COMPREHENSIVE STUDY ON SCOUR DOWNSTREAM CURVED WEIRS

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ABSTRACT

The efficiency of weirs to pass water is measured by their capacity of passing high discharges on their crest level with small acting head. Curved weirs (in plan) have a large capacity of passing water in comparison with straight ones due to the increase of their crest length for same channel width. The present study aims to predict the scour downstream curved weirs and compare it with that downstream straight ones. The effect of different flow parameters, bed materials, sudden drop in the bed behind the weir and using downstream sills on this scour were experimentally investigated. Five models of weirs having different crest length and different downstream face were built across a trapezoidal channel located in the Hydraulic Laboratory of Civil Engineering Department, Assiut University. The channel bed slope was kept constant at 0.0001, while the discharge was varied with their normal flow depth downstream the weir. Also, the bed materials were changed from fine to coarse sand. The study revealed that the curved weir type-3 was exposed to minimum scour dimensions in comparison with the other types. So, to minimize this minimum scour, two groups of sills were located on the solid apron downstream and the scour was studied. Empirical equations were developed to predict scour length, maximum depth and its location.

Keywords: Curved Weirs, Scour, Erodible bed, Bed Drop, Sills

INTRODUCTION

Scour downstream hydraulic structures may be investigated theoretically or experimentally. Also, both may be performed on solid beds or on movable ones. The solid bed investigations aimed to predict the length of solid floor downstream hydraulic structures to prevent or to minimize the local scour. Most of these investigations are based on velocity distributions approach [1, 12 and 19]. The effect of drop downstream of clear overfall weir was investigated by Yassin et al. [19] by means of velocity distributions. Investigations on local scour of alluvial channel near rigid apron are based on the examination of topography of scour hole produced by different hydraulic conditions [2, 3, 5, 9, 10, 11, 14, 16 and 20]. In these investigations the effect of the size of bed material (within sand range) was considered. Many
empirical formulas were developed. The effect of using sills with solid aprons on scour length and depth was investigated by many researchers [4, 6, 15 and 18]. Ali [4] found that the use of end sills may increase the scour behind the regulators, while he found the proper location of the baffle sills depend on the sill height and tail water depth and may reduce the length required to prevent scour by 25%. Ashour et al. [6] found that the use of two rows of baffles with a distance between them equals to 1.2 of baffle height is optimal number of baffles to dissipate the energy of flow and reduce the volume of scour hole. Nasr and Nagy [13] studied theoretically scour downstream spillway and they developed a theoretical formula for estimating scour hole depth.

From the previous literature, it is found that little attention has been paid to the study of scour downstream curved weirs. So, in the present investigation, curved weirs with different arrangements in the direction of flow, with different flow parameters and with different bed materials were studied. The drop of bed level and using sills downstream curved weirs were also studied.

**DIMENSIONAL ANALYSIS**

In the analysis of the problem of scour behind weirs, the variables considered are; $d_s =$ maximum scour hole depth, $d_{50} =$ mean particle diameter, $g =$ gravitational acceleration, $L_s =$ scour hole length from the end of the weir, $L_w =$ crest length, $Q =$ discharge over the weir, $V_b =$ bed velocity at the end of solid apron, $V_2 =$ normal mean velocity at the downstream cross section of the channel, $X_s =$ location of maximum scour hole depth from the end of rigid apron, $y_1 =$ upstream water depth, $y_2$ or $y_n =$ downstream normal water depth, $\gamma_w =$ specific weight of water and $\gamma_s =$ soil particle specific weight, $\mu =$ absolute viscosity, $\rho =$ water density, [See Fig. 1].

![Fig. 1 Definition sketch showing the geometry of the scour hole.](image)

The geometry of the scour hole may depend upon the other remaining parameters as follows:

$$L_s \text{ or } d_s \text{ or } X_s = \phi_1(y_1, y_2, L_w, V_b, V_2, Q, d_{50}, g, \rho, \rho_s, \mu, \gamma_w, \gamma_s) \quad (1)$$
Using $\pi$ - Theorem, it yields:

$$\frac{L_s}{y_n} \text{ or } \frac{d_s}{y_n} \text{ or } \frac{X_s}{y_n} = \phi_2 \left( \frac{y_1 - y_n}{y_n}, \frac{Q}{\sqrt{g y_n^3 L_w}}, \frac{V_2}{\sqrt{g y_n^2}}, \frac{\rho V_2 y_n}{\mu}, \frac{\gamma_w V_b^2}{g d s_0 \gamma_s}, \frac{\gamma_w V_2^2}{g d s_0 \gamma_s} \right)$$

(2)

In which the working head $H = y_1 - y_n$, $\rho V_2 y_n / \mu = \text{Reynolds' number (} R_e)$, $V_2 / \sqrt{g y_n} = \text{Froude number (} F_e)$, $\tau_b = \rho_w f V_b^2 / 8$ is the bed shear stress at the end of solid apron, $\tau_m = \rho_w f V_m^2 / 8$ is the main shear stress, $f = \text{friction coefficient obtained from the following formula [3]}:

$$\frac{1}{\sqrt{f}} = 2.00 \log \left( \frac{12.6 y_n}{d_s} \right)$$

(3)

and $\tau_c$ is the critical shear stress obtained from Shields diagram, it may be given by:

$$\tau_c = (\gamma_s - \gamma_w) \varepsilon d_{s_0}$$

(4)

Where $\varepsilon$ is a constant varies from 0.04 to 0.1.

Eq. (2) may be written as:

$$\frac{L_s}{y_n} \text{ or } \frac{d_s}{y_n} \text{ or } \frac{X_s}{y_n} = \phi_3 \left( \frac{H}{y_n}, \frac{Q}{\sqrt{g y_n^3 L_w}}, F_e, R_e, \frac{\tau_b}{\tau_c}, \frac{\tau_m}{\tau_c} \right)$$

(5)

In free surface model studies, the viscous force doesn’t affect relatively the flow field and hence $R_e$ in Eq. (5) may be dropped [4 and 7]. Egyptian canals are working under low values of Froude number [17] So, the present study was performed within narrow range of Froude number, the head effect ($H$) may be considered in the variables ($Q$) and ($L_w$) while the main shear stress ($\tau_m$) was taken to be less than ($\tau_c$) to safeguard the channel against degradation. Then, Eq. (5) may be reduced to:

$$\frac{L_s}{y_n} \text{ or } \frac{d_s}{y_n} \text{ or } \frac{X_s}{y_n} = \phi_4 \left( \frac{Q}{\sqrt{g y_n^3 L_w}}, \frac{\tau_b}{\tau_c} \right)$$

(6)
MATERIALS AND METHODS

CHANNEL: The investigations reported herein were conducted in a sloped-bed channel of trapezoidal cross section as shown in Fig. 2. The trapezoidal cross section has 0.84 m bed width, 0.6m depth and 1:1 side slopes. The total length of the channel is 18.5 m. The longitudinal bed slope was kept constant at 0.0001. The uniform water flow depth could be adapted by means of a tail gate installed at the end of the channel. The flow rate was regulated by a gate valve located on the feeding pipeline and was measured by a calibrated V-notch. Water depths and bed levels were measured by point-gauges. The velocity was measured by a calibrated Pitot-tube.

SAND BASIN: The channel was furnished by a false bed, which could be divided into three parts. The first part is a horizontal channel of trapezoidal cross-section with 3.8 m long, 0.87 m bottom width and side slopes of 1:1. Its walls were constructed from bricks and its base was made from plain concrete. The second part is a rectangular cross-section 1.25 m long with 0.84 m bottom width. Its walls were constructed from bricks with a height of 0.70 m above the bed level and its base was made from plain concrete. The model of the weir was constructed in this section. The third part is a sloped bed main channel of trapezoidal cross-section with 13.45 m long, 0.60 m bottom width, side slopes 1:1. This part was furnished by a false bed which could be divided into three portions. The first portion was made of concrete extended 0.7m behind the model of the weir with 20 cm height above the original channel bed. This length (0.7 m) is sufficient to maintain the hydraulic jump on it, while the second portion was a sand basin of 20 cm in depth and 2.5 m long. Three sand sizes of mean diameter ($d_{50} = 0.52, 0.82$ and $1.75$ mm) were used in the sand basin, respectively. The remaining part of the channel was a solid bed with 20 cm height above the original channel bed.

![Schematic diagram for the experimental facilities.](image-url)
**EXPERIMENTAL MODELS:** The experimental work was carried out on five different models of the weirs. These types are shown in Fig. 3. The first is weir type-1. It is straight in plan and having an inclination of 1:2 in the downstream face. This type was chosen for comparing its results with those of other models. The second is weir type-2. It is straight in plan but with a curved downstream face. The third is weir type-3; it is curved in plan with concave in the flow direction. The forth one is weir type-4 and is curved in the plan with convex in the flow direction. Both latter two mentioned types are vertical in the upstream and downstream face, while the fifth is weir type-5. It is curved in plan with concave in the direction of flow but with a curved downstream vertical face. In order to investigate the effect of sills on the scour hole dimensions downstream of weir type-3, a model of sills was fixed and arranged downstream of the weir as shown in Fig. 4a. The shown arrangements indicate two types of sill groups Fig. 4b and Fig. 4c.

**TEST CATEGORIES:** The experimental program concerning scour hole profile measurements downstream the models was divided into six main categories: The first is for investigating the influence of changing discharge on scour downstream the model. The second is: for studying the influence of weir type and its arrangement in the flow direction; while the third is to show the effect of grain size on scour hole dimensions downstream of weir type-3.

![Fig. 3 Model of weirs.](image)

![Fig. 4b Weir type-3 with group of sill-1](image)

![Fig. 4c Weir type-3 with group of sill-2](image)

![Detail A](image)
The effect of bed drop and floor sills on scour hole dimensions for weir type-3 with normal depths are the forth and fifth categories, respectively. The sixth category is to study the effect of changing the downstream water depth from normal depth on scour downstream weir type-3.

**RUN PROCEDURE**

The test procedures were as follows:

1) The channel bed was leveled to take a slope of 0.0001; 2) The model of the weir was fixed in the rectangular part of the channel with its arrangement to the direction of flow; 3) The sand material of a certain grain size was furnished in the sand basin and leveled to the false bed level; 4) The downstream main portion of the channel was filled with water to a depth greater than the desired normal water depth; 5) The gate valve at the feeding pipe was gradually opened till the required discharge is maintained; 6) The downstream uniform water depth was controlled and adjusted to the corresponding normal water depth of the selected discharge; 7) The scour hole depth reaches to its maximum value after 4 hours from the beginning of the test [8]. So, the test-run time was selected to be 4 hours; 8) The measurements of upstream water depth $y_1$, downstream water depth $y_n$, scour hole profile was taken especially, the $L_s$, $d_s$, and $X_s$; 9) The discharge was changed and the steps from 3 to 8 were repeated. Six discharges were selected; 10) Sand materials in the sand basin was changed and the steps from 4 to 9 were repeated. Three sand sizes were selected with weir type-3; 11) After that the model of weir was changed and the procedures from 2 to 9 were repeated. A drop in channel bed level downstream weir type-3 and sills are used with fine sand are also studied.

**OBSERVATION ON FLOW CHARACTERISTICS BEHIND THE TESTED WEIRS**

At first and before going to analyze the results, it is important to discuss the characteristics of flow over the tested weirs. Figure 5 illustrates the drawing of flow patterns behind all the tested weirs based on the experimental observations. From the figure, it is clearly seen that the flow behind weir type-1 (clear overfall weir) drawdown through the inclined surface 1:2 of the weir face. This inclination of weir surface sliding the stream lines and energetic them, but the impingement of flow onto the solid bed dissipates a part of this energy. On the other hand, for weir type-2 the stream lines accelerated through its movement on the curved face and this maximize its energy than weir type-1. Beside that the curvature of the surface decreases the impingement of flow onto the solid bed and minimizes the dissipation of energy and maximizes the scour than weir type-1. For weir type-3, the downstream surface of the weir is vertical and convex. This makes the stream lines fall vertically downwards and dissipates most of its energy on the solid bed. Also, the curvature of its crest decreases the discharge of water per one meter length of the crest than ordinary weirs (weir type-
and weir type-2). This may slowdown the surge of the falling water and minimizes the scour. The convexity of the surface downstream makes the stream lines to be directed away from the centerline of the channel, this leads the scour hole to form beside the walls. For weir type-4 the downstream surface is concave and this resulted in accumulation of all stream lines in one point on the centerline of the channel downstream the weir, this accumulation of stream lines leads to a high surge of flow along the centerline of the channel and maximize the scour. This leads the scour hole to form along the centerline of the channel. Weir type-5 was gathering of weir type-2 and weir type-3 in which the scour hole in this type formed also besides the walls, the pattern of flow of these types of weirs is a combination between weir type-2 and weir type-3 hence the amount of water discharged per one meter length of the crest is less than conventional types (straight ones). This releases the surge of water onto the floor, besides the convexity directs the flow toward the walls but the curvature downstream of this type contributed to accelerate the flow lines. This may explain the increase of scour length than weir type-3.

![Flow pattern behind the tested weirs.](image)

**Fig. 5** Flow pattern behind the tested weirs.
RESULTS AND DISCUSSION

1. SCOUR HOLE PROFILE (CONTOUR MAPS)

To show the typical features of scour behind the tested weirs, the scour holes are represented by both contour maps and sectional elevations through maximum scour hole depth. Shown in Figs. 6, 7 and 8 are the chosen examples of these drawing. The plots are for downstream normal flow depth with Froude number \( F_e = 0.1429 \) and fine sand. It is clearly seen from these figures that, the scour hole profile are symmetrical in plan around the centerline of the channel for all plots. This confirms the symmetry of downstream flow.

For weir type-3 as shown in Figs. 6 and 7, the maximum scour holes are shifted beside the channel side walls. This may due to the formation of eddies beside the channel walls [see Fig. 5]. It is seen from Fig. 6 that, weir type-3 (curved weir) gives minimum scour hole depth in comparison with the others. Furthermore with weir type-3 having group of sills, the scour hole depth reduces again. From the sectional elevation of scour hole, it is seen that the slope of the sides of stable scour holes is flatter than those predicted from the soil angle of repose. Form Fig. 8, the maximum scour depth and length are coinciding with the channel centerline due to the accumulation of eddies at channel centerline and gives higher depth in comparison with all studied weirs.

![Fig. 6 Scour hole profile downstream weir type-3 for fine sand at \( F_e = 01429 \).](image-url)
Fig. 7 Scour hole profile downstream weir type-3 with group of sill-1 for fine sand at $Fe = 0.1429$.

Fig. 8 Scour hole profile downstream weir type-4 for fine sand at $Fe = 0.1429$. 
Another presentation of scour holes are shown in Figs. 9 and 10 for all types of weirs and for weir type-3 with different sills conditions respectively. From Fig. 9 weir type-3 gives minimum scour volume while weir type-4 is associated with maximum scour. The effect of using sills downstream weir type-3 is shown in Fig. 10, where using sills with the mentioned arrangements reduces the scour.

Fig. 9 Comparison between scour behind all types of weirs for fine sand.

Fig. 10 Comparison between scour behind weir type-1, weir type-3 with group of sill-1 and weir type-3 with group of sill-2 for fine sand.

2. SCOUR LENGTH

The parameter $Q / \sqrt{g y_n^3 L_w}$ includes all the practical variables which affect the weir capacity of passing discharge and scour downstream. So, the experimental results of $L_s/Y_n$, with $Q / \sqrt{g y_n^3 L_w}$ are shown plotted in Fig. 11 and the weir type is taking as a third dimension. For all weir types, the scour hole length decreases with the increase of $Q / \sqrt{g y_n^3 L_w}$ values. It is clearly seen from the figure also that the flow over weir type-3 gives minimum values of $L_s/Y_n$ while weir types-2, 4 and 5 generated higher values in comparison with weir type-1. It is also noticed that the rate of decreasing of $L_s/Y_n$ is faster in case of weir type-2 and 4. One can notice a point of intersection between weir type-1 and weir type-2. This means that in case of low discharges the value of scour length of weir type-2 is higher than that weir type-1 to a value of $Q / \sqrt{g y_n^3 L_w}$ equals 0.162 then the values of scour length at high discharges for weir type-2 are less than weir type-1. This can explained as follow, when the discharge increases the downstream normal water depth increases, which also may considered as a defense wall for the jet of the falling water, and resulted in a decrease in scour length. Also, it
is seen that low values of the parameter $Q / \sqrt{g y_w^3 L_w}$ for curved weirs because the increase of their crest lengths. The correlation of the experimental results may have the following relationship:

$$\frac{L_s}{Y_n} = C_1 \ln \left( \frac{Q}{\sqrt{g Y_n^3 L_w}} \right) + C_2$$  \hspace{1cm} (7)

Where $C_1$ and $C_2$ are constants depending on weir type and given in Table (1).

<table>
<thead>
<tr>
<th>Weir type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>-10.356</td>
<td>-35.303</td>
<td>-19.527</td>
<td>-48.112</td>
<td>-15.84</td>
</tr>
<tr>
<td>$C_2$</td>
<td>-11.059</td>
<td>-56.492</td>
<td>-31.062</td>
<td>-77.412</td>
<td>-20.328</td>
</tr>
</tbody>
</table>

One of the main uses of the weirs is to be built at a sudden drop. Because weir type-3 gives minimum values of scour length downstream in comparison with the other types, it is taken to be studied with different drops. So, to investigate the effect of local drop on the scour hole length downstream of weir type-3 for normal flow conditions, the experimental results for $L_s/Y_n$ and the parameter $Q / \sqrt{g y_w^3 L_w}$ are plotted, taking into consideration the value of drop as a third dimension as shown in Fig. 12. It is clearly seen the effect of local drop downstream the weir, where the increase of drop increases the $L_s/Y_n$ values for same value of $Q / \sqrt{g y_w^3 L_w}$. This may due to the increase of the falling energy. The relationship between $L_s/Y_n$ and $Q / \sqrt{g y_w^3 L_w}$ for different downstream drops may take the following form:

$$\frac{L_s}{Y_n} = C_1 \ln \left( \frac{Q}{\sqrt{g Y_n^3 L_w}} \right) + C_2$$  \hspace{1cm} (8)

where $C_1$ and $C_2$ are constants depending on downstream drop as given in Table (2).

<table>
<thead>
<tr>
<th>Drop value</th>
<th>$h_d/h_w = 0$</th>
<th>$h_d/h_w = 0.32$</th>
<th>$h_d/h_w = 0.52$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>-19.527</td>
<td>-24.525</td>
<td>-24.2988</td>
</tr>
<tr>
<td>$C_2$</td>
<td>-31.062</td>
<td>-40.216</td>
<td>-40.669</td>
</tr>
</tbody>
</table>
Generally, and from the literature, the use of sills minimizes the scour downstream the hydraulic structures if it is positioned at a suitable location on the downstream floor. To study the effect of sills' arrangement on scour length behind the weir type-3, two sill groups are examined. Shown in Fig. 13 are the plots of $L_s/Y_n$ versus $Q/\sqrt{gY_n^3L_w}$ for weir type-3 without sills and weir type-3 with two groups of sills. It is clearly seen from the figure that the effect of using sills decreasing the scour length by about 11.9% in case of group sill-1 in comparison with weir type-3 without sills. In this case the number of sills is very large and lead to a high cost of construction. On the other hand, group of sill-2 has a less number of sills than group of sill-1 and the scour length decreased by about 6.1% in comparison with weir type-3 without sills.

To establish the relation between the ratio of $L_s/Y_n$ and the bed shear stress, the experimental results are plotted as shown in Fig. 14. The weir type is taking as a third dimension. The values of maximum and minimum critical shear stresses are shown in the figure. It is found from this figure that, in case of weir types-4 and 5 the value of the bed shear stress is higher than the maximum critical shear stress. This means that main cause of scour is due to the high bed velocity of the falling water besides the associated high turbulence that formed especially in case of weir type-4 [see Fig. 5]. On the other hand and by exploitation of the experimental regard, it is found that in case of weir types-1, 2 and 3 the cause of the scour is mainly due to the high turbulence.
3. MAXIMUM SCOUR DEPTH AND ITS LOCATION

Because the complete protection of hydraulic structures against scour due to flowing water is difficult, the prediction of maximum scour hole depth and its location is important to minimize the risk of failure. In order to investigate the effect of bed shear stress at the end of solid floor on the maximum scour hole depth and its location, Figs. 15 and 16 are drawn as the relations between \( d_s/Y_n \) and \( X_s/Y_n \) against \( \tau_b/\tau_c \) respectively. The figures demonstrate that, the weir type-4 gives larger values of \( d_s/Y_n \) and \( X_s/Y_n \) and weir type-3 gives the minimum ones for same \( \tau_b/\tau_c \). Furthermore, if the value of \( d_s/Y_n \) from Fig. 15 is divided by the corresponding values of \( X_s/Y_n \) from Fig. 16 for same value of \( \tau_b/\tau_c \) it gives the slope of the sides of the scour hole and resulted in flat upstream and downstream slopes of scour hole.

It is important to define the effect of \( Q/\sqrt{gY_n^3.L_w} \) on the maximum scour hole depth and its location behind the solid floor. So, the values of \( d_s/Y_n \) and \( X_s/Y_n \) are plotted against the parameter \( Q/\sqrt{gY_n^3.L_w} \) as shown in Figs. 17 and 18, respectively. Both of the two relationships take straight line for each of weir type. The straight crested weir have larger values of scour hole depth and location than the curved ones. Weir type-3 gives minimum value of scour hole dimensions. The following equations give the correlation of the both relationships:
Fig. 15 Variation of $d_s/Y_n$ with $\tau_b/\tau_c$ for all types of weirs and fine sand.

Fig. 16 Variation of $X_s/Y_n$ with $\tau_b/\tau_c$ for all types of weirs and fine sand.

Fig. 17 Variation of $d_s/Y_n$ with the parameter $Q/\sqrt{gY_n^3L_w}$ for all types of weirs and fine sand.

Fig. 18 Variation of $X_s/Y_n$ with the parameter $Q/\sqrt{gY_n^3L_w}$ for all types of weirs and fine sand.

\[
\frac{d_s}{Y_n} = C_1 \text{Lin} \left( \frac{Q}{\sqrt{gY_n^3L_w}} \right) + C_2
\]

\[
\frac{X_s}{Y_n} = C_3 \text{Lin} \left( \frac{Q}{\sqrt{gY_n^3L_w}} \right) + C_4
\]

where the values of $C_1$ to $C_4$ can be obtained from Table (3).
Table (3). The values of $C_1$ to $C_4$ in Eqs. (10) and (11) respectively.

<table>
<thead>
<tr>
<th>Weir type</th>
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<td>$C_1$</td>
<td>1.3219</td>
<td>1.0098</td>
<td>0.9014</td>
<td>0.7027</td>
<td>1.0125</td>
</tr>
<tr>
<td>$C_2$</td>
<td>2.792</td>
<td>2.2492</td>
<td>1.8736</td>
<td>2.07</td>
<td>2.4019</td>
</tr>
<tr>
<td>$C_3$</td>
<td>4.9204</td>
<td>4.8482</td>
<td>0.9024</td>
<td>5.1703</td>
<td>4.0232</td>
</tr>
<tr>
<td>$C_4$</td>
<td>10.09</td>
<td>10.173</td>
<td>2.3594</td>
<td>13.003</td>
<td>9.1643</td>
</tr>
</tbody>
</table>

The effect of drop downstream of weir type-3 on scour depth and its location behind the floor was experimentally studied for downstream normal flow conditions. The values of $d_s/Y_n$ are plotted against $Q/\sqrt{g Y_n^3 \cdot L_w}$ as shown in Fig. 19. The scour depth ratio $d_s/Y_n$ increases with the increase of the parameter $Q/\sqrt{g Y_n^3 \cdot L_w}$ in a straight line relationship. This means that the increase of drop in the bed downstream increases the scour depth.

![Fig. 19 Variation of $d_s/Y_n$ with the parameter $Q/\sqrt{g Y_n^3 \cdot L_w}$ for weir type-3 at different downstream drops and fine sand.](image)

To investigate the effect of using sills on the scour hole depth and its location downstream of weir type-3, the experimental results of $d_s/Y_n$ and $X_s/Y_n$ with $Q/\sqrt{g Y_n^3 \cdot L_w}$ as shown in Figs. 20 and 21. From Fig. 20 the values of $d_s/Y_n$ increase with the increase of $Q/\sqrt{g Y_n^3 \cdot L_w}$. Also, the use of group of sill-1 decreases the scour hole depth by average value of 67% than for the case without sills, while in case of group of sill-2 the percentage of decrease is 38%. This may due the increase of the intensity of sills for group of sill-1 than that of group of sill-2. The practical selection in this case depends on the economical point of view. The change of downstream water depth from its normal one may happen due to the constriction of any structure across the channel or due to the variation of water consumption. This may lead to a
variation of the hydraulic behavior of flow downstream and consequently on scour. So, the effect of the parameter $Q / \sqrt[3]{gY_n^2 \cdot L_W}$ on scour length and maximum scour depth with a drop in the downstream are shown plotted as in Figs. 22 and 23. This drop gives wide range of changing $y_2$. Figure 22 shows the increase of $L_s/Y_n$ with the increase in $Q / \sqrt[3]{gY_n^2 \cdot L_W}$ values. The rate of this increase is small for small values of $Q / \sqrt[3]{gY_n^2 \cdot L_W}$. Also, the bed drop behind the weir increases the scour length by different values.

Fig. 20 Variation of $d_s/Y_n$ with the parameter $Q / \sqrt[3]{gY_n^2 \cdot L_W}$ for weir type-3 at different downstream sills arrangements and fine sand.

Fig. 21 Variation of $X_s/Y_n$ with the parameter $Q / \sqrt[3]{gY_n^2 \cdot L_W}$ for weir type-3 at different downstream sills arrangements and fine sand.

Fig. 22 Variation of $L_s/Y_2$ with the parameter $Q / \sqrt[3]{gY_n^2 \cdot L_W}$ for weir type -3 at different drops

Fig. 23 Variation of $d_s/Y_2$ with the parameter $Q / \sqrt[3]{gY_n^2 \cdot L_W}$ for weir type -3 at different drops.
The relation between $L_s/y_2$ with $Q / \sqrt{gY_2^3L_w}$ may take the following form:

$$
\frac{L_s}{Y_2} = C_1 \left( \frac{Q}{\sqrt{gY_2^3L_w}} \right)^2 + C_2 \left( \frac{Q}{\sqrt{gY_2^3L_w}} \right) + C_3
$$

(12)

where $C_1$, $C_2$ and $C_3$ are constant depend on $h_d/h_w$ as in Table (4).

<table>
<thead>
<tr>
<th>Drop value</th>
<th>$h_d/h_w = 0$</th>
<th>$h_d/h_w = 0.32$</th>
<th>$h_d/h_w = 0.52$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>598.7</td>
<td>524.84</td>
<td>393.62</td>
</tr>
<tr>
<td>$C_2$</td>
<td>-117.87</td>
<td>-75.224</td>
<td>-39.718</td>
</tr>
<tr>
<td>$C_3$</td>
<td>9.85</td>
<td>6.5653</td>
<td>4.8992</td>
</tr>
</tbody>
</table>

Figure 23 shows a decrease in $d_s/y_2$ with $Q / \sqrt{gY_2^3L_w}$ till a value of $Q / \sqrt{gY_2^3L_w}$ near normal water depth of same discharge, and then $d_s/y_2$ increases with the increase of $Q / \sqrt{gY_2^3L_w}$. The constants in the following relationship show the effect of bed drops:

$$
\frac{d_s}{Y_2} = C_1 \left( \frac{Q}{\sqrt{gY_2^3L_w}} \right)^2 + C_2 \left( \frac{Q}{\sqrt{gY_2^3L_w}} \right) + C_3
$$

(13)

Table (5) shows the effect of bed drop on the constants $C_1$, $C_2$ and $C_3$ of Eq. (13).

<table>
<thead>
<tr>
<th>Drop value</th>
<th>$h_d/h_w = 0$</th>
<th>$h_d/h_w = 0.32$</th>
<th>$h_d/h_w = 0.52$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>23.962</td>
<td>17.36</td>
<td>18.098</td>
</tr>
<tr>
<td>$C_2$</td>
<td>-6.1102</td>
<td>-3.5668</td>
<td>-3.6756</td>
</tr>
<tr>
<td>$C_3$</td>
<td>0.4611</td>
<td>0.2975</td>
<td>0.3105</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The findings from this research can be summarized as follows:

1- In addition to its large capacity for passing discharge, weir type-3 gave minimum scour downstream.
2- Weir type-4 was associated with higher scour downstream more than the other studied weirs.
3- Using sills downstream weir type-3 reduced the scour length by a ratio from 6.1% to 11.9% and the scour hole depth by about 38% to 67% depending on sill arrangements.
4- Increasing the bed drop downstream weir type-3 increases scour behind the weir.
5- Empirical equations defining scour length, maximum scour hole depth and its location with the practical parameters were developed.

REFERENCES


NOTATIONS

\( d_s \)  
Maximum depth of scour,

\( d_{50} \)  
Mean particle diameter of bed material,

\( F_e \)  
Downstream Froude number,

\( g \)  
Acceleration of gravity,

\( L_s \)  
Maximum length of scour,

\( Q \)  
Water discharge over the weir,

\( R_e \)  
Reynolds’ number,

\( V_b \)  
Bed velocity of water at the end of the solid apron,

\( V_2 \)  
Mean velocity of flow in the downstream channel,

\( X_s \)  
Location of maximum depth of scour from the of solid apron,

\( y_1 \)  
Upstream water depth,

\( y_2 \)  
Downstream water depth,

\( y_n \)  
Downstream normal depth,

\( \gamma_s \)  
Specific weight of soil particles,

\( \gamma_w \)  
Specific weight of water,

\( \rho \)  
Water density,

\( \rho_s \)  
Soil particles density,

\( \mu \)  
Dynamic viscosity,

\( \tau_b \)  
Bed shear stress, and;

\( \tau_c \)  
Critical shear stress.