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Estimation of the Minimum Floor Length Downstream Regulators under Different Flow Scenarios

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***Abstract*—The correct design of the regulators structure requires complete prediction of the ultimate dimensions of the scour hole profile formed downstream the solid apron. The study of scour downstream regulator is studied either on solid aprons by means of velocity distribution or on movable bed by studying the topography of the scour hole formed in the downstream. In this paper, a new technique was developed to study the scour hole downstream regulators on movable beds. The study was divided into two categories; the first is to find out the sum of the lengths of rigid apron behind the gates in addition to the length of scour hole formed downstream, while the second is to find the minimum length of rigid apron behind the gates to prevent erosion downstream it. The study covers free and submerged hydraulic jump conditions in both symmetrical and asymmetrical under-gated regulations. From the comparison between the studied categories, we found that the minimum length of rigid apron to prevent scour (L_s) is greater than the sum of the lengths of rigid apron and that of scour hole formed behind it ($L+X_s$). On the other hand, the scour hole dimensions in case of submerged hydraulic jump is always greater than free one, also the scour hole dimensions in asymmetrical operation is greater than symmetrical one.

***Keywords*—Movable bed, Regulators, Scour, Symmetrical and asymmetrical operation

I. Introduction

MOST of the existing hydraulic structures such as regulators consist of multi-vents and most of the problems downstream such structures are due to wrong operation of the multi-vents leading to unpredicted velocity distributions which in turn leads to unexpected scour patterns. Due to the existence of piers and abutments as parts of these structures, the flow issuing out of their gates behaves as flow in sudden expanding stilling basins when all gates are working together. Mostly, symmetric flow in sudden expanding stilling basins resulted in symmetric scour downstream of the basin and vice versa [1], [2]. Such scour can be controlled through the use of different energy dissipation tools such as sills, [3], [4]. On the other hand, velocity distribution over rigid bed upstream of the movable bed helps in depicting the nature of scour patterns downstream of the rigid bed. Studies on velocity distribution downstream of single vent regulator may be found in [5]–[8]. Moreover, the submerged flows are the mostly encountered in the field downstream of the control structures such as regulators.

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Many studies are available in the literature about the submerged flow and submerged hydraulic jump characteristics under numerous flow conditions [9]–[15]. Most of these investigations concluded that the length of the roller of submerged hydraulic jump is longer than that of free one; consequently the scour length may be largely extended in case of submerged jump. Attempts to verify these results will be investigated in this study.

The experimental work was carried out under free and submerged hydraulic jumps over a partially rigid apron extended to an erodible bed; also both symmetrical and asymmetrical under-gated operations were taken into consideration to cover all possible cases that may encounter in the field during operation. A new technique was introduced in this paper to study the scour hole dimensions downstream hydraulic structures over movable bed, where all the previous studies on movable bed, predict the scour length by assuming an arbitrary length of rigid apron L, less than the expected scour length, L_s, and they consider that the length of the scour hole L_s, is equal to the length of the rigid floor plus the length of the scour hole formed in the downstream; $L_s = L + X_s$. Actually, this technique gives smaller scour lengths than the actual ones.

This paper solves this problem by extending the arbitrary length of the rigid floor, L repeatedly by same value of the length of the scour hole X_s until no scour hole is allowed to form. For this purpose, three millimeters steel sheets with the same channel width and different lengths according to the length of the scour hole X_s, were used to extend the rigid apron length behind the model of the regulators to prevent the formation of the scour hole. We found that the minimum length of rigid apron to prevent scour L_s is always greater than the sum of the lengths of the arbitrary rigid apron and that of scour hole formed behind it ($L+X_s$) for the same flow conditions. Also the scour hole dimensions is found to be greater in case of submerged hydraulic jump than free one, furthermore the dimensions increase in case of asymmetrical operation than symmetrical one.

II. Dimensional Analysis

In the analysis of the problem of scour downstream regulators, different parameters should be considered. Fig. 1 represents these parameters. L_s : minimum length of rigid apron to prevent scour measured from the gates (no scour hole is allowed), L : arbitrary length of rigid apron behind the gates, X_s : length of scour hole formed downstream the rigid apron having length (L), d_s : maximum scour hole depth, d_{50} : median diameter of the bed material located in the sand basin, g : gravitational acceleration, Q : discharge passed through the gates of the regulators, V_b : bed velocity at the end of the solid floor, S: longitudinal bed slope of the channel, Y_1 : upstream water depth, Y_2 : downstream water depth, μ : absolute viscosity of water, ρ_s : soil particles density, and ρ : water density. Limited variation of this dimensions appear not to have any considerable effect of flow pattern [16], [17]. On the other hand, in case of mild slope, which is the case of the most Egyptian irrigation channels, the channel bed slope has weightless effect on the scour reach downstream of sluice gates [16]. So, in this study the longitudinal bed slope will be kept constant at 0.0001. On the other hand the effect of changing the size of bed material was investigated by many researchers. They concluded that the force exerted by the flow on the sediment particles to be lifted up and move is higher in case of large sediment size than small one, consequently as the particle size increases the scour hole dimensions slightly decreases. So, the bed material size in the sand basin will be kept constant at 0.502 mm.

From the aforementioned presentation, the geometry of the scour hole represented by L_s or $(L + X_s)$, and d_s, may depend upon the other remaining parameters as follows:

$$L_s or (L + X_s) or d_s = \phi_1(Y_1, Y_2, Q, V_b, \rho, \mu, g) \tag{1}$$

Using π – Theorem, it yields;

$$\frac{L_s}{Y_2} or \frac{(L + X_s)}{Y_2} or \frac{d_s}{Y_2} = \phi_2\left(\frac{Y_1}{Y_2}, \frac{V_b^2}{gY_2}, \frac{\rho V_b Y_2}{\mu}, \frac{Q}{Y_2^2 V_b}\right) \tag{2}$$

$$\frac{L_s}{Y_2} or \frac{(L + X_s)}{Y_2} or \frac{d_s}{Y_2} = \phi_3\left(\frac{H}{Y_2}, F_e, R_e, \tau^*\right) \tag{3}$$

in which H, is the working head defined as the difference between the upstream and downstream water levels (Y_1-Y_2), V_b^2 / gY_2, is the Froude number, $\rho V_b Y_2 / \mu$, is the Reynolds' number, $\tau^* = \tau_b / \tau_c$ is the normalized bed shear stress, τ_b, is the bed shear stress calculated at the separation point between the solid floor and the sand basin, it may be given as [16]:

$$\tau_b = \rho f V_b^2 / 8 \tag{4}$$

in which f is the friction coefficient obtained from the following formula [16];

$$\frac{1}{\sqrt{f}} = 2.00 \log\left(\frac{12.6 Y_2}{d_{50}}\right) \tag{5}$$

and τ_c, is the critical shear stress obtained from shields' diagram [18], it may be calculated from the following formula:

$$\tau_c = (\gamma_s - \gamma_w) \varepsilon d_{50} \tag{6}$$

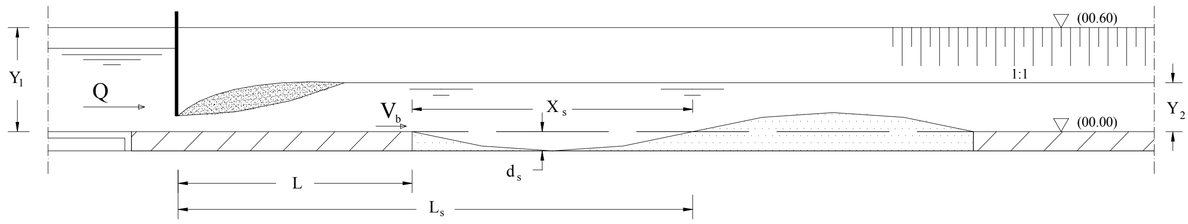

Fig. 1 Definition sketch showing the geometry of the scour hole and the different parameters considered in this study.

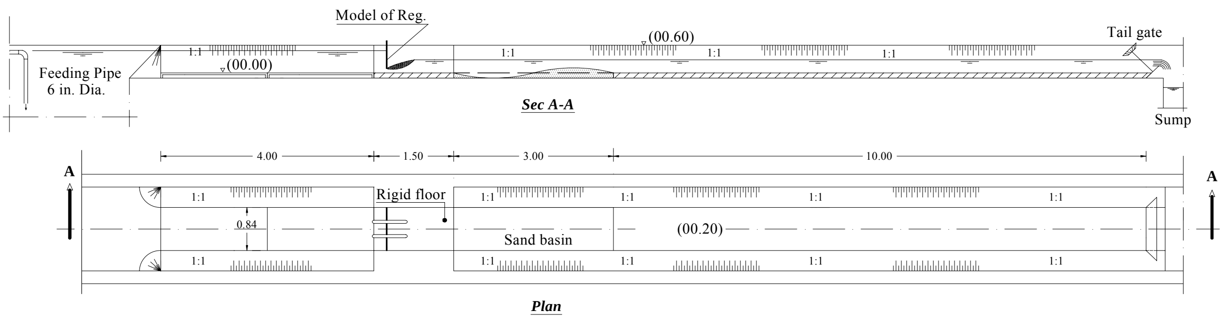

Fig. 2 Different parts of the experimental channel

where γ_s, and γ_w, are the specific weights of soil particles in the sand basin, and water respectively, and ε, is a parameter ranges from 0.04 to 0.1 [18].

In free surface model studies, the viscous force does not affect the flow field, and therefore R_e, in (3) may be dropped [19], [20]. In open channel flow, [21] found that the gravity starts to affect the flow resistance when F_e equals to 2.49.

Reference [22] revealed that the importance of Froude number appears only when roll waves develop to form a state of unstable flow. Hence, (3) reduces to;

$$\frac{L_s}{Y_2} or \frac{(L + X_s)}{Y_2} or \frac{d_s}{Y_2} = \phi_4\left(\frac{H}{Y_2}, \tau^*\right) \tag{7}$$

III. Materials And Methods

A. Channel

The investigations reported herein were conducted in a sloped-bed channel of trapezoidal cross section as shown in Fig. 2. Generally the channel has a bed width of 0.84 m, and a depth of 0.6 m. It consists of four parts, the first part is trapezoidal with side slope 1:1 and total length of 4.00m, the second part is rectangular which has a length of 1.50 m. This part is the testing section in which the model of regulators was fastened in it. The third part is trapezoidal with side slopes 1:1 and length of 3.00 m. In this part sand with 0.502 mm diameter was placed with a depth of 20 cm. The fourth part has a trapezoidal cross section with side slopes 1:1 and a sufficient length of 10.00 m to create a uniform flow in the downstream. The uniform water flow depth could be adapted by means of a tailgate installed at the channel end. 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.

B. Model

Three sluice gates and two intermediate piers were formed a model of three-vents regulator as shown in Fig. 2. Each gate has 0.24 m width, 0.60 m height and 6 mm thickness with sharp edge. The pier is 60 mm in width, 0.60 m total length, 0.38 m of them behind the gates and it has two 7x8 mm groves to hold the gates in a vertical position. The gates can be lifted and lowered to give the desired under-gated opening height that permits to form free or submerged hydraulic jump conditions on the solid bed.

C. Experimental Method

The experimental work was divided into two categories:

i. First category: In this category, the experiments were performed to determine the total length of the scour hole as the previous studies whereas, the length of the scour hole is equal to the sum of the arbitrary length of the solid floor and the length of scour hole formed behind the regulator ($L+X_s$). The experimental procedures were as follows:

1- The three gates were lifted up to give a certain opening-height, h (case of symmetrical regulation).
2- The downstream portion of the channel was filled with water to a certain limit.
3- The run was started with low flow rate, and then gradually increased to the required one.
4- The downstream water depth was adjusted by the tail gate till the formation of free hydraulic jump just behind the gates and between the piers (case of free jump) or the formation of a submerged hydraulic jump between the piers (case of submerged jump) with maximum upstream water depth (Y_1) not more than 2.2 times the downstream water depth (Y_2) [23].
5- After 4 hours run time [24], the water depths upstream (Y_1) and downstream the gates (Y_2), the discharge (Q), the gate opening height (h) and the velocity near the bed at the end of rigid floor were recorded. Then the flow was stopped and the scour hole length (X_s) and its depth (d_s) were measured.
6- The gates opening or the discharge was changed and the procedures from 1 to 5 were repeated.
7- For asymmetric flow, the left hand side vent of the model of the regulator was closed and the same procedures from 1 to 6 were repeated.

ii. Second category: In this category, tests were performed to find out the minimum scour length where no tail erosion is encountered on the erodible basin. Three millimeters steel sheets with 0.84 m wide and different lengths were used to extend the rigid apron length behind the model of the regulator as shown in Fig. 3.

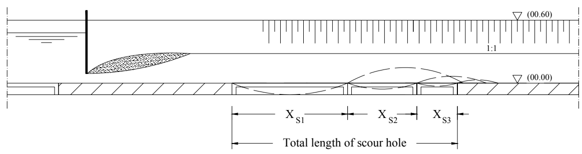

Fig. 3 Definition sketch showing the technique used to extend the rigid floor to prevent the formation of the scour hole

The total length of the scour hole in this case is as follows:

$$L_s = L + \sum_{k=1}^{n} X_s \tag{8}$$

where L is the length of the rigid floor, and the term $\sum_{k=1}^{n} X_s$, represents the summation of all possible lengths that can be added to the arbitrary length of the rigid floor to prevent scour. The test procedures in this case were as follows:

1- In symmetrical case and for both the formation of free or submerged hydraulic jump downstream the gates of the regulator, the gates opening (h), discharge (Q), downstream water depth (Y_2) and consequently upstream water depth (Y_1) were chosen.
2- The rigid apron length behind the model was extended gradually; the recorded erosion rate was decreasing till there was no erosion encountered. Then, the minimum length of rigid apron measured from the end of the gates to the beginning of the erodible bed (L_s) was recorded to the nearest 10 mm. At this moment the velocity near the bed at the end of rigid apron was measured.
3- The gates opening or the discharge was changed, and then steps 1 and 2 were repeated.
4- For case of asymmetrical under-gated regulation, the left hand side vent of the model of the regulator was closed and same procedures from 1 to 3 were repeated.

IV. Application And Discussion Of Results

Most investigations on local scour of alluvial channels near rigid aprons were based upon examination of topography of scour holes produced by different hydraulic conditions [25]–[28].

In the present study, another approach is considered, where the scour reach will be represented by both the minimum floor length (L_s) to prevent scour behind the model of three vents regulator or by the summation of an arbitrary length ($L < L_s$) besides the length of scour hole formed behind it (X_s). For this reason the analysis of the scour length in the following sections will be represented either by L_s or by ($L + X_s$).

Fig. 4 indicates the relationship between the dimensionless head difference, H/Y_2, and the dimensionless scour length L_s/Y_2 or $(L+X_s)/Y_2$ for the free and submerged cases.

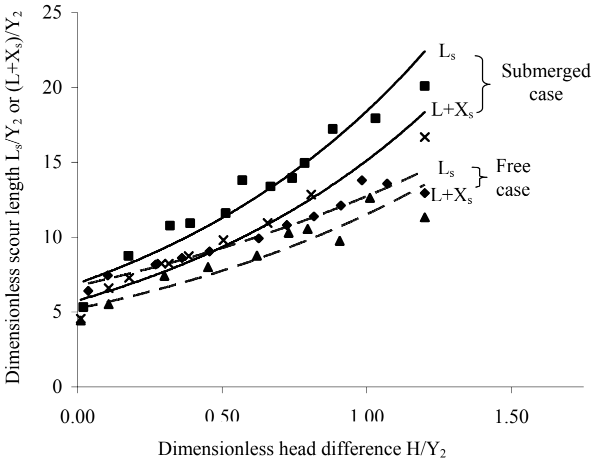

Fig. 4 Variation of L_s/Y_2 or $(L+X_s)/Y_2$ with H/Y_2 for free and submerged under-gated regulations (symmetrical case)

It is clear that the submerged scour length L_s/Y_2 or $(L+X_s)/Y_2$ is always greater than the free one. These results are in agreement of other researchers who concluded that the length of the rollers of submerged hydraulic jump is longer than that of free one and as a result, the produced scour length in case of submerged hydraulic jump is greater than the length of free one [9], [26], [29].

One of the famous formulas to predict scour length downstream control structures such as regulators based on the acting head is the Bligh's formula [30].

$$L_s = C\sqrt{H} \tag{9}$$

where L_s is the floor length behind the piers of regulator to prevent scour, H is the maximum working head difference between upstream and downstream water levels, and C is a parameter depending of the bed materials (takes the values from 8-10 for silt, and sand range). For this reason we will derive some relationships from this study to predict scour length based on the acting head. The relation between the scour length L_s/Y_2 or $(L+X_s)/Y_2$, and the acting head H/Y_2, is given in the following forms (symmetrical free or submerged case):

In case of submerged hydraulic jump:

$$L_s/Y_2 = 6.92\exp^{0.98(H/Y_2)} \tag{10}$$

$$(L+X_s)/Y_2 = 5.77\exp^{0.96(H/Y_2)} \tag{11}$$

In case of free hydraulic jump:

$$L_s/Y_2 = 6.76\exp^{0.63(H/Y_2)} \tag{12}$$

$$(L+X_s)/Y_2 = 5.22\exp^{0.79(H/Y_2)} \tag{13}$$

One can distinguish that, the submerged scour length is always greater than the free one. On the other hand the scour length L_s with no scour hole allowed is always greater than the sum of the arbitrary length of the rigid floor plus the length of the scour hole ($L+X_s$). From the authors point of view, the main cause of increasing the scour hole L_s in comparison to the other scour length ($L+X_s$), is that the scour hole formed in the second case have a slightly stable slopes and in return this slope is largely enough to permit any excessive sediments to transport from the scour hole. On the other hand if the scour hole is filled or covered with a solid bed, scour starting again, but the scour hole dimensions in that case is observed to be less than the previous case. This process was repeated different times until no scour hole is noticed as shown in Fig. 3.

From this point it is recommended for practical purposes, to increase the scour length obtained from the examination of the topography of the erodible bed by the previous studies with an average value of 7.50%, and 23% in case of free and submerged cases respectively.

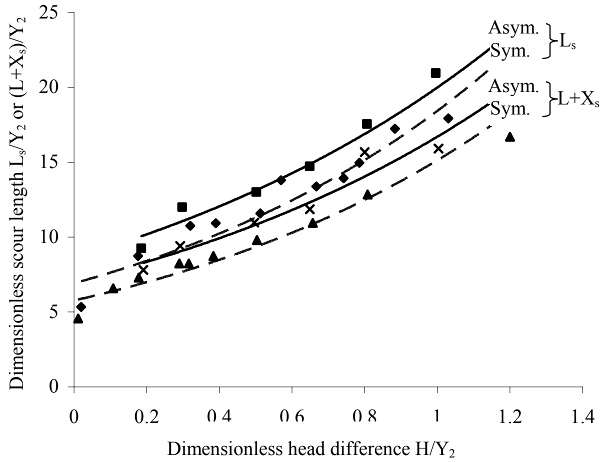

Fig. 5 Variation of L_s/Y_2 or $(L+X_s)/Y_2$ with H/Y_2 for symmetrical and asymmetrical under-gated regulations (submerged case)

Also the relationship between the dimensionless head difference, H/Y_2, and the dimensionless scour length L_s/Y_2 or $(L+X_s)/Y_2$ in case of symmetrical and asymmetrical under-gated submerged regulation is shown plotted in Fig. 5.

We can verify that the scour length generated in case of asymmetrical under-gated regulation is always greater than that of symmetrical one. The correlation of L_s/Y_2 or $(L+X_s)/Y_2$ and the acting head H/Y_2, is given in the following forms (Submerged asymmetrical case):

$$L_s/Y_2 = 8.69\exp^{0.83(H/Y_2)} \tag{14}$$

$$(L+X_s)/Y_2 = 7.04\exp^{0.88(H/Y_2)} \tag{15}$$

Comparing (10), and (14) it is important to increase the submerged scour length obtained in case of symmetrical under-gated regulation by an average value of 5% to cover the unexpected asymmetrical operation.

In order to investigate the relationship between the shear stress and the bed motion of soil particles found in sand basin downstream of the regulators, the relative values of scour length L_s/Y_2 were plotted against the relative values of bed shear stress (τ_b / τ_c) as shown in Fig. 6. The data are scattered without any trend or notable relation.

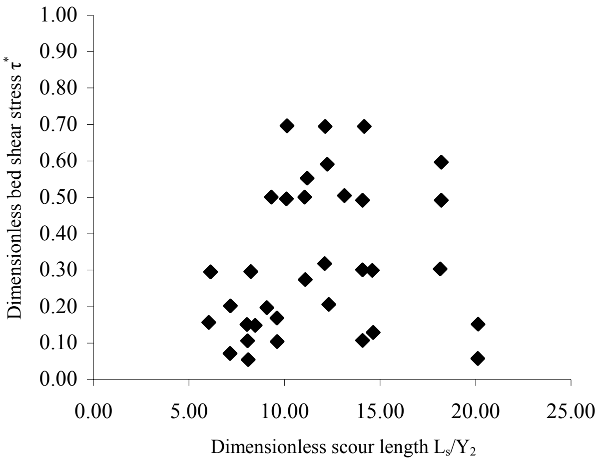

Fig. 6 Variation of L_s/Y_2 with the values of τ^*

The values of (τ_b / τ_c) do not exceed the unity. This confirms that no bed motion of the solid particles due to the flow movement over the erodible materials found in the sand basin behind the rigid floor of length (L_s). So L_s is considered the minimum length of rigid floor behind the gates of the regulators to prevent scour.

On the other hand, plotted in Fig. 7 the relation between the dimensionless scour depth (d_s/Y_2) and the dimensionless bed shear stress τ^* in case of an arbitrary length (L) of the rigid floor.

As shown, the scour hole depth depends on the bed shear stress and the values of τ^* are always greater than unity. This means that the bed shear stress due to the flow motion is greater than the critical one for moving the soil particles in the sand basin behind the arbitrary length (L) of the rigid floor. The relation between the dimensionless scour depth and the dimensionless bed shear stress is given in the following form

$$L_s / Y_2 = 0.22 \exp^{0.31\tau^*} \qquad (16)$$

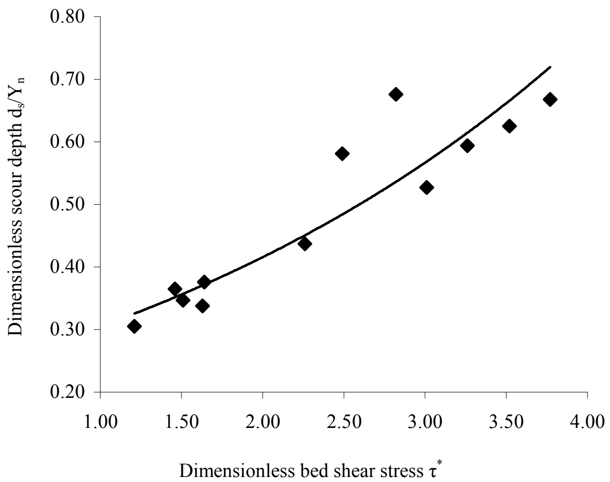

Fig. 7 Influence of bed shear stress on the scour hole depth formed downstream rigid floor having length (L).

In practice, flow downstream regulators may be asymmetric under-gated regulation when: 1) One or many vents are working while the adjacent are closed because of periodic maintenance. 2) There is a lock besides the regulator for navigation purposes. From this point it is essential to investigate the effect of asymmetrical regulation on the scour reach downstream regulators. The left hand side vent of the model was closed completely while the others were working. Shown in Fig[s]. 8 and 9 are the plotting of the contour lines of the developed scour hole for both symmetrical and asymmetrical regulations respectively.

Keeping the ratio H/Y_2, the discharge, Q and the floor length, L constant, it is seen that for asymmetrical regulation the scour hole depth and length are greater than those measured for symmetrical regulation. Also, the soil particles are accumulated forming a hill downstream of the closed gates. This may due to the increase of the amount of turbulence with the formed reverse currents.

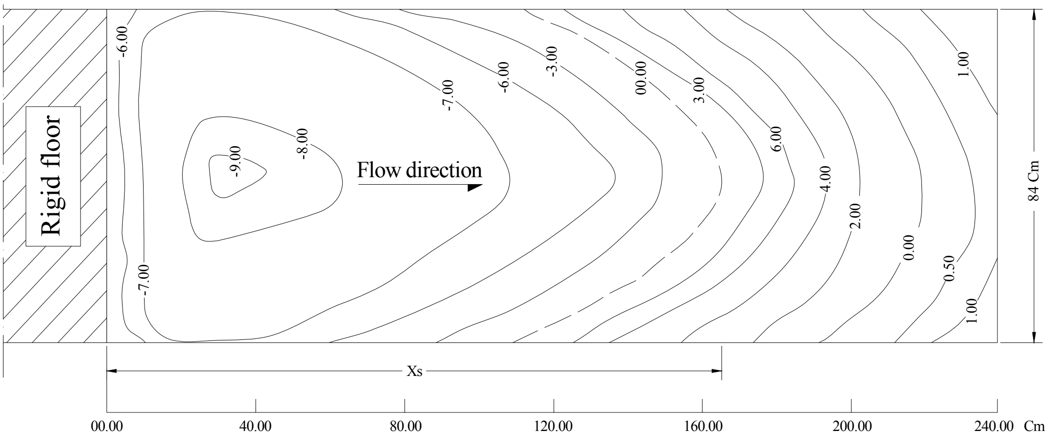

Fig. 8 Contour lines of the movable bed showing the scour hole profile behind the rigid floor of length, L = 0.60 m for symmetrical under-gated regulation (H = 0.16 m, Q = 21 Lit./s and h_g =32mm)

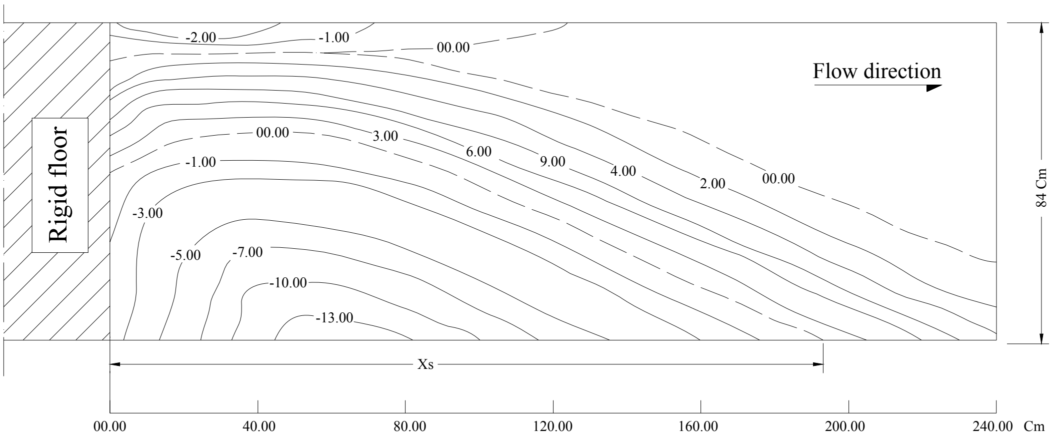

Fig. 9 Contour lines of the movable bed showing the scour hole profile behind rigid floor of length, L = 0.60 m for asymmetrical under-gated regulation (H = 0.16, Q = 21 Lit./s and h_g =43mm)

V. Comparison between the Results Obtained from this Study and other Studies

Moreover the present results on (L_s) are depicted in Fig. 10 showing the variation of (L_s/Y_2) against (H/Y_2) with the predicted results of El-Dardeer [31]. Apparently, the scour length obtained from the movable bed presented herein is found to be about 3.6 times that predicted from the velocity distribution method presented by [31]. This means that the erosion depends on the amount of turbulence which is not represented by the direct measurements of the velocity distributions. Also shown in Fig. 8 the existing scour lengths for six barrages found on the River Nile designed previously.

These data are quoted from Ali [16]. The scour reaches of Assiut and old Esna barrages have been taken after the recent remodeling of these structures for the protection against the tail erosion noticed downstream of the rigid floor [16]. It is seen that present results on L_s are in agreement with the existing ones for the mentioned structures.

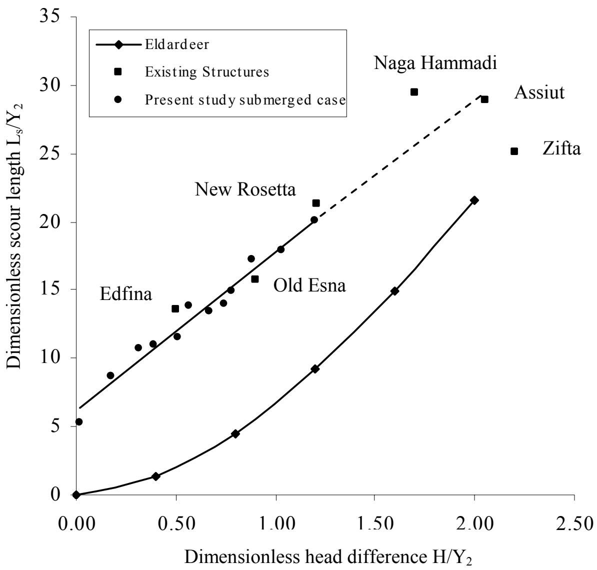

Fig. 10 Comparison between L_s predicted from the present study, velocity distribution [31] and that found at existing structures [16] for symmetrical under-gated regulation

VI. Conclusion

Accurate predictions of scour depth and length downstream control structures such as regulators are essential for the stability of structure. This article has introduced the problem of scour downstream regulators using experimental point of view. Furthermore, the study of local scour downstream control works was investigated either by study the velocity distribution over a solid bed or by the examination of topography of scour holes produced by different hydraulic conditions. This research introduces a new technique for studying the scour hole over movable bed, where the scour hole was examined either by the minimum length of scour, L_s where no scour hole is allowed or by the total length of the rigid floor, L plus the length of the scour hole X_s, formed downstream the rigid floor, ($L+X_s$). The study was performed under different flow scenarios, where free, submerged, symmetrical, and asymmetrical conditions have been examined to try to cover all possible cases that might occur in the field. The following conclusions could be derived from this research:

1- Scour hole dimensions increase in case of submerged under-gated regulations in comparison to free case.
2- The minimum scour hole length, L_s with no scour hole allowed is found to be longer than the length of arbitrary length of rigid floor, L plus the length of the scour hole X_s, formed downstream the rigid floor, ($L+X_s$).
3- Asymmetrical under-gated regulation is not recommended as a working regulation otherwise its effect must be taken into consideration during design process.

SYMBOLES

The following symbols are used in this paper

d_s: Maximum scour depth,
d_{50}: Mean particle diameter of bed material,
f : Friction coefficient,
F_e: Froude number,
g :Acceleration of gravity,
H: Head difference between upstream and downstream water levels,
L: Arbitrary length of rigid apron behind the gates ($L<L_s$),
Ls: Minimum length of rigid apron behind the gates to prevent scour,
Q: Water flow rate,
R_e: Reynolds' number,
S: Longitudinal bed slope,
V_b: Velocity of flow at the end of the solid apron,
X_s: Length of scour hole,
Y_1: Upstream water depth,
Y_2: Downstream water depth,
γ_s :Specific weight of soil particles,
γ_w :Specific weight of water,
ε : Parameter,
μ :Dynamic viscosity,
ρ :Water density,
ρ_s :Soil particles density,
τ_b :Bed shear stress, and;
τ_c :Critical shear stress.

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