SILL EFFECT ON LOCAL SCOUR DOWNSTREAM GATES

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ABSTRACT

Local scour due to submerged horizontal jet is experimentally studied. This paper also investigates the presence of sill on the apron as energy dissipator and its effect on the value of the maximum scour depth and scour length downstream the apron. A sum of 45 experiments was performed to investigate the effect of gate opening, downstream Froude number, relative length of apron, height of the sill and the distance between the gate and the sill on the formation of local scour downstream the apron. Empirical equations are developed to estimate the maximum scour depth as well as the maximum scour length and head loss due to submerged horizontal jet.

Keywords: Local scour, Energy dissipator, Head loss, Sluice gate- submerged horizontal jet.

Notations

ds	maximum equilibrium scour depth in the presence of sill (cm),
ds_o	maximum equilibrium scour depth without a sill (cm),
d_{50}	sieve opening that passes 50% of the bed material (mm),
$E_{U.S}$	specific energy just upstream the gate (cm),
Fr	Froude number of the downstream channel,
Fr_g	Froude number of the flow through the sluice gate,
g	gravitational acceleration (cm/sec^2),
Hs	Height of the sill (cm),
L_{ap}	Length of the rigid apron (cm),
L_{sp}	distance between the gate and the sill (cm),
L_T	total distance of the submerged jet (cm),
Ls	maximum equilibrium scour length (cm),
T	time required to reach equilibrium stage in minutes,
t	scour time in minutes,
V	average velocity downstream the apron (cm/sec),
V_g	average velocity through the gate (cm/sec),
u	local velocity (cm/sec),
U_{cr}	average critical velocity for the grains forming the bed mixture (cm/sec),
U_m	Maximum local velocity (cm/sec),
x	distance between any arbitrary point and the gate (cm),
X_M	the distance between the maximum quilibrium scour depth and the rigid apron cm),
y	vertical distance from the bed (cm),
$Y_{D.S}$	normal water depth downstream the rigid apron (cm),
Y_g	gate opening (cm),
$Y_{U.S}$	water depth just upstream the gate (cm),
Y_2	sequent depth of the gate opening (cm),
Y_3	water depth just downstream the gate (cm),
δ	thickness of the submerged jet, as shown in Figure (6) (cm),
δ_1	vertical distance between the location of one half the maximum velocity and the bed level (cm) Figure (6),
γ	specific weight of the fluid (gm/cm^3),
γ_s	specific weight of bed material (gm/cm^3),
ρ	density of fluid (gm$_m$/cm^3), and
τ_c	critical shear stress of the bed mixture (gm/cm^2)

INTRODUCTION

Local scour downstream control structures occurs due to diffusing water jets into a larger body of slower flow over a movable bed. The formed local scour undermines the control structure apron that may break the apron causing failure of the whole structure.

Chatterjee and Ghosh [2] studied theoretically and experimentally the velocity distribution over the rigid apron and erodible bed downstream submerged jet. They developed an empirical equation to estimate the velocity distribution at location of maximum scour depth over sand in term of apron length, horizontal distance from the gate, length of the submerged jet, normal downstream depth of flow, gate opening and the afflux of the jet. They also measured the critical shear stress of the sand mixture "τ_c" by considering the shear stress exerted by the flow in the equilibrium scour hole as critical shear stress. Neglecting the effect of bed mixture properties they developed an empirical equation to determine the critical shear stress in term of apron length and gate opening.

Hassan and Narayanan [5] measured the depth and the velocity distribution at the rigid apron and at the scour hole during the development of scour hole till it reaches its equilibrium . They drew the relationship between the maximum scour depth and the time and concluded that the scour depth reaches 75% of the maximum equilibrium scour depth after about 15 minutes and the time required to reach the equilibrium scour hole is about four hours. They also developed an empirical equation to express the variation of the maximum velocity "U_m" along the rigid apron in term of mean velocity through the gate opening, distance from the gate and the gate opening. They concluded that the mean velocity profiles over the rigid apron downstream of the sluice gate is similar to a wall jet modified by the existence of the reverse flow.

Ali Uyumaz [1] studied experimentally scour created when water was passing through a sluice gate and in the case of simultaneous flow over and under the gate. He found that the final depth of scour hole was smaller when there was simultaneous flow over and under the gate, as compared to the case of flow under or over the gate. He obtained from the results of his experiments an empirical equation to estimate the maximum scour depth in term of the unit discharge over under the gate.

Mohammed and McCorquodale [7] did experimental study on short term scour downstream apron. They stated that local scour due to plane horizontal supercritical jets under low tailwater conditions was related to the energy dissipation regime that dominates the flow.

Chatterjee and Ghosh [3] studied the development of local scour downstream gates with time. They obtained empirical expressions to estimate the time required to reach the maximum equilibrium depth and the dimensions of the maximum equilibrium scour hole in term of gate Froude number, median diameter of bed mixture, gate opening and duration of scour process. The effect of the length of the rigid apron and the flow characteristics downstream the gate were neglected in the obtained empirical equations.

Hoffmans and Pilarczyk [6] derived a semi-empirical relationship for the slopes of the upstream face of the scour hole and calibrated it with large number of flume experiments. They found that the slope of the upstream face is a function of the mean grain size distribution, the submerged specific weight of the grain, the relative turbulence intensity, the average velocity and the ratio of the average shear stress to the critical shear stress of the bed mixture. They did not take into consideration the effect of gate opening in their calculation of the slope of the upstream face of the scour hole.

The aim of this study is to investigate the factors affecting the development of the scour hole downstream the apron due to horizontal submerged jet and to examine the effect of sill height and sill spacing from the gate on the value of maximum equilibrium scour depth and length. Also the aim of this study is extended to develop an empirical equation to estimate the dimensions of the equilibrium scour hole in terms of sediment properties, hydraulic conditions and geometry of the apron.

ANALYSIS OF THE PROBLEM

i- *Submerged horizontal jet flows over a plane rigid apron*

If a sluice gate is constructed to regulate a subcritical flow in an Alluvial channel and the gate opening produces a sequent depth less than the downstream normal water depth, a submerged horizontal jet will be created just downstream the gate. The horizontal jet will diffuse in the large body of the flow at distance equals "L_T" as shown in Figure (1).

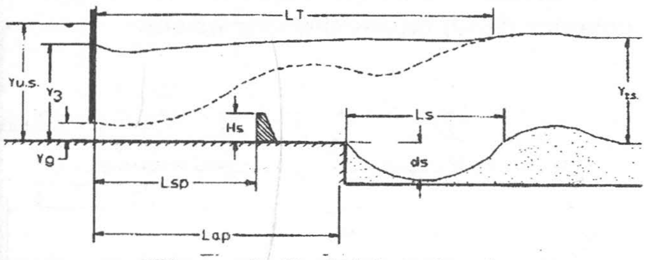

Figure 1. Definition sketch.

If the diffusion length is greater than the length of the rigid apron and the average velocity of the submerged jet just downstream the apron is greater than the critical velocity of the bed material, sediments will be entrained forming a scour hole. The eroded material will be transported in the downstream direction to a place where the sediment load is equal to the sediment transport capacity. The deposited material will form a mound just downstream the scour hole. The volume of the scour hole will increase with time, and consequently the thickness of the jet will be increased. Therefore, the average jet velocity will decrease with time and sequential the rate of erosion will decrease with time till the erosion ceases. At that moment the scour hole reaches equilibrium, where no further erosion will take place. According to the foregoing process, the equilibrium scour depth depends mainly on the characteristics of the submerged jet. The submerged jet is characterized by the length at which the submerged jet is diffused on the flow "L_T", the thickness of the submerged jet "δ" and the vertical velocity distribution of the jet. Rajartnam [8] developed an empirical equation to determine the total length of jet diffusion over a rigid apron and drew the variation of the jet thickness along the rigid apron. Applying the least square method, on the Rajartnam's [8] measurements of jet thickness, the following equation is obtained to estimate the jet thickness along the rigid apron:

$$\frac{\delta}{Y_{D.S}}=6.4732\left(\frac{x}{L_T}\right)^6-16.225\left(\frac{x}{L_T}\right)^5+5.5781\left(\frac{x}{L_T}\right)^3-0.5792\left(\frac{x}{L_T}\right)^2+1.241\left(\frac{x}{L_T}\right)+0.123 \qquad (1)$$

Where x is the distance form the gate and L_T is the length of the submerged jet which can be determined by the following equation:

$$L_T=\left(\frac{4.9(Y_{D.S.}-Y_2)}{Y_2}+6.1\right)Y_2 \qquad (2)$$

In which Y_2 is the sequent depth of the gate opening "Yg". The correlation coefficient of equation (1) equals 0.999. The maximum length of the scour hole can be assumed equals to the difference between the total length of jet diffusion and the length of the rigid apron which can expressed as follows:

$$Ls = L_T - L_{ap} \qquad (3)$$

Since the channel in the uniform flow downstream the apron is stable, it can be assumed that the thickness of the submerged depth over the maximum scour depth equals the downstream normal water depth. Therefore, the maximum scour depth "ds" can assumed equals to the difference between the normal water depth of the flow downstream the apron and the jet thickness downstream the apron. The maximum scour depth can be obtained from the following equation:

$$ds = Y_{D.S} - \delta \qquad (4)$$

In which δ is the jet thickness at $x = L_{ap} + Ls/2$ and can be computed form equation (1).
Experiments are conducted to evaluate equations (3) and (4).

ii- *Submerged horizontal jet flows over a rigid apron having a sill*

When a submerged horizontal jet flows over an apron having a sill and the sill height is less than the jet thickness "δ", the jet thickness just downstream the sill will be increased and consequently the horizontal length of the jet will be decreased. Due to the increase of the thickness of the submerged jet the maximum equilibrium scour depth will be decreased. The thickness of the jet will be influenced by the sill height, the distance between the sill and the gate.

The dimensions of the equilibrium scour hole, which can be described by the maximum equilibrium scour depth and the length of the equilibrium scour hole will have a symbol "ξ", is a function of the properties of sediment forming the bed, the flow characteristics downstream the apron and the geometry of both gate and apron. The properties of sediments can be characterized by the median diameter d_{50} and the critical velocity U_{cr} of the bed mixture. The downstream flow can be described by the downstream depth of flow "Y_{DS}" and the average velocity "V". The geometry of the gate opening and apron will be delineated by the gate opening "Yg", Length of the apron "L_{ap}", height of the sill "Hs" and distance between the sill and the sluice gate "L_{sp}". The maximum depth of scour hole "ds" can described as follows:

$$\xi = f(d_{50}, U_{cr}, Y_{DS}, V, Vg, Yg, L_{ap}, Hs, L_{sp}, g) \quad (5)$$

The application of the π theory on equation (5), leads to the following dimensionless form:

$$\frac{\xi}{d_{50}} = f_1\left(\frac{V}{\sqrt{gY}}, \frac{V_g}{\sqrt{gY_g}}, \frac{L}{Yg}, \frac{V}{U_{cr}}, \frac{Hs}{Yg}, \frac{L_{sp}}{L_{ap}}\right) \quad (6)$$

In order to find a function of equation (6), experiments should be carried out.

EXPERIMENTAL SETUP

In order to study the effect of gate opening and the rate of flow on the formation of equilibrium scour hole downstream a rigid apron, a set of 45 experiments was performed in irrigation and hydraulics laboratory, Faculty of Engineering Alexandria University. The experiments were conducted in a glass walled tilting flume of 12.0 m long and 0.86 m wide. A wooden bed of length 1.0 m, 0.86 m width and 0.25 m height was installed the upstream end of flume as shown in Figure (2). A sluice gate was installed over the wooden bed so that the wooden bed will form a rigid apron having length equals 60 cm. The rest of the channel was filled with sand mixture of thickness 25 cm. The median diameter of the sand mixture equals 0.065 cm and the geometric standard deviation equals 1.65. A weir of height 10 cm was placed at the downstream end of the flume to ensure minimum tailwater depth equals the weir height.

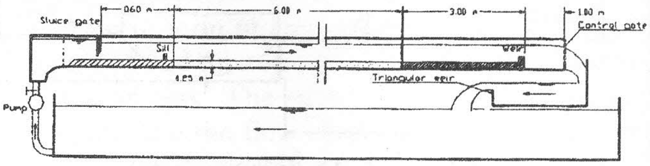

Figure 2. Experimental setup.

The experimental runs were performed to study the formation of scour hole downstream the rigid apron with and without a sill. For the case of plane apron, a set of 24 experiments was conducted to study the effect of Froude number of the downstream flow and gate Froude number on the formation of scour hole. The scheme of these experiments is given in Table (1).

A wooden sill of height equals 10 cm, 1.25 cm thickness and 86 cm length was placed across the flume at distance 10 cm downstream the sluice gate. A set of experiments was conducted to study the effect of gate opening and rate of flow on formation of scour hole. Four sills having height equals 8, 6, 4 and 2 cm and length equals the flume width, were installed at distance equals 10 cm downstream the gate to study the effect of sill height on the formation of scour hole, the details of these experimental runs are given by Table (2). The effect of sill spacing from the gate was studied by performing a set of experiments on the sill of height 2 cm. The spacing of the sill from the gate was 10, 20, 30, 40, 50 and 60 cm. The details of these experiments are also given by Table (2).

For all runs, the sand mixture was leveled to the apron elevation, the reach downstream the gate was gradually filled with water to the weir crest level, then the pump was started and the valve was gradually opened to the desired discharge. The water surface downstream the apron and upstream the sluice gate were measured and the discharge was calculated. The water was left circulating for about six hours at which the scour hole is in equilibrium (i.e. the shape and the dimensions of the scour hole remains constant with time). After draining the flume, the bed elevations along the center line of the scour hole were recorded.

Table 1. Details of the first set of experimental runs and results for no sill.

Run No	Q (L/sec)	$Y_{D.S}$ (cm)	$Y_{U.S}$ (cm)	Yg (cm)	ds (cm)	Ls (cm)
1	7.747	10.30	19	1	1.7	17
2	9.762	11.00	26	1	2.8	18
3	13.894	12.10	42	1	4.8	70
4	7.747	10.80	11	2	0.6	12.5
5	10.366	10.90	13.5	2	1.4	14
6	13.894	11.90	18	2	2.7	22
7	16.312	12.30	22.5	2	6.3	55
8	21.133	13.50	32.5	2	4.3	95
9	8.025	10.80	8.5	3	0.2	2.5
10	13.559	12.10	11.5	3	2.9	25
11	17.388	12.60	14.5	3	4.8	45
12	21.133	13.55	18.5	3	7.8	70
13	26.770	14.5	24.50	3	8.40	110
14	10.366	11.2	8.50	4	0.50	7
15	15.608	12.45	12.50	4	4.00	30
16	21.911	13.3	14.50	4	7.60	50
17	28.460	15.1	20.00	4	8.80	70
18	30.185	15.3	23.00	4	11.00	110
19	12.248	11.7	10.00	5	0.70	20
20	16.668	12.65	10.50	5	2.50	25
21	21.133	13.4	12.50	5	5.20	40
22	26.770	14.45	14.50	5	8.30	60
23	32.388	15.6	17.50	5	9.60	85

ANALYSIS OF THE EXPERIMENTAL RESULTS

The measurements for bed elevations just downstream the rigid apron show that the equilibrium scour hole have always the same shape except for the case when the sill is installed at the downstream end of the rigid apron. The shapes of the local scour for both cases are shown in Figure (3). The occurrence of the sill at the end of the rigid apron will cause separation and back water flow just downstream the sill which may deposit the eroded sediment above the apron elevation as shown in Figure (3).

For the first set of experimental runs when no sill was installed, the dimensions of equilibrium scour depth and length increase with the increase of the discharge for the same gate opening. The relationship between the ratio of gate Froude number to Froude number of the downstream flow "Fr_g/Fr" and the maximum relative equilibrium scour depth "ds/d_{50}" and scour length "Ls/d_{50}" are shown by Figure (4) and (5),respectively. In which the relative scour depth and length increase with the increase of the ratio of "Fr_g/Fr" for constant gate opening. The experimental results show a big discrepancy between the measured results of "Ls" and "ds" with the values obtained from equations (3) and (4). This discrepancy occurs because the length, in which the submerged jet diffuses, decreases with the development of the scour hole and because the horizontal length of the submerged jet determined from equation (1) was developed for only rigid aprons.

Table 2. Details of the second set of experimental runs and results **with a sill.**

Run No.	Q (L/sec)	$Y_{D.S.}$ (cm)	$Y_{U.S.}$ (cm)	Yg (cm)	Hs (cm)	L_{sp} (cm)	ds (cm)	Ls (cm)
24	20.365	14.10	36.50	2	10	10	4.4	35
25	20.748	14.00	27.50	3	10	10	5.3	35
26	21.133	13.85	20.00	4	10	10	5.3	36
27	21.911	14.20	18.00	5	10	10	6.2	50
28	21.133	13.30	15.00	8	10	10	5.3	35
29	21.133	13.70	19.50	4	10	20	6.5	43
30	21.133	13.90	20.00	4	10	30	6.9	50
31	21.133	13.65	20.00	4	10	40	11.2	58
32	21.133	13.40	18.50	4	10	50	14.8	52
33	21.133	13.20	17.50	4	10	60	7.0	75
34	21.133	13.40	19.50	4	8	10	6.3	41
35	21.133	13.30	19.00	4	6	10	6.4	41
36	21.133	13.40	17.50	4	4	10	6.6	43
37	21.133	13.30	17.00	4	2	10	6.3	41
38	21.133	13.60	17.00	4	2	20	3.0	35
39	21.133	13.20	16.00	4	2	30	3.2	58
40	21.133	13.40	16.50	4	2	40	4.4	70
41	21.133	13.35	16.00	4	2	50	3.8	60
42	21.133	13.50	16.00	4	2	60	2.4	46
43	21.133	13.55	17.00	4	2	20	3.3	37
44	21.133	13.40	15.50	4	2	30	2.6	63
45	21.133	13.70	16.50	4	2	10	6.1	39

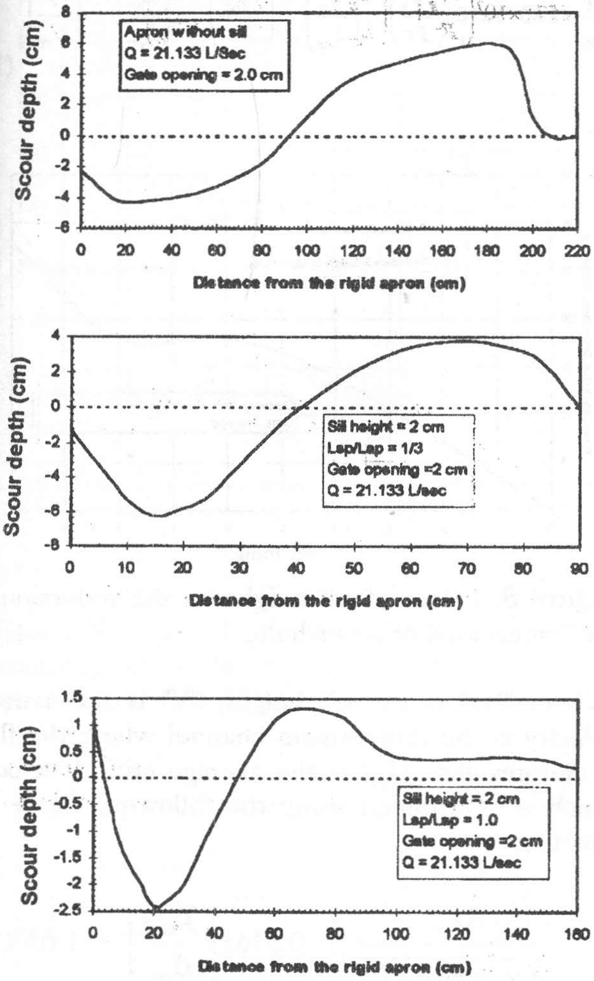

Figure 3. Bed surface profile downstream the rigid apron.

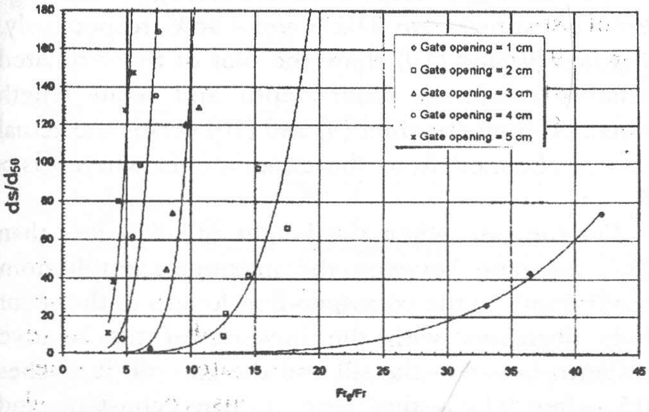

Figure 4. Relationship between the ratio of gate Froude number to Froude number for the flow downstream the apron and the relative maximum scour depth for the case of plane apron.

In the presence of the sill, the experimental results show that for sill having height greater or equals to the vertical distance between the location of one half the maximum local velocity and the bed "δ_1", the sill will behave as a submerged weir. Figure (6) shows a scheme of the vertical velocity distribution of the submerged jet over the rigid apron and the definition sketch of "δ_1". The value of "δ_1" can be determined using Hassan and Nryanan [4] equation which is expressed as follows:

$$\frac{\delta_1}{Y_g} = 0.5 + 0.065\left(\frac{L_{sp}}{Y_g}\right) \tag{7}$$

Where L_{sp} is the horizontal distance between the gate and the sill

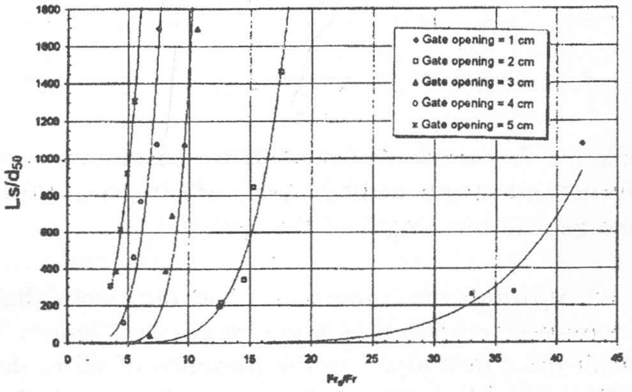

Figure 5. Relationship between the ratio of gate Froude number to Froude number for the flow downstream the apron and the relative maximum scour length for the case of plane apron.

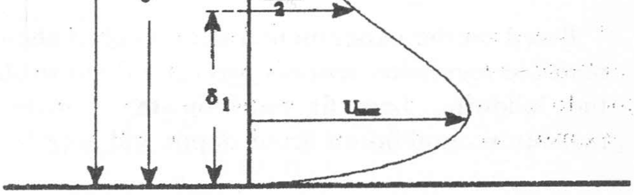

Figure 6. Longitudinal velocity distribution over the rigid apron after Hassan [5].

For the case when the sill height is greater than "δ_1" (submerged weir), the maximum equilibrium depth and length of scour hole increases with the increase of the distance between the sill and the gate (Figure (7)) and its dimensions is greater than that without a sill (Figure 12).

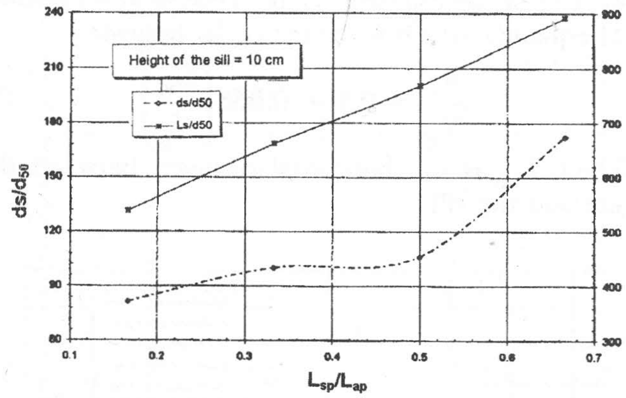

Figure 7. Variation of the relative maximum scour depth and length with the ratio of sill spacing from the gate to the length of the apron.

Comparing the dimensions of the scour hole (maximum equilibrium scour depth and length of scour hole) developed in the presence of sill to that developed without a sill under the same flow conditions, it is found that the presence of sill over the apron reduces the dimensions of the scour hole. Moreover, the increase of sill height reduces the dimensions of scour hole when the sill is located far from the downstream apron edge. Figure (8) shows the effect of sill height on the % reduction on the dimensions of scour hole. The % reduction on the dimensions of scour hole is defined as follows:

$$\textbf{\% reduction of the dimensions of scour hole} = \left(1-\frac{\textbf{Scour hole dimensions produced with a sill}}{\textbf{Scour hole dimensions produced without a sill}}\right)\times 100 \qquad (8)$$

Based on the experimental data, a comprehensive multiple regression analysis was carried out to obtain the following best fit equation to estimate the maximum equilibrium scour depth and length:

$$\frac{ds}{d_{50}} = 1563.13\left(\frac{Fr_g}{Fr}\right)^{1.88}\left(\frac{Y_g}{L_{ap}}\right)^{2.73}\left(\frac{Y_{D.S.}}{Hs}\right)^{0.102}\left(\frac{L_{sp}}{L_{ap}}\right)^{0.46}\left(\frac{V}{U_{cr}}\right)^{6.41} \qquad (9)$$

$$\frac{Ls}{d_{50}} = 1.8575\times 10^{7}\left(\frac{Fr_g}{Fr}\right)^{5.47}\left(\frac{Y_g}{L_{ap}}\right)^{8.16}\left(\frac{Y_{D.S.}}{Hs}\right)^{0.133}\left(\frac{L_{sp}}{L_{ap}}\right)^{0.231}\left(\frac{V}{U_{cr}}\right)^{7.184} \qquad (10)$$

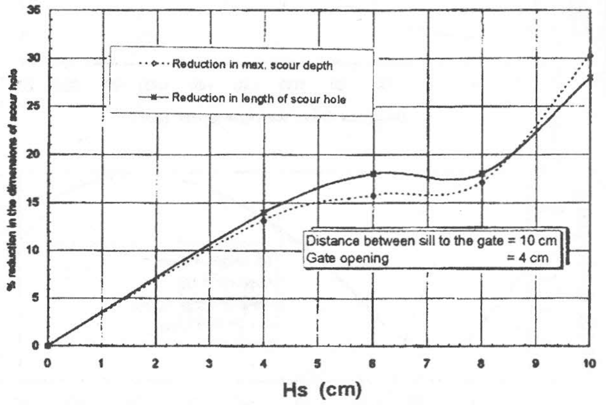

Figure 8. Effect of sill height on the reduction of the dimensions of scour hole.

Where "Hs" is the sill height, "V" is the average velocity at the downstream channel where the flow is uniform and "U_{cr}" is the average critical velocity which is determined using the following Garde [4] equation:

$$\frac{U_{cr}}{\sqrt{(\gamma_s-\gamma)d_{50}/\rho}} = 0.5\log\left(\frac{Y_{D.S}}{d_{50}}\right) + 1.63 \qquad (11)$$

The correlation coefficients for equations (9) and (10) are 0.84 and 0.929, while the average percentage error of estimate are 9.02% and 4.46%, respectively. Figures (9) and (10) show the plot of the estimated relative maximum scour depth and scour length obtained from equation (9) and (10) versus the actual values obtained from the experiments where Hs > δ_1.

For the case when the height of sill is less than "δ_1", the ratio between the maximum equilibrium scour depth to the corresponding length of the scour hole decreases with the increase of the relative distance between the sill and the gate till it reaches 0.5, after which this ratio remains constant and equals about 0.06 as shown by Figure (11).

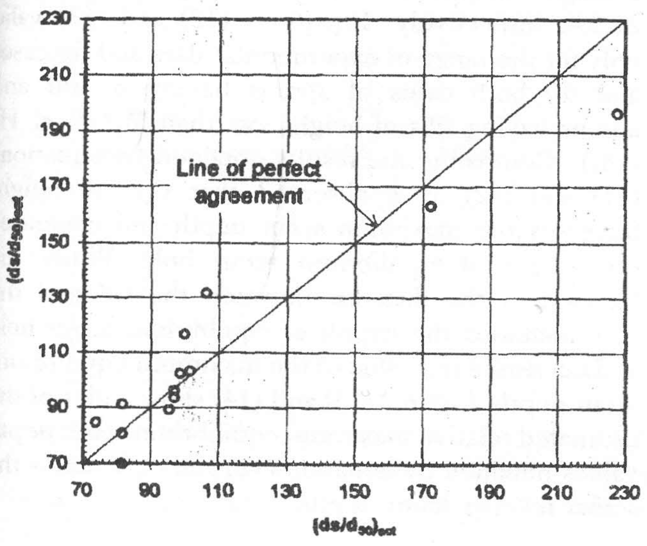

Figure 9. Plot of the actual relative values of maximum scour depth versus that obtained from equation (14) [$Hs>\delta$].

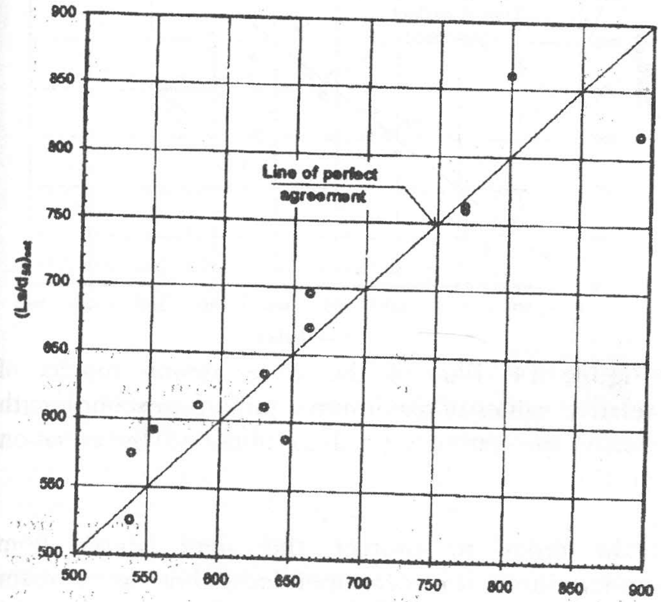

Figure 10. Plate of he actual maximum equilibrium scour length versus that obtained from equation (15) [$Hs>\delta$].

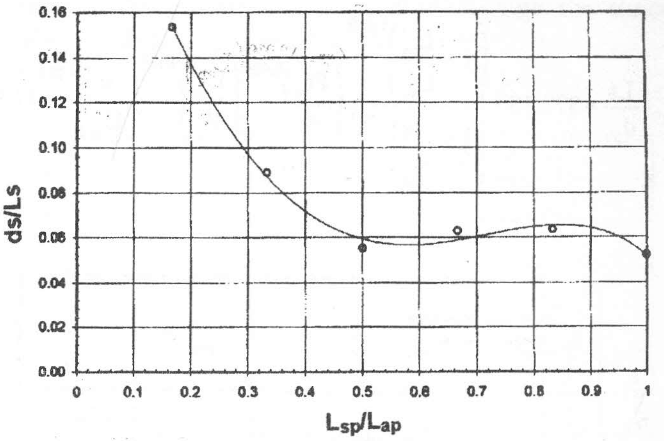

Figure 11. Variation of the ratio between the maximum equilibrium scour depth to scour length with the relative sill spacing from the gate.

Comparing the values of maximum equilibrium scour depth formed downstream aprons having sill with that developed downstream aprons without sill, it was found that for the case when sill height is greater than "δ_1", the maximum scour depth is greater than that occurred without a sill and its value increases with the increase of sill spacing from the gate as shown by Figure (12). While for the case of apron having sill height less than "δ_1" the value of maximum scour depth is less than the maximum equilibrium scour depth occurred for the case of apron having no sill (Figure 12). This phenomenon takes place because the sill increases the thickness of the jet flow and consequently decreases the value of the maximum velocity and its vertical location from the free water surface. Figure (12) shows that influence of sill spacing from the gate on the depth of scour hole is almost constant when the sill spacing is greater than one third the apron length.

Based on the experimental data for the case of plan aprons and the case of aprons having a sill, a multiple regression analysis has been made to derive the following empirical relationship to find the function of equation (4):

$$\frac{d_s}{d_{50}} = 1.04382 \frac{\left(1+\frac{Hs}{Y_g}\right)^{0.389}}{\left(1+\frac{L_{sp}}{L_{ap}}\right)^{1.233}} \left(\frac{Fr}{Fr_g}\right)^{1.781} \left(\frac{L_{ap}}{Y_g}\right)^{3.575} \left(\frac{V}{U_{cr}}\right)^{4.742} \qquad (12)$$

$$\frac{Ls}{d_{50}} = 373.193 \frac{\left(1 + \frac{L_{sp}}{L_{ap}}\right)^{1.256}}{\left(1 + \frac{Hs}{Y_g}\right)^{1.102}} \left(\frac{Fr_g}{Fr}\right)^{0.039} \left(\frac{L_{ap}}{Y_g}\right)^{0.777} \left(\frac{V}{U_{cr}}\right)^{3.293} \quad (13)$$

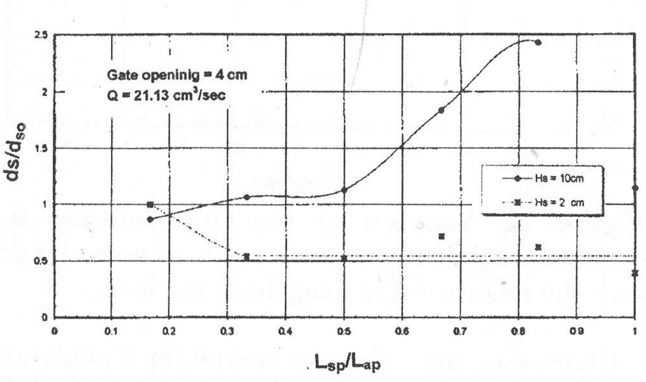

Figure 12. Variation of relative sill spacing with the ratio between maximum scour depth to the corresponding scour depth obtained without a sill under the same hydraulic conditions.

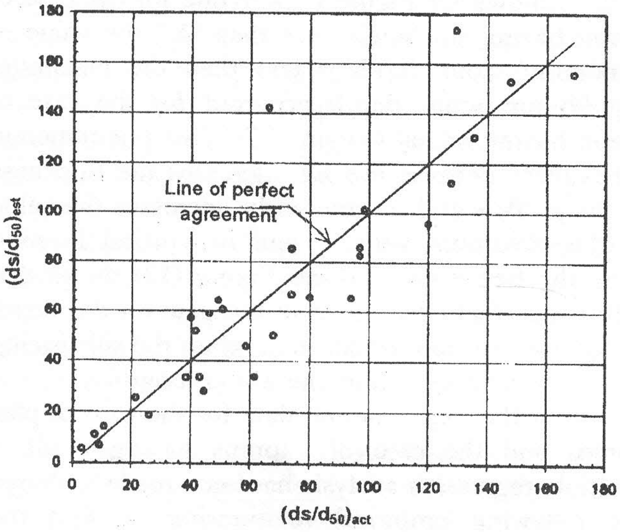

Figure 13. Plot of the experimental results of relative values of maximum equilibrium scour depth versus the estimated values obtained by equation (17).

The correlation coefficients of equation (12) and (13) are 0.93 and 0.98, respectively. The percentage average standard error of estimate are 23.02% and 21.2%, respectively. Equations (12) and (13) valid only for the range of experimental data and for cases and for both cases of aprons having no sill and aprons having sills of height less than "δ_1" ($0 \leq Hs < \delta_1$) . Comparing the results obtained by equations (11) and (12), it is observed that the sill height increases the maximum scour depth and decreases the length of equilibrium scour hole. While the increase of the distance between the sill and the gate increases the length of equilibrium scour hole and decreases the value of the maximum equilibrium scour depth. Figures (13) and (14) show a plot of the estimated relative maximum equilibrium scour depth values obtained by equation (12) and (13) versus the actual relative scour depth.

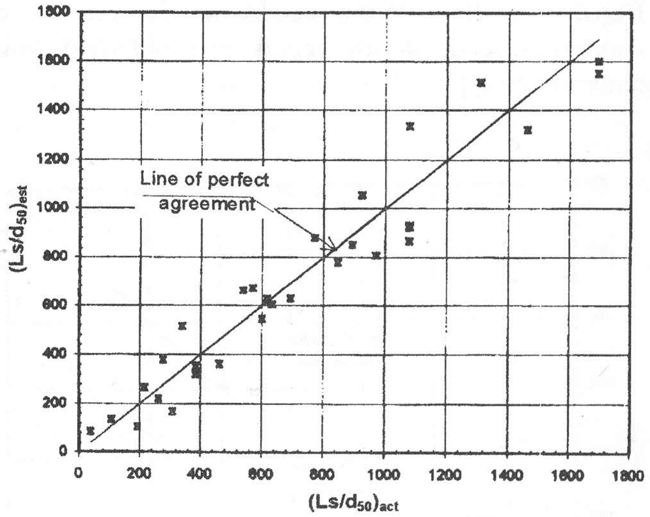

Figure 14. Plot of the experimental results of relative values of maximum equilibrium scour length versus the estimated values obtained by equation (18).

In order to protect the rigid apron from undermining, it is recommended to line downstream the apron to a distance equals or greater than the value of "Ls" obtained from equation (13) or lower the bed just downstream the rigid apron to a value equals "ds" obtained form equation (12) and for a distance equals "Ls".

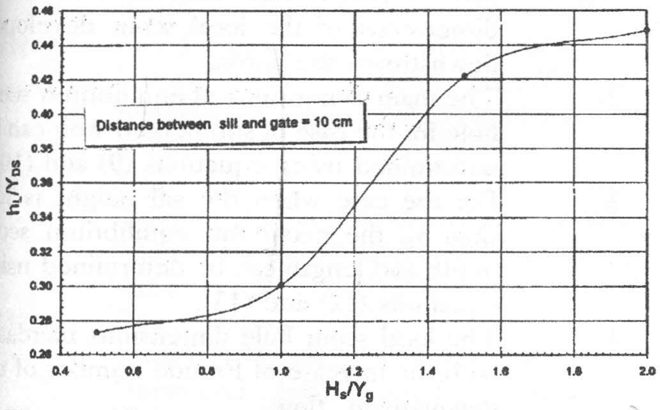

Figure 15. Relationship between the ratio of sill height to gate opening versus the ratio of the loss of energy to the normal water depth downstream the apron.

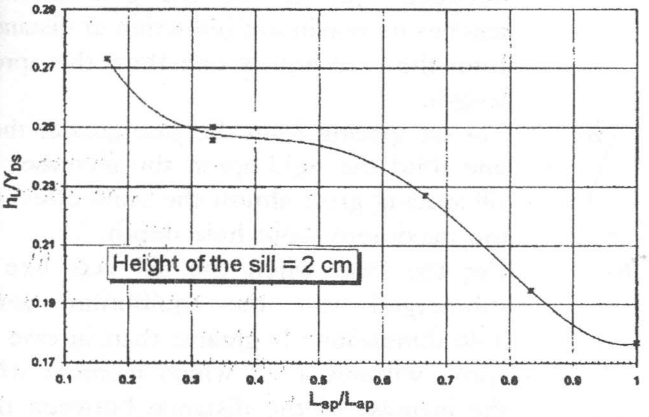

Figure 16. Effect of relative sill spacing "L_{sp}/L_{ap}" on the value of relative head loss "h_L/Y_{DS}".

The head loss between the section just upstream the gate and downstream the apron has been calculated by applying the energy equation between the section just upstream the gate and at section where the water depth downstream the apron is uniform. It was found that the loss of energy increases with the increase of sill height as shown in Figure (15), while it decreases with the increase of the distance between the sill and the gate. Figure (16) shows the effect of increasing the relative distance between the sill and the gate "L_{sp}/L_{ap}" on the relative loss of energy "h_L/Y_{US}". In the presence of sill on the apron, the experimental results show that the loss of energy increases with the decrease of gate opening. The variation of the relative head loss and Froude number for the flow through the sluice gate is shown in Figure (17).

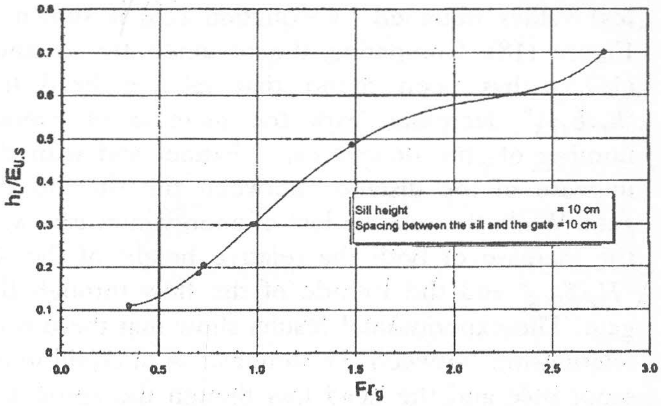

Figure 17. Relationship between Froude number for the flow through the gate versus the ratio between the energy loss through the gate and the apron to the energy just upstream the gate.

All experimental results show that the loss of energy is affected by the average downstream velocity, normal water depth, gate opening, height of the sill and the distance between the sill and the gate. The head loss through the gate and the rigid apron can be expressed as follows:

$$h_L = f_2(Y_{D.S}, V, Y_g, Hs, L_{sp}, L_{ap}, V_g, g, E_{U.S}) \qquad (14)$$

Equation (14) can be expressed in a dimensionless form by applying Buckinghum theory (π- theory) as follows:

$$\frac{h_L}{E_{U.S}} = f_3\left(\frac{Hs}{Y_{D.S}}, Fr, Fr_g, \frac{L_{ap}}{L_{sp}}\right) \qquad (15)$$

Where "E_{US}" is the specific energy just upstream the gate and "V_g" is the velocity of flow through the gate.

Based on the experimental results a multiple regression analysis has been made to obtain the following empirical equation to determine the loss of energy in case of existing a sill:

$$\frac{h_L}{E_{U.S}} = 0.0616\frac{Fr_g^{0.883}}{Fr^{0.838}}\left(\frac{L_{ap}}{L_{sp}}\right)^{0.068}\left(\frac{Hs}{Y_{D.S}}\right)^{0.285} \qquad (16)$$

The correlation coefficient of equation (16) equals 0.981 and the average percentage standard error of estimate equals 8.75%. A plot of the actual relative head loss values versus the estimated relative head loss values obtained by equation (16) is shown in Figure (18). Comparing the obtained by equation (16), it has been found that relative head loss "$h_L/E_{U.S}$" decreases with the increase of Froude number of the downstream channel and with the increase of the distance between the sill and the gate. While the relative loss of energy increases with the increase of both the relative height of the sill "$H_s/Y_{D.S}$" and the Froude of the flow through the gate. The experimental results show that there is no relationship between the dimensions of equilibrium scour hole and the head loss though the apron and the gate.

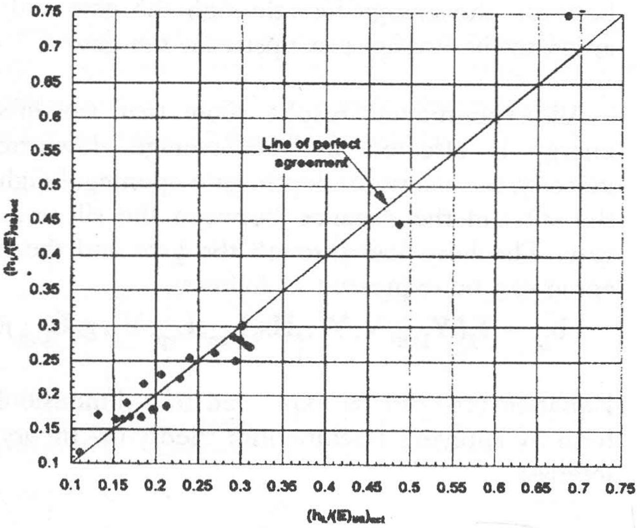

Figure 18. Plot of estimated relative head loss determined from equation (21) versus the actual values obtained from the experimental results.

CONCLUSIONS

Local scour downstream rigid apron created by a submerged horizontal jet is experimentally studied. Based on the analysis of 45 runs, the following are the main conclusions which can be applied for the range of the experimental runs:

1- Sills can be divided into two types according to its height;
  i- sills having height equal or greater than the submerged jet thickness "δ_1" which act as a submerged weir and
  ii- sills of height less than δ_1 reduce the dimensions of the local scour developed downstream the apron.
2- The main dimensions of equilibrium scour hole for the case of submerged weir can be determined using equations (9) and (10).
3- For the case when the sill height is less than δ_1, the maximum equilibrium scour depth and length can be determined using equations (12) and (13).
4- The local scour hole dimensions increases with the increase of Froude number of the downstream flow.
5- For the case when the sill height is less than δ_1 the experiments reveal that;
  i- The maximum equilibrium scour depth decreases with the increase of the distance between the sill and the gate until it reaches its maximum reduction at distance from the gate equals one third the apron length.
  ii- For sill spacing from the gate greater than one third the rigid apron the increase of sill spacing gives almost the same effect on the maximum scour hole depth.
6- For the case when the sill acts like a submerged weir, the equilibrium scour hole dimensions is greater than in case of apron without a sill which increase with the increase of the distance between the sill and the gate and also with the increase of sill height.
7- The presence of sill of height less than "δ_1" develops scour hole less than the corresponding scour hole produced in the case of plane apron.
8- The head loss due to the sill action and the gate can be determined using equation (16).
9- The energy dissipated by the gate and the rigid apron increases with the increase of sill height and with the decrease of the sill spacing from the gate.
10- It is recommended to study in the future the effect of bed roughness and shape of the scour hole on the length of the horizontal jet.

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