Scour depth downstream weir with openings
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doi:10.6088/ijcser.201203013025

ABSTRACT

Local scour downstream hydraulic structures may cause damage or complete failure of this structures. Weir may be used for measuring of discharge, decreasing the water slope in canals and distribution of water between canals for irrigation etc. Most of the past studies concentrate on discharge coefficient of combined flow, little information available on scour downstream of this flow. So, the objective of this research is to investigate the influence of using openings in weirs on scour hole depth downstream of this structure. The study was based on an experimental program included 171 runs. These runs were carried in a rectangular flume with openings fixed in the body of weirs. Three cases of opening arrangements were included, no opening, one opening and three openings. Different diameters of openings 1.27 cm, 1.9 cm and 2.54 cm, different heights at 0, 0.25 and 0.5 of weir height were tested under different flow conditions. The experiments showed that for most considered values of openings diameter either case of one opening or three openings, the value of h/p = 0.25 gave the smaller values of scour depth, while the value of h/p = 0.5 gave the higher values of scour depth. Also, it was noticed that for most considered values of openings height, the value d/p = 0.149 gave the smaller values of scour depth for case of one opening but for case of three openings, the value d/p = 0.075 gave the smaller values of scour depth. Finally empirical formula was developed for estimating scour hole depth in terms of downstream flow conditions, Froude number, height of the weir, number of openings, area of openings, diameters and heights of the openings.

Keyword: Scour, weir with openings, combined flow, one opening, three openings, flume.

1. Introduction

Scour is the removal of boundary material by the action of flowing water, it occurs naturally as a part of the morphological changes of rivers and man-made structures. Many researchers studied scour downstream weirs. For example, (Ashour, M.A. et al., 2005) studied the influence of bed material, weir shape and time on scour dimensions. They found that: 1- The depth of water in the downstream, mean particle diameter, Froude number and the time had a significant effect on the predicted scour depth. 2- The clear over fall weir produced the highest values of scour depth than the arched weir. 3- As the particles size decreased the scour hole dimensions increased. 4- The maximum depth of scour increased with the time until a limiting value was reached, after which the depth was almost constant. (Amen, k. A, 2008) developed a mathematical model for predicting the scour profile downstream weirs in non–cohesive bed material. The scour dimensions were found to be dependent on the discharge passed, the sediment particle size, Froude number and the time. (Hamed, Y. A. et al., 2009) studied the influence of oblique weir angle and V-notch angle on scour parameters.
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It was concluded that: 1- Scour dimensions could be increased by placing the V-notch weir with high oblique angle. 2- The variation of scour dimensions for small V-notch angles 30, 60 and 90 were not significant but these decreased dramatically by using V-notch angle 120°. 3- The maximum scour length/depth would be decreased significantly near by one of the walls when decreasing oblique weir angle. (Dehghani, Amir. Ahmed et al., 2009) studied the local scour hole parameters downstream of weirs, they concluded that an decrease in Froude number led to a drop in scour dimensions. In addition, for constant Fr, the maximum depth of scour decreased as a result of decreasing of weir height.

Some researchers studied the combined flow for example, (Wolters et al., 1987) made various experiments to calculate the discharge for system consisted of a specific weir and a pipe. They suggested rating curves for all weirs they studied. (Abdel halim et al., 1991) calibrated experimentally the flow over existing Fayoum weirs with orifices. A mean value for the coefficient of discharge for the combined structure was found to be 0.623 which was very close to the theoretical values.

Few researchers studied scour downstream combined flow. (Uyumaz, 1988) dealt with the scour phenomenon in non-cohesive soil below the vertical gates. The vertical gate was investigated in case of simultaneous flow over and under the gate. In the experiments, two various bed materials of homogeneous non-cohesive soil were used. He developed an empirical equation for estimating scour depth in term of height of water at the outlet, total discharge, head and grain size. (Dehghani, Amir Ahmed et al., 2009) investigated the dimensions of scour hole downstream of combined free over weir and below gate experimentally. They found the ratio of $D_s/y_o$ decreased when increasing the $H/a$ and $w/a$, the $D_s/y_o$ was greatest when $w/a=6$ (a was the gate opening, $H$ was the head over weir, $w$ was the vertical distance between the gate top and the weir bottom and $y_o$ was approaching water depth).

2. Dimensional analysis

In the analysis of the problem of scour downstream weir with openings, the variables considered were: $H =$ the water head above the crest of weir, $Y =$ tail water depth, $Q =$ water discharge through the flume, $V =$ the mean velocity at the downstream cross section of flume, $g =$ gravitational acceleration, $\rho =$ water density of the flow, $\mu =$ dynamic viscosity of the water $d_0 =$ mean particle diameter, $\rho_s =$ soil particle density, $L_{ap} =$ length of apron, $P =$ weir height, $h =$ height of opening measured from the channel bed, $d =$ diameter of opening, $S_o =$ bed slope of the flume, $B =$ width of flume, $D_s =$ maximum scour depth, (see Figure 1). The functional relationship for the maximum scour depth $D_s$, could be expressed as follow

![Figure 1: Definition sketch showing the geometry of scour hole](image)
H might be considered in variable $Q$, $Q$ might be considered in variable $V$, the slope of flume was kept constant so $S_0 =$ constant. In this study $P$, $B$, $d_{50}$, $\rho_s$, $L_{ap}$ were kept constant. Then, the above relation might be written in the following form:

$$D_s = f\left(V, Y, g, \rho_s, d, P, h, \mu\right)$$

(2)

$$f\left(\frac{V}{Y}, \frac{D_s}{Y^2}, d, \frac{P}{Y}, \frac{h}{Y}, \frac{\mu}{\rho V Y}\right) = 0$$

(3)

But, $F_r = \frac{V}{\sqrt{g Y}}$, $R_n = \frac{V Y}{v}$, and $v = \rho

So, relation (3) could be written as

$$f\left(\frac{1}{F_r}, \frac{D_s}{Y}, \frac{d}{Y}, \frac{P}{Y}, \frac{h}{Y}, \frac{1}{R_n}\right) = 0$$

(4)

where $\frac{1}{F_r} = \lambda^{-1}$

$$\frac{D_s}{Y} = f\left(\lambda^{-1}, \frac{d}{p}, \frac{h}{p}\right)$$

(5)

3. Materials and methods

The experimental equipment included flume, tail gate, measuring carriage and devices for measuring the discharge and water surface level.

3.1 The flume

It was rectangular recirculating flume with 14 m length, 0.6 m width, and 0.6 m height. The flume was made from plexiglass fixed to a steel frame as shown in photo (1), the inlet part of the flume consisted of elevated tank with dimensions (1.72 m length x 0.92 m width x 1.6 m height). The head tank was connected by the channel through a vertical sluice gate. The operating system was re-circulated through underground reservoir with 2m width, 3m length and 2m height which was constructed to supply the flume with water. Centrifugal pump driven by induction motor to re-circulated the flow from an underground reservoir to the flume. To control the water flow rate, a gate valve was installed on the pipe line at delivery side of the pump. The return channel passed water from the main channel to the underground reservoir. The return channel was built up from brick. The depth of water in the flume was adjusted by tail gate provided at the downstream end of the flume. Water depths and bed levels were measured by a point-gauge.

3.2 The experimental models

The model was a Fayoum type weir made of wood was used as a heading-up structure. The weir had 5 cm crest width, 50 cm crest length, 17 cm height, slope of 1:2 and two side contraction wing walls each of 5 cm width, the weir was followed by a solid floor of length 1.5 m, and 0.60 m width and made of Perspex to avoid the deformations under the action of water, the openings was fitted in weir body, the experimental runs were categorized in three
sets as follow. 1- The first set of the experiments was carried out without opening in weir. 2- The second set of the experiments was carried out using one opening in middle of weir. It included three positions of opening where \( h/P = 0, 0.25, \) and 0.5. For each position of opening, three relative diameters of opening, \( d/P = 0.075, 0.112, \) and 0.149 were used (see photo2). 3- The third set of the experiments was carried out using three openings had the same position and diameter of opening as mentioned for the second set (see photo3). For each set, three values of discharge were used, for each value of discharge, three values of downstream water depth were used.

3.3 The experimental procedures

After the flume was filled with bed material (sand) and accurately leveled, the leveling accuracy was checked by means of a point gauge. The following steps were carried out for each run: 1- The opening was fitted with certain height and diameter only in case of weir with opening, 2- The tail gate was completely closed, back water feeding was started first until its depth reached higher than the desired downstream water depth, 3- The control valve at the feeding opening was gradually opened till the required discharge was maintained, 4- The exact water discharge was measured using the sharp crested weir, 5- The tail gate was screwed gradually until the required downstream water depth was arrived at using the point gauge, 6- The running time of the test was started, 7- After 2 hours (where there is no appreciable change in scour hole profile), the pump was switched off, 8- The flume was emptied from water by tail gate very slowly in order not to disturb the scour hole obtained, 9- After the scour hole was drained, the maximum scour depth was recorded using point gauge at centerline of flume as the scour hole was symmetry. Steps 2 to 9 were completely repeated at weir without openings.

**Photo 1:** The flume

**Photo 2:** Case of one opening the first height
4. Results and discussion

Figure 2 Shows variation of $D_s/Y$ with $\lambda^{-1}$. It's found that for all considered heights and diameters either case of one opening or three openings, increasing of $\lambda^{-1}$ leads to decrease in $D_s/Y$. This means that, increasing of Froude number leads to increase in $D_s/Y$.

(Case of one opening): For $h/p = 0$ and 0.25, the value of $d/p = 0.149$ gives the smaller values of $D_s/Y$. For $h/p = 0.5$, for $\lambda^{-1} < 12$ ($F_t > 0.29$), the value of $d/p = 0.149$ gives the smaller values of $D_s/Y$, while for $\lambda^{-1} > 12$ ($F_t < 0.29$), the value of $d/p = 0.075$ gives the smaller values of $D_s/Y$.

(Case of three openings): For all considered values of height, the value of $d/p = 0.075$ gives the smaller values of $D_s/Y$. It is observed that for case of one opening, the influence of $d/p$ is less significant than the case of three openings. The reason for this may be for case of one opening the values of $D_s/Y$ are very close as the discharge over weir is very high if compared with flow through opening, so the influence of diameter of opening on $D_s/Y$ is not effective. The effect of $\lambda^{-1}$ on $D_s/Y$ give higher rate for $d/p = 0.075$ especially (case of three openings). It is evident that, for the two cases of one opening and three openings for relatively smaller value of $\lambda^{-1}$, the value of $d/p$ has less influence on the value $D_s/Y$ than for relatively higher value of $\lambda^{-1}$.

Figures (3.a) and (3.b) illustrate the variation of $D_s/Y$ with $h/p$ for different values of $\lambda^{-1}$ and $d/p$, for cases of one opening and three openings alternatively. These figures show that for case of one opening the influence of $d/p$ is less significant than for case of three openings for the same reason mentioned before.

(Case of one opening): Figure (3.a) shows that for most values of $\lambda^{-1}$, the value of $d/p = 0.149$ gives the smaller values of $D_s/Y$, but the value of $d/p = 0.075$ gives the smaller values of $D_s/Y$ for $\lambda^{-1} = 11.11$ and $h/p > 0.36$, for $\lambda^{-1} = 15.5$ and $h/p > 0.25$, $\lambda^{-1} = 18.11$ and $h/p > 0.31$ and $\lambda^{-1} = 20.85$ and $h/p > 0.31$. For $\lambda^{-1} = 13.62$, the value of $d/p = 0.112$ gives the smaller values of $D_s/Y$.

(Case of three openings): Figure, (3.b) shows that for most values of $\lambda^{-1}$, the value of $d/p = 0.075$ gives the smaller values of $D_s/Y$, while the value of $d/p = 0.112$ gives the smaller of values of $D_s/Y$ for $\lambda^{-1} = 13.62$ and $h/p < 0.38$ and for $\lambda^{-1} = 18.11$ and $(0.17 < h/p < 0.35)$ and for $\lambda^{-1} = 11.89$ and $(0.1 < h/p < 0.4)$. 

Photo 3: Case of three opening the first height
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Figures 4(a) and 4(b) Show variation of $D_s/Y$ with $d/p$ for different values of $\lambda^{-1}$ and $h/p$, for cases of one opening and three openings alternatively.

**(Case of one opening):** Figure (4.a) shows that for most values of $\lambda^{-1}$, the value of $h/p = 0.25$ gives the smaller values of $D_s/Y$, but the value of $h/p = 0.5$ gives the higher values of $D_s/Y$ for all of $\lambda^{-1}$ except $\lambda^{-1} = 8.96$, the value of $h/p = 0$ gives the higher values of $D_s/Y$. For $\lambda^{-1} = 15.5$, the value of $h/p = 0$ and 0.25 are very close.

**(Case of three openings):** Figure (4.b) shows that for most values of $\lambda^{-1}$, the value of $h/p = 0.25$ gives the smaller values of $D_s/Y$, but the value of $h/p = 0$ gives the smaller values of $D_s/Y$ for $\lambda^{-1} = 13.62$ and $d/p > 0.131$, $\lambda^{-1} = 18.1$ and $d/p > 0.135$, $\lambda^{-1} = 15.5$ and $\lambda^{-1} = 20.85$. The value of $h/p = 0.5$ gives the higher values of $D_s/Y$ for all of $\lambda^{-1}$.

The reason of previous results may be for $h/p = 0$ the head on opening is high if compared with $h/p = 0.25$, $h/p = 0.5$. So the velocity through opening is faster and near to the bed so the scour value is considerable. If the opening moved in vertical direction to $h/4$ ($h/p = 0.25$), the increase in velocity will be occurred far away from the channel bed and still there is small velocity near bed so this case is the preferable than the $h/p = 0$, and the last height ($h/p = 0.5$), the opening is very near to water surface and this causes turbulence, disturbance (surface, subsurface), some vortices and eddies and this affect on scour depth in bad manner and this was very clear in case of three openings.

Experimental results are utilized for developing the following empirical formulas (using Data Fit software program) for the used sand.

$$D_s/Y = -2.541 \times 10^{-2} (1/Fr^2) - 0.481 (d/p) + 0.107(h/p) - 1.687 \times 10^{-3} (n) + 2.218(A/p^2) + 0.723$$

The correlation factors ($R^2$) = 0.814  
Standard error = 0.04

Where: $A$ = Area of openings
Figure 2: Variation of $D/Y$ with $\lambda^{-1}$ (1 opening, 3 openings).
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Figure 3(a): Variation of $D_s/Y$ with $h/P$ (1 opening)
Figure 3(b): Variation of $D_s/Y$ with $h/P$ (3 opening)
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![Graphs showing variation of Ds/Y with d/P for 1 opening.](image)

Figure 4(a): Variation of Ds/Y with d/P (1 opening)
Figure 4(b): Variation of $D_r/Y$ with $d/P$ (3 opening)

5. Conclusion

1. For two cases of one opening and three openings, increasing of kinetic flow factor ($\lambda^{-1}$) leads to decrease in the maximum scour depth for all considered opening arrangements.

2. For two cases of one opening and three openings, increasing of $h/p$ leads to decrease in the scour depth till $h/p = 0.25$, after this scour depth starts to increase. So the value of $h/p = 0.25$ gives the smaller values of scour depth, while the value of $h/p = 0.5$ gives the higher values of scour depth for most considered values of $\lambda^{-1}$ and opening diameters.

3. Changing of $d/p$ has no trend on scour depth, for the case of one opening, the value of $d/p$ has no effect on scour depth for $h/p = 0, 0.25$ but for $h/p = 0.5$, the value of $d/p = 0.075$ gives the smaller values of scour depth moreover for case of three openings, the value of $d/p = 0.075$ gives the smaller values of scour depth for all heights of openings.
6. References


