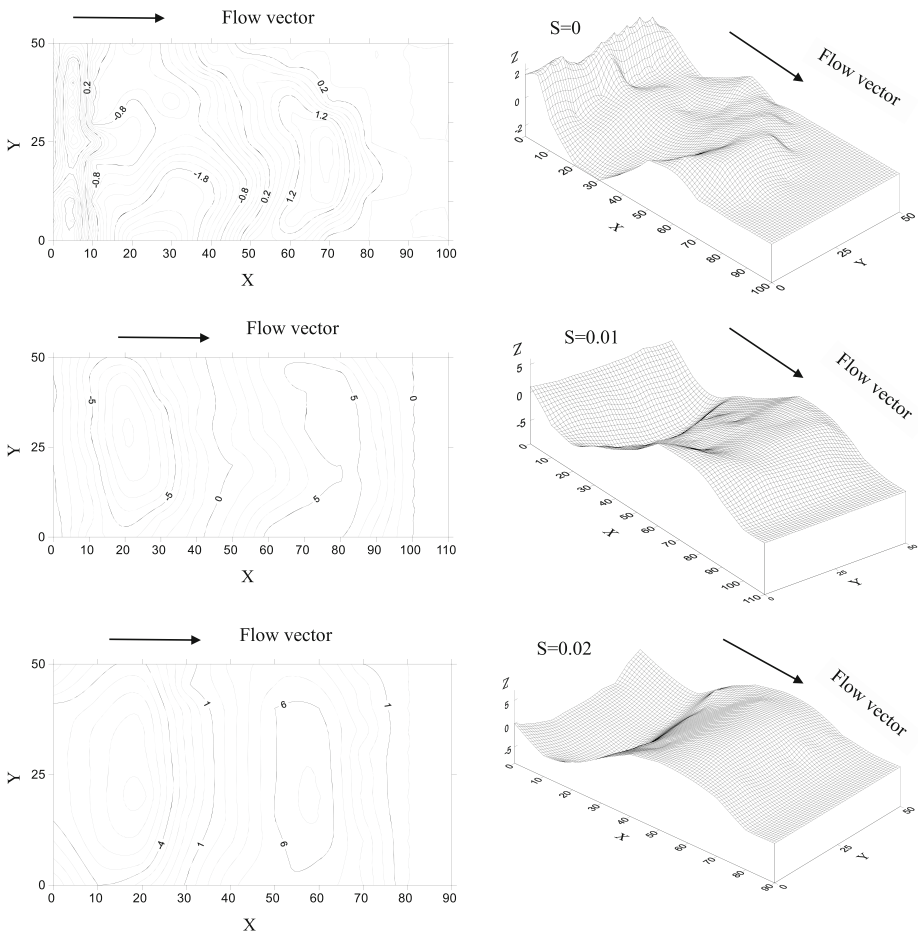

Fig. 14 The topography and contour line on 13 discharge for different slope of stilling basin (−0.01 and − 0.02)
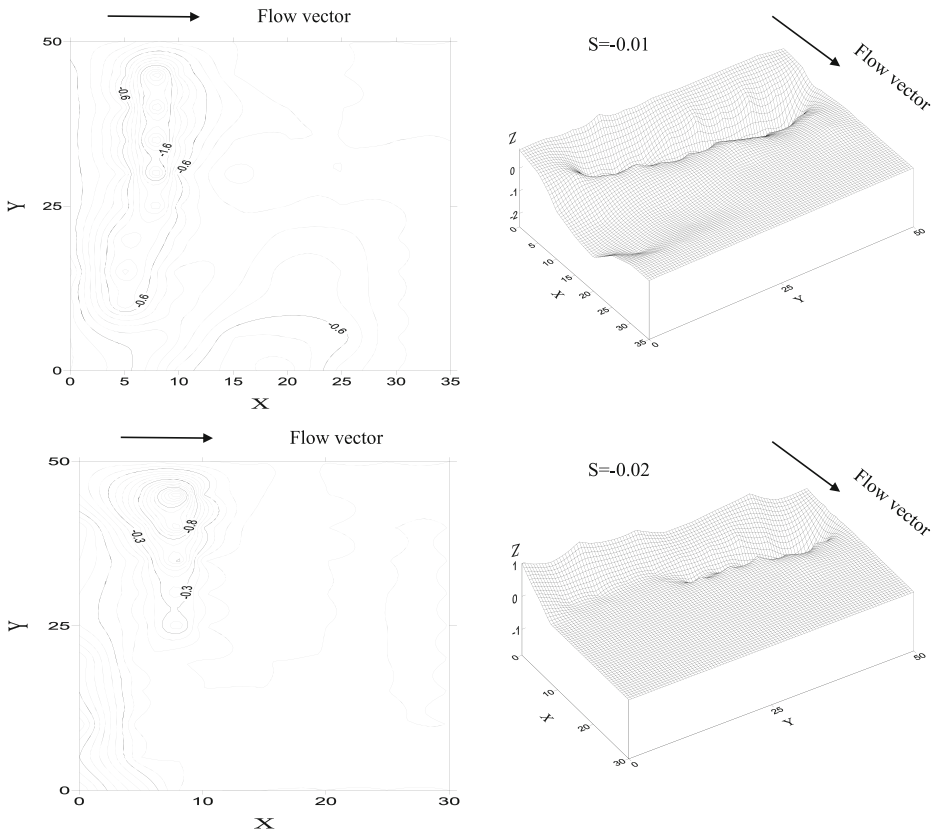
Fig. 14 (continued)

4 Conclusion

In this study, the geometry of scour hole downstream of stiiling basin in presence of stepped spillway was investigated considering diferent discharge and stilling basin slope. The velocity of flow and the head of water in four point and the parameter that affected on scour geometery were taken to analysis and obtain the result. The stepped spillways are very efficient means of lowering scour depth. The results indicated that the chenges on stilling basin considerably can decresed the scour depth. Based on these findings, the following conclusions can be drawn:

The average of relative velocity increased by increasing the slope of stilling basin and inverse.

Energy dissiplin was decresed by increasing material's Froude number. When discharge become higher and higher, the contact between flows and stepped was decrease and it caused that energy dissiplin decresed.

In stilling basin, energy dissiplin increased by increasing material's Froude number.

The scour depth not only depended to the discharge, the flow jet affect on it eighter. If the angle of jets flow is too close to the 90º (the second type of jet flow) the maximum of scour depth will be created.

When the slope of stilling basin is 0.02, the critical scour depth happend that the average of relative scour depth 47% increased.

The best slope of stiiling basin in this study is −0.02 that decreased the average of relative scour depth 52.2%.

When the material's Froude number increased, maximum depth distance to sill increased too in each stilling basin slope and if consider it constant the distance incresed if stilling basin slope increased.

only the distances of scour hole increased by increasing the discharge in each slope.

5 Notation

All symbols that used in this paper shown on Table 2.

Table 2 The symbols are used in this paper

b	step length	d_{50}	bed material diameter, which is finer by weight
h	step height	d_{84}	grain size, for which 84% of the material is finer
H_{dam}	total height of stepped spillway	σ_g	specific gravity
L	stilling basin length	Fr_d	densimetric Froude number
L_t	total scour length	ρ	mass density of water
h_s	sill height	ρs	mass density of bed material
d_s	maximum scour depth	E	specific energy
L_s	distance between maximum scour depth and the sill	E_{max}	Total energy head at top of stepped channel
y_1	the water depth on point 2	ΔE	Head of energy loss between top and end sections of stepped spillway
V_d	velocity distribution	E_{res}	Residual energy head
V_s	water velocity on stepped spillway	y_c	Critical depth
d	stilling basin's flow height	H_e	Drop height
q	water discharge per unit width	f	Friction factor
h_g	control gate high	f_{max}	Friction factor
h_t	tailwater depth	X	flume length
Cu	coefficient of uniformity	Y	flume height
d_{16}	grain size, for which 16% of the material is finer		chute angle

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