

EVALUATION OF LOCAL SCOUR DEVELOPMENT DOWNSTREAM AN APRON OF DIFFERENT ANGLES FOR AN OGEE SPILLWAY

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ABSTRACT

Local scour downstream of hydraulic structures, such as low head and high head structures, spillways, and culverts is an important research field due to its significant practical value. In this study laboratory experiments were conducted to compute the local scour downstream apron of an ogee spillway under different slopes of apron to study its effect on the characteristics of the scour. Developed physical models for spillway and aprons are installed into the water in the channel where conducted under subcritical flow and clear-water condition by using uniform cohesionless (soil) as bed material with a medium grain size ($d_{50} = 0.65$ mm).

Four angles of an apron were used $(0^{\circ}, 2.73^{\circ}, 5.19^{\circ}, \text{ and } 7.43^{\circ})$ to show the effect of the slope for apron on local scour. It is found that the slope of an apron is one of the important parameter to reduce the local scour depth and the extent of scour hole. The influence of slope for aprons angle showed a reduction of about (53, 46, and 35) % in the maximum scour depth and about (33, 49, and 33) % in the maximum scour length compared with horizontal apron for angles (2.73°, 5.19°, and 7.43°), respectively.

KEYWORDS: Spillway; Apron; Local scour

الخلاصة

الانجراف الموقعي لمؤخر المنشآت الهيدروليكية مثل المنشآت ذات الارتفاع الواطئ والمرتفع والمطافح المائية والعبارات هو من البحوث الحقلية المهمة نتيجة لقيمته العملية الهامة. تم في هذا البحث اجراء تجارب مختبرية لحساب الانجراف الموقعي في مؤخر أرضية المسيل المائي بأستخدام ميول مختلفة للأرضية ودراسة تأثير ذلك على خصائص الأنجراف. استخدمت نماذج مادية للمسيل المائي والارضيات وثبتت في المجرى المائي للقناة المختبرية تحت ظروف الجريان الخالي من حمل الرسوبيات (CLEAR-WATER CONDITION) ، وباستخدام تربة رامية وغير متماسكة كمادة للقاع حيث كان متوسط حجم الحبيبات (D₅₀=0.65).

استخدمت اربع زوايا للارضية (0° و 2,73° و 5,19° و7,43°) لدراسة تأثير ميل الارضية على الانجراف الموقعي. وجد ان ميل الارضية واحدة من العوامل المهمة لتقليل عمق الانجراف الموقعي وامتداده الطولي. ان تأثير زاوية ميل الأرضية اظهر نقصان حوالي (53 و 46 و 35) % بالنسبة لعمق الانجراف الاعظم وحوالي (33 و 49 و 33)% بالنسبة لطول الانجراف الاعظم بالمقارنة مع الارضية الافقية للزوايا (2.73° و 5.15° و 7.43°) على التوالي.

1. INTRODUCTION

The ogee spillway, which is also known as overflow or S-shaped spillway, is the most common type of spillways that is used to release water from a dam or levee reservoirs and other hydraulic structures to the downstream channels. Water flowing over an ogee spillway crest always remains in contact with spillway surface as it smoothly flows to the downstream. Water flowing over an ogee spillway contains a high kinetic energy that can cause erosion at its end and leads to dam and other hydraulic structures failure. Therefore, stilling basins of different designs are used to dissipate the energy of the flowing water and establish safe flow conditions to protect the downstream end of the spillway from erosion. These basins are usually equipped with a combination of chute blocks, baffle blocks, and end sills in order to stabilize, reduce the length of the hydraulic jump, and improve its performance (Khlif, 2013). Local scour phenomena are difficult to be treated theoretically because of the complexity of its dynamics. Consequently, experimental studies play a major rule in attributing the scour features (depth, length, shape, and time development) to the hydraulic and sediment variable (Othman, 2007). Most of the conducted studies on scour are empirical studies due to complexity of the physical processes. Novak (1955) expressed the scour depth downstream of hydraulic jump basins as determined from model experiments of relatively low head structures with coarse sand and limited field. Higss (1995) studied the spillway apron length at the existing elevation that would retain the hydraulic jump for various flows. A laboratory work to examine the similarity of the development of scour profiles, the controlling scour mechanism and predictions of the scour geometry downstream spillway was studied by Dargahi (2003). Othman (2007) presented an experimental investigation on the problem of local scour downstream ogee spillway by using two types of non-cohesive bed materials. A hydraulic model of Namrood dam to estimate stone size that is able to resist scouring as result of basin turbulent outlet flow was made by Taebi and Fathi (2009). Oliveto and Comuniello (2011) conducted a laboratory experiments on local scour downstream of low-head stilling basins to highlight end sill effects on the scour morphology.

The studies of the aforementioned investigators have made important contributions to the knowledge of the phenomena of local scour downstream of hydraulic structures in the relevant flow situations. The aim of the present research is focusing on evaluation of the depth and extent of local scour downstream from an Ogee spillway under different angles of apron and hydraulic conditions and to find out empirical equations to predict the depth and extent of this scour.

2. DIMENSIONAL ANALYSIS

For clear water approach flow conditions, the maximum scour depth (D_S) and the total length of scour (L_t) at downstream of an apron may be considered as a function of the following parameters as shown in Eqs. (1) and (2):

$$(D_{s})=f\{y_{t}, v, v_{c}, \rho, \rho_{s}, g, \Theta, d_{50}, \mu, \sigma_{g}, H_{d}, S_{o}\}$$
(1)

$$(\mathbf{L}_{t}) = \mathbf{f} \{ \mathbf{y}_{t}, \mathbf{v}, \mathbf{v}_{c}, \boldsymbol{\rho}, \boldsymbol{\rho}_{s}, \mathbf{g}, \boldsymbol{\Theta}, \mathbf{d}_{50}, \boldsymbol{\mu}, \boldsymbol{\sigma}_{g}, \mathbf{H}_{d}, \mathbf{S}_{o} \}$$
(2)

Where: y_t =tail water depth, v=mean approach flow velocity, v_c =critical velocity, ρ =density of fluid, ρ_s =density of the sediment, g=gravitational acceleration, Θ =angle of apron, d_{50} =medium particle grain size, μ =dynamic viscosity of fluid, σ_g =geometric standard deviation, H_d=water head above the crest of spillway and S₀=slope of the channel. Using non-dimensional analysis, Eqs. (1) and (2) can be written as:

$$\frac{Ds}{vt} = f(v/v_c, \rho_s/\rho, Fr, \Theta, d_{50}/y_t, Re, \sigma_g, H_d/y_t, S_o)$$
(3)

$$Lt/v_{t} = f(v/v_{c}, \rho_{s}/\rho, Fr, \Theta, d_{50}/y_{t}, Re, \sigma_{g}, H_{d}/y_{t}, S_{o})$$
(4)

As the previous equations are simplified and by eliminating the parameters with constant and negligible values and applying the assumption (single sediment size, effect of viscosity, and relative density). Eqs. (3) and (4) can be written as:

$$D_{s}/y_{t} = f(v/v_{c}, Fr, \Theta, H_{d}/y_{t})$$
(5)

 $L_t/y_t = f(v/v_c, Fr, \Theta, H_d/y_t)$

3. EXPERIMENTAL WORK

Investigation experiments were performed in an open channel at the Hydraulic Laboratory in Al-Najaf Technical Institute, Department of Civil Techniques. Fig. 1 shows the laboratory flume used in this study. The main structure is a glass fiber. It is molded in steel stiffeners which has a net inner dimensions of a (15.0) m in length, (0.5) m in width, and (0.5) m in depth.

The flume has a closed-loop water system, and the flow to the flume was supplied from the reservoir under the ground by a centrifugal pump that is situated on a fabricated steel base plate. The centrifugal pump lying beside the flume at upstream that has a maximum rate capacity of 40 l/s was used to deliver flow to the flume. The flow delivery from the pump passes through many pipes that are shown in front view on the flume before entering the flume.

A V-notch sharp crested weir is located below the outlet of the inlet tank measuring the actual discharge that passes through the flume section.

Two movable carriages with a point gage were mounted on brass rail at the top of the flume sides that provide an accuracy (± 0.1 mm). Finally, a moveable gate is installed at the end of the flume to regulate the tail water depth.



Fig. 1. Schematic of flume accessories (Ismail, 2012)

1-Reservoir under the ground. 2- Centrifugal pump. (3and 7)- Valves which controlled the flow rate. 4-Power supply. 5- Inlet tank. 6-Supplied pipes. 8 through 12- Screens. 9- V-notch sharp crested weir. 10- Well box. 11- Stilling tank. 13- Point gauge. 14- Working section. 15- The accessories of slope bed system. 16- Tail gate. 17- The end of the close-loop water system.

(6)

To ensure conformity of measured discharge from weir with applied (actual) discharge, a specified calibration has been conducted. The standard method of capacity is used to examine the applied flow rate from which the accumulated volume of water is measured by using known-volume container and stop watch, where thirteen different discharges were taken to increase the accuracy of the relationship (USBR, 2001).

A calibration curve is plotted in Fig. 2, and the obtained relationship then is used to calculate the actual required value of discharge.



Fig. 2. Discharge calibration curve

The bed material consists of cohesionless sand with a medium particle size (d_{50}) equal to 0.65 mm. The geometric standard deviation of the sand size (σ_g) equals to 1.217, which implies that the sand is of uniform size distribution.

The ogee spillway model is made of wood. The profile of the crest should be tangential to the vertical face and should have zero slopes at the crest axis to ensure that there is no discontinuity along the surface of flow as shown in Fig. 3.



Fig. 3. Physical model of ogee spillway with slope 1:1

Four different models of aprons were used in the experimental laboratory. In these models the main angles of the aprons are changed as $(0^{\circ}, 2.73^{\circ}, 5.19^{\circ}, \text{ and } 7.43^{\circ})$ as shown in Fig. 4. To decide what dimensions have to be considered for the models, a balance between many limitations is worthy. These limitations are the flume height of (50cm), sand bed depth which must be at least (10cm), and ensuring free space over spillway within the flume height to pass the different discharges that cover all flow regimes. So, the spillway height is 30cm over the

sand bed and width of the spillway is 50cm. The longitudinal flume slope fixed with (0°) angle of inclination. Models were built from plywood and coated with varnish to avoid swelling and to reduce the roughness coefficient effects of the models, in agreement with concrete roughness coefficient.

In order to find a more realistic equilibrium scour time, four preliminary tests are performed on the horizontal apron and the larger apron from models for two flow conditions. Scour is recorded at different time intervals by using a point gauge to measure the maximum scour at the downstream of apron. The scour depth has sharply increased during the first half of test duration and the development of scour has become approximately constant. Values of scour depth at various test durations as a percentage of final scour depth can be calculated. It is noticed that 90% of the local scour can be achieved in 3 hours.

Steady subcritical flow is used for performing all the experiments at clear water conditions with a plain bed.

The spillway model is fixed at 2.4m from the beginning of the flume then the apron is fixed after it. A box of 0.1m depth and 3m length is placed downstream of apron across the whole width of the flume. It was filled with sand in the working section. A scraper was used to the level of sand bed. The sand level was kept at 10 cm relative to flume solid bed, and this might be a useful tool to scrape the sand bed to a desired level, i.e., 10 cm at any point of working section. Levels were also checked by using the point gauge.

The tail gate is raised and the working area is filled with water by a hose from downstream portion of the flume in order to allow any air bubbles to expulsion from the bed. That is done to avoid any settlement downstream endsill of the apron and to control the hydraulic jump site at the toe of spillway to prevent any abrupt high velocity which causes the disturbance in sand bed after starting pumping.

After starting pumping, the tail gate is gradually lowered until the hydraulic jump becomes clear at the toe of spillway. The test is conducted over three hours, which is considered as a suitable period to reach the equilibrium condition.

At the equilibrium time, the scour depth is recorded by using a point gauge at the downstream of apron by making a mesh for the entire scour region. After that, the flow is stopped, and the flume is drained slowly to avoid any changes in the scour hole. The sand is allowed to dry, and the required measurements of sand bed downstream longitudinally and transversely are recorded (Fig. 5).





Fig. 5. The final scoured surface

Fig. 4. The physical models of apron

4. RESULTS AND DISCUSSION

The following three subsections discuss the results obtained from the laboratory work according to the seven parameters tested. The fourth subsection illustrates the statistical determination for constants proposed by the dimensional analysis for the scour depth and length formulas.

4.1. Effect of flow rate on the scour depth and the extent of scour

A set of experiments was conducted on four aprons with different angles and different flow rates to observe the effect of discharge on depth and extent of scour. It is clear from Fig. 6 that the rate of scour increases with increasing the discharge for each apron due to increase in water energy. The effect of discharge on extent of scour can be shown in Fig. 7. It is also clear from figure that (L_t) increases with increment in discharge for each angle. The contour map and 3D development of scour hole for (runs: 1 and 4) are also shown for comparison, see Figs. 8 a and b and 9 a and b.



Fig. 6. Development of scour depth with the discharge



Fig. 7. Variation of extent of scour with the discharge



Fig. 8a. Contour map for scour downstream apron, run1

Fig. 8b. 3D development of scour hole downstream apron, run1



Fig. 9a. Contour map for scour downstream apron, run4

Fig. 9b. 3D development of scour hole downstream apron, run4

4.2. Effect of Froude Number on the scour depth and the extent of scour

The dimensional analysis has shown that the Froude number ($F_r = v/\sqrt{gy}$) is an important parameter for scour downstream spillway. Therefore, runs are conducted for different angles of aprons as shown in Figs. 10 and 11.

In order to deduce the effect of Froude Number (F_r) on the depth and length of scour, the data are used to plot a relationships between scour depth (D_s) and Froude Number (F_r) and between total length of scour (L_t) and Froude number (F_r) another once.

It has been found that the depth and length of scour increase with increasing Froude number for each apron because Froude number ($Fr = v/\sqrt{gy}$) and the scour increase with increasing flow velocity.

Figs. 12 a and b and 13 a and b show the effect of the Froude number on the contour map and 3D development of scour hole for (runs: 7 and 11).



Fig. 10. Development of scour depth with Froude number





Fig. 12a. Contour map for scour downstream apron with $(F_r=0.171)$

Fig. 12b. 3D development of scour hole downstream apron with (F_r=0.171)



Fig. 13a. Contour map for scour downstream apron with $(F_r=0.147)$

Fig. 13b. 3D development of scour hole downstream apron with $(F_r=0.147)$

4.3. Effect of an angle of apron on the scour depth and the extent of scour

It is observed that as the length and slope of apron increase, the scour depth increase, but the length of scour decreases at the downstream face, as shown in Figs. 14 and 15.

As the slope and the length of apron increase, the flow piles up in the basin and impinges the movable bed some distance closer from the apron which leaves the hole with a larger depth and a shorter length. Erosion under the apron was initiated by the moving vortex system that caused scouring near the edge of the channel. The scour cavities were developed almost similar on both sides. Each cavity caused a local flow separation that created clockwise vortices. These vortices increase with increasing of apron slope. With increasing scour time, the flow velocities were reduced and the vortex weakened.

Through laboratory experiments, it was found that the lowest depths of the scour occurred when the angle of apron equal to 2.73° because it was the least adopted slope. In addition, the depths and lengths of scour in the horizontal apron were greater than those calculated from aprons with slope. The average value of decreasing in scour depth was 53%, 46%, and 35% for angles 2.73° , 5.19° , and 7.43° , respectively.

Finally, it was found that the effect of the angle on the depths of the largest impact on the lengths of scour. Where, the average value of decreasing in scour length was found equal to 33%, 49%, and 33% for angles 2.73° , 5.19° , and 7.43° , respectively.

The contour map and 3D development of scour hole for (runs: 8 and 20) are also shown for comparison between angles, see Figs. 16 a and b and 17 a and b.





Fig. 14. Development of scour depth with Angle of apron





Fig. 16a. Contour map for scour downstream apron with Θ =2.73°

Fig. 16b. 3D development of scour hole downstream apron with Θ =2.73°



Fig. 17a. Contour map for scour downstream apron with Θ =7.43°



Fig. 17b. 3D development of scour hole downstream apron with Θ =7.43°

4.4. Developed Equations for scour depth and extent of scour

Eqs. (5) and (6) can be written as:

For depth of scour:

$$\frac{\mathrm{Ds}}{\mathrm{y}_{\mathrm{t}}} = c_1 \times \left(\frac{\mathrm{v}}{\mathrm{V}_{\mathrm{c}}}\right)^{c_2} \times (\mathrm{Fr})^{c_3} \times \left(\frac{\mathrm{H}_{\mathrm{d}}}{\mathrm{y}_{\mathrm{t}}}\right)^{c_4} - c_5 \cos\theta \tag{7}$$

In which C_1 , C_2 , C_3 , C_4 , and C_5 are empirical constants and can be found by using the experimental obtained data. By using SPSS V16.0 program the constants can be found. Accordingly, Eq. (7) can be written as:

$$\frac{Ds}{y_t} = 29.738 \times \left(\frac{v}{v_c}\right)^{0.01} \times (Fr)^{-0.002} \times \left(\frac{H_d}{y_t}\right)^{0.011} - 29.383 \cos \theta$$
(8)

Values of (Ds/y_t) were calculated from the Eq. (8) and presented with the laboratorymeasured values as shown in Fig 18, which shows the extent of correlation between the measured and calculated values. The coefficient of determination (R^2) for this formula is (0.89).

For extent of scour:

$$\frac{L_{t}}{y_{t}} = \left(\frac{V}{V_{c}}\right)^{c_{1}} \times (Fr)^{c_{2}} \times \left(\frac{H_{d}}{y_{t}}\right)^{c_{3}} \times \cos\theta$$
(9)

By using the experimental obtained data, C_1 , C_2 , and C_3 are empirical constants can be found by using SPSS V16.0 program. Accordingly, by the same way of scour depth equation, Eq. (9) can be written as:

$$\frac{L_{t}}{y_{t}} = \left(\frac{v}{v_{c}}\right)^{4.37} \times (Fr)^{-1.203} \times \left(\frac{H_{d}}{y_{t}}\right)^{-1.247} \times \cos \theta$$
(10)

Values of (Ls/y_t) were calculated from the Eq. (10), and those obtained from laboratorymeasured values as shown in Fig. 19, which shows the extent of correlation between the measured and calculated values. The coefficient of determination (R^2) for this formula is (0.95).



Fig. 18. Comparison of equation (13) with experimental data



Fig. 19. Comparison of equation (15) with experimental data

5. CONCLUSIONS

- 1. The secondary (tail water) flow system caused two scour regions to be developed (main scour and local scour).
- 2. All the tests showed that the scour processes were faster in the early stages of each experiment in contrast to later stages that were marked by slower changes in bed profile. It was clear that the shape of the scour hole changed with time until an equilibrium stage was reached.
- 3. Maximum scour depth was observed at the edge of channel, this mean that local scour is the maximum.
- 4. The greatest value of maximum scour depth and length was observed at the horizontal apron.
- 5. The scour depth downstream apron increased with increasing slope of apron while the length decreased.
- 6. The scour depth decreased by about (53) %, (46) %, and (35) % with increasing the angle for slope of an apron from the floor to (2.73°), (5.19°), and (7.43°), respectively.
- 7. The angle for slope of an apron that gives the largest average value of decreasing in scour length about (49) % is (5.19°) and about (33) % for both angles (2.73°) and (7.43°).
- 8. Formulas for the temporal evolution of the maximum depth and length of scour are developed by using the dimensional analysis techniques. These formulas are restricted to the laboratory data. The scour depth and length are represented as a function of Froude number, flow velocity, operating head, and angle of an apron. The formulas gave a good determination coefficient, and it also gives an idea to evaluate maximum scour depth and length for similar conditions covered in this study.

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