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SCOUR CHARACTERISTICS DOWNSTREAM CONVERGING SPILLWAYS

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ABSTRACT

Flow over spillways or underneath gates has a tremendous amount of potential energy, which is converted into kinetic energy downstream control structures. This energy should be dissipated to prevent the possibility of excessive scouring of the downstream waterway bed, minimize erosion and undermining of structures, which endanger the structure safety. In this paper, an experimental study was conducted to predict the scour geometry downstream a sloped spillway and to minimize the scour using a stepped spillway with certain arrangements. It was found that the using of stepped spillway instead of the sloped one reduced the relative scour depth and increased the relative energy loss and the spillway with three steps gave the smallest value of scour depth. The dimensional analysis was employed to drive expressions correlating the different variables affecting the scour phenomena. Prediction equations were developed using the multiple linear regression (MLR) to model the relative scour depth Ds/yup and the relative the relative energy loss ΔE/Eup. A good agreement was obtained between the predicted and the measured values. Finally, this study yielded conclusions which can be recommended in the design procedure and practical applications.

1. INTRODUCTION

When the reservoir's storage capacity is exceeded, water flows over the spillway crest and accelerates down the spillway face to produce high velocities at the spillway toe, which may cause dangerous scour in the natural channel below the structure. Some form of stilling basin structure located at the foot of the spillway has been used for energy dissipation. Depending on the expected Froude Number (F1) of the incoming flow, the form of the stilling basin can range from a simple concrete apron to a complex structure that may include rows of chute blocks, baffle piers and a plain or dentated end-sill. This can add substantially to the overall costs. Consequently, alternative solutions to the problem are worth investigating. One possible solution is to consider a stepped spillway instead of the traditional sloping spillway, where a series of drops are provided from near the crest to the toe. Over a wide range of operating conditions, the stepped spillway is expected to generate substantial energy losses on the spillway structure itself, thereby reducing the need for a more costly form of stilling basin. Young (1982) studied the feasibility of a stepped spillway and managed a 75% energy reduction. Sorensen (1985) performed a physical model investigation for stepped spillways, where he found that adding a few steps to the face of the spillway eliminated the deflecting water jet. Christodoulou (1993) found that energy loss due to the steps depends primarily on the ratio of the critical

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depth to the height of the step, as well as on the number of steps. Chamani and Rajaratnam (1999a, b) developed an equation to predict the incipient value of the ratio of the critical depth to step height, which agreed well with most of their experimental observations. Chanson (1999) proposed a pre-design calculation method that provides a general trend for preliminary designs. Chanson (2000) discussed the issues of operation and safe design of stepped chutes and described the operation of several structures worldwide focusing on accidents and failures. Jean and Bassam (2004) performed an experimental investigation into the hydraulics of ogee-profile stepped spillways, examined their viability as an alternative to smooth-back spillways and investigated their efficiency in reducing the downstream energy and length of the hydraulic jump. They concluded that the number of steps is the overbearing factor in expending flow kinetic energy and, therefore, reducing the length of the downstream forming hydraulic jump. Carvalho et al. (2009) studied stepped spillway with Hydraulic Jumps by using both of numerical and experimental model. A large scale model was adapted and an experimental study was conducted to examine similarity of hydraulic jumps on each step, minimizing hydraulic jump length and maximizing discharge per unit width. Roshan et al. (2010) used stepped spillway model as energy dissipater through two physical models with different numbers of steps. Hunt et al. (2010) studied the energy dissipation downstream of the inception point on flat-sloped stepped spillways. A two-dimensional, physical model was built to investage the inception point, velocities, air concentrations, and energy dissipation in. Chafi et al. (2010) indicated that the stepped spillway dissipates the energy flow better than the spillway of a smooth profile, the energy dissipation is inversely proportional to the flow discharge and the nappe flow dissipates better than that of skimming regime. Dermawan and Legono (2011) mentioned that the stepped spillway raise the depth of the flow at the toe of spillway approximately twenty times than conventional chutes and decrease residual energy at the toe of spillway approximately six to seven times than smooth chutes. Felder et al. (2011) Studied hydraulics of stepped spillway with non-uniform step heights. They found that the rate of energy dissipation was about the same for uniform and non-uniform stepped configurations, and the non-uniform stepped configurations might induce some flow instabilities for smaller flow rates. Sobeih et al. (2012) investigated experimentally the influence of using openings in weirs of different arrangements and diameters on scour hole depth downstream of this structure.Tuna (2012) studied the effect of off take channel base angle of stepped spillway on scour hole. The results demonstrate that the maximum scour depth increases with the increase in both the chute angle and the unit discharge. Helal et al. (2013) studied experimentally using sills of different arrangements (no sill, single line sill and fully silled floor with different heights) to minimize scour downstream hydraulic structures. The study showed that the case of fully silled floor gave the smaller values of scour parameters. Maatooq et al. (2014) studied the energy dissipation by constructing a traditional stepped spillway and Labyrinth stepped spillway. They found that the energy dissipation with labyrinth shape stepped spillway was more than resulted with the traditional shape.

The present paper aims to investigate experimentally the effect of using stepped spillway instead of the sloping one on the scour and energy loss characteristics downstream the stilling basin in a convergent channel due to the importance of this case to water transition from a wide lake to a narrow river.

2. DIMENSIONAL ANALYSIS

Fig. 1 shows a definition sketch for the flow over a stepped weir and the free hydraulic jump formed in a convergent stilling basin downstream the weir. The following function can be formed:

$$f(B, b, h_w, L_b, h_{st}, y_{up}, y_1, y_2, L_j, v_0, v_2, g, \rho, \mu, D_{50}, L_S, L_d, D_S, D_d) = 0 \quad (1)$$

In which ρ is the water density, g is the gravitational acceleration (g =9.81m/sec2), μ is the dynamic viscosity of the fluid, B is the width of channel, b is the contracted width, h_{st} is the step height where N is the number of steps $N=h_w/h_{st}$, L_b is the length of basin, yup is the upstream water depth, y_1 is the initial depth of jump, y_2 is the sequent depth of jump, L_j is the jump length, v_0 is the upstream flow velocity, v_2 is the flow velocity at the end of jump, D_d is the Max. Deposition depth, D_s is the Max. Scour depth, L_d is the Max. deposition length, L_s is the Max. scour length. Using the dimensional analysis principle based on the three repeating variables ρ, y_{up} and V_0, Eq. (1)becomes.

Similar relationships for the energy loss ratio ($\Delta E/E_{up}$) could be obtained where $\Delta E= E_{up} - E_2$, E_{up} is the upstream energy and E_2 is the energy at sequent depth

$$\frac{D_s}{y_{up}} = f\left(N, \frac{y_2}{y_1}, \frac{L_j}{y_{up}}, F_{up}, \frac{L_s}{y_{up}}, \frac{L_d}{y_{up}}, \frac{D_d}{y_{up}}\right) \qquad (2)$$

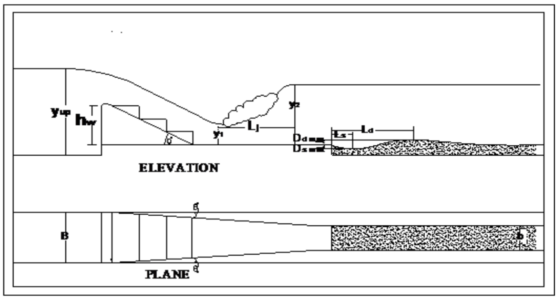


Fig. 1 Definition sketch of the flow over a stepped weir in a convergent stilling basin

3. EXPERIMENTAL WORK

Experiments were carried out in the Hydraulics Laboratory of the Faculty of Engineering, Zagazig University, Egypt, using a re-circulating adjustable flume of 15.6 m long, about 50 cm deep and 30 cm wide. A pre-calibrated orifice meter fixed in the feeding pipeline was used to measure the discharges. The tail-water depth of flow was controlled by a tailgate fixed at the end of the flume. The basin was made from a clear prespex to enable visual inspection of the phenomenon being under investigation. The model was fixed in the middle third of the flume between its two side-walls as shown in Fig. 2. The model consists of a sloped spillway of fixed height (17.5cm) and aback slop of 30°. The spillway was placed in a width of 30cm which contracted to 20.5cm through an angle of convergence of 2.86°. The length of the basin (L_b) downstream the spillway was 114cm. The mobile bed of sand was extended to 210cm with 20cm thickness. The sieve analysis of the sand layer was shown in

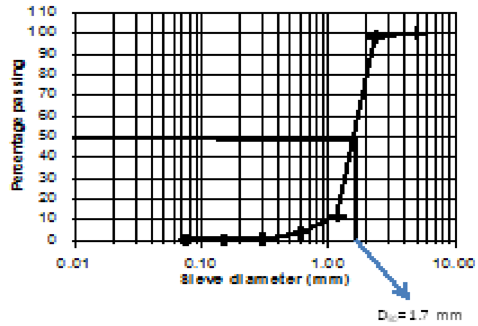


Fig. 3. The model sand is non uniform (uniformity coefficient $=D_{60}/D_{10}=$ 1.8) with $D_{50}=$ 1.7mm, and geometric mean $=D_{85}/D_{15}$ =1.69.

Fig. 2 general view of the measuring instruments

The experimental study was started by studying the effect of sloped spillway on the scour chartieristics downstream stilling basin as reference. The second case was studying the effect of stepped spillway on the scour chartieristics with different number of steps (N= 2, 3, 4, 5, 7and 8).

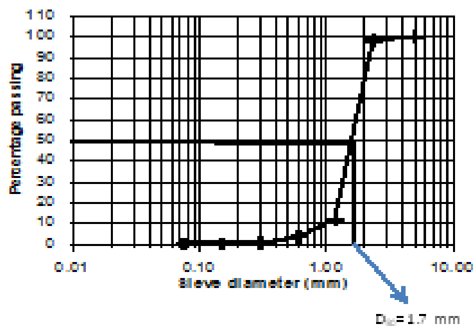


Fig. 3 Sieve analysis of the sand

A typical test procedure consisted of (a) a selected discharge was allowed to pass. (b) The tailgate was adjusted until a jump is formed just downstream the spillway. Starting test time of the run was recorded, and water surface profiles were measured and recorded during the test. (c) Once the stability conditions were reached, flow rate, length of the jump, water depths upstream and at the vena contracta downstream of the spillway, the sequent depth of the jump, and the tail water depth are recorded. (d) After 120 minutes the pump was stopped. (e)After the sand drained from water, the maximum scour depth, the maximum deposition, their locations and also a survey of the scour hole mesh were measured. These steps were repeated for different discharges until the required ranges of the parameters being under investigation were covered.

4. STATISTICAL REGRESSION

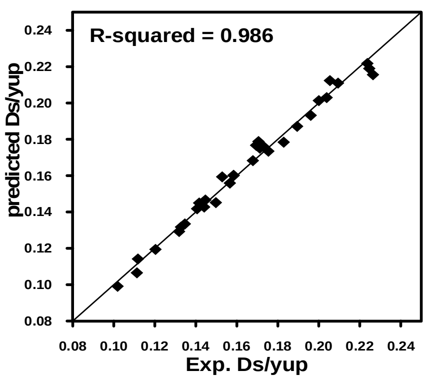
The regression tool was used to carry out the necessary regression tasks and statistical analysis. With that tool and based on the experimental data, the statistical equations (4 and 5) were built to predict the relative scour depth D_s/y_{up} and the relative the relative energy loss $\Delta E/E_{up}$.

$$\frac{D_s}{y_{up}} = 7.02\ F_o + 0.07\ \frac{h_{st}}{h_w} - 0.75\ F_2 + 0.04 \qquad (3)$$

$$\frac{\Delta E}{E_{up}} = -3.67\ F_o + 4.45E-06\ \frac{h_{st}}{h_w} + 0.52 F_2 + 0.333 \qquad (4)$$

Fig. 4 and

Fig. 5 show a comparison between the measured D_s/y_{up} and $\Delta E/E_{up}$ and the predicted ones using statistical models Equations (4 and 5), respectively for different cases of the study. The coefficients of determination R^2 between statistical and experimental values are (0.986, and 0.982) respectively, and between the residuals and the statistical values are (4.56E-015, 1.13E-013 and 1.79E-015) respectively. The comparison indicated a good agreement between the models predictions and experimental data.



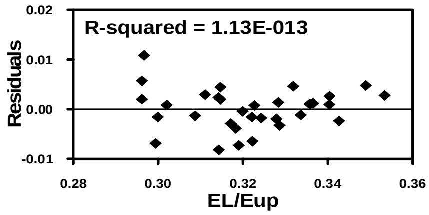


Fig. 4 [a] Relation between experimental values of D_s/y_{up} and the predicted ones [b] Comparison between residuals and the predicted values of D_s/y_{up}

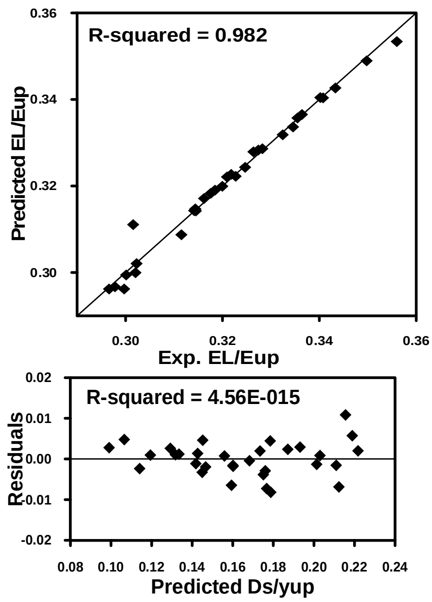


Fig. 5 [a] Relation between experimental values of $\Delta E/E_{up}$ and the predicted ones [b] Comparison between residuals and the predicted values of $\Delta E/E_{up}$

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental results which obtained from the experimental work that aimed to study the effect of using stepped spillway of different number of steps instead of the sloped one are analyzed and discussed to investigate the energy loss, scour depth downstream stilling basin and jump characteristics. The experimental results are plotted in a set of figures for the purpose of comparing that results.

5.1. Effect of steps on the relative maximum scour depth (D_s/y_{up}) and the relative energy loss ($\Delta E/E_{up}$)

Fig. 6 shows the relationship between the relative scour depth (D_s/y_{up}) and the upstream Froude number (F_0) for different number of spillway steps. The figure showed that the maximum scour depth was increased with increasing of upstream Froude number (F_0) for all different spillway steps numbers. Also for the same upstream Froude number (F_0), the relative maximum scour depth was decreased with increasing numbers of steps. The spillway with three steps gave the smallest value of scour depth because of increasing energy dispersion at it while the greatest value of maximum scour depth occurred at the sloped spillway.

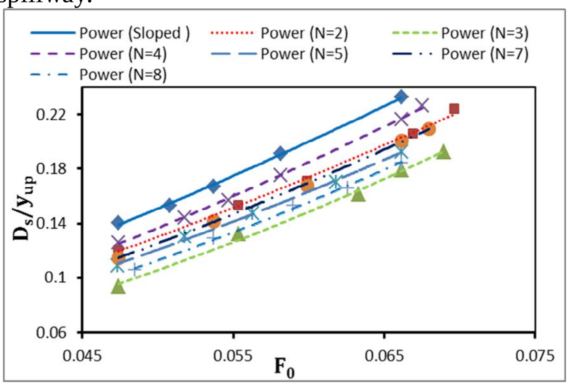


Fig. 6 The relationship between (D_s/y_{up}) and (F_0) for different number of spillway steps.

The relative energy loss ($\Delta E/Eup$) plotted against upstream Froude number (F0) for different numbers of steps as showing in Fig. 7. It was noticed that the relative energy loss decreased with the increasing upstream Froude number (F0). Moreover, for the same upstream Froude number (F0) the spillway with N=3 produced the maximum relative energy loss while the sloped spillway produced minimum energy dispersion.

In fact there is interaction between the relative energy loss throw the structure and the maximum scour depth. As the relative energy loss through the structure and its basin was increased, the velocity downstream was decreased and hence the scour depth was reduced also.

The decreasing rates of relative scour (D_s/y_{up}) and the increasing rates of relative energy loss ($\Delta E/E_{up}$) in comparison with the case of sloped spillway were presented in Figure 7 . Referring to this table, the maximum decreasing relative scour rate and maximum increasing relative energy loss rate are obtained with the stepped spillway with three steps(N=3)

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The decreasing rates of relative scour (D_s/y_{up}) and the increasing rates of relative energy loss ($\Delta E/E_{up}$) in comparison with the case of sloped spillway were presented in Fig. 8 . Referring to this figure, the maximum decreasing relative scour rate and maximum increasing relative energy loss rate are obtained with the stepped spillway with three steps(N=3).

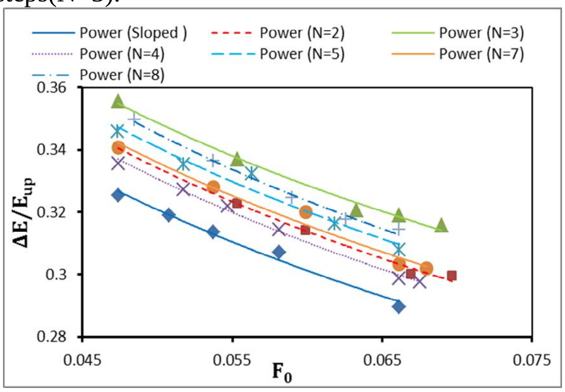


Fig. 7 The relationship between ($\Delta E/E_{up}$) and (F_0) for different number of spillway steps

Table 1 Percentages of decreasing and increasing in (D_s/y_{up}) and($\Delta E/E_{up}$)

N0. of steps	***Relative step height (h_{st}/h_w)***	***F_0***	***Ds/y_{up} Decreasing %***	***$\Delta E/E_{up}$ Increasing %***
N=2	0.5	0.047	14.29	4.68
N=3	0.33		33.27	9.27
N=4	0.25		10.20	3.13
N=5	0.2		22.45	6.23
N=7	0.142		18.37	4.68
N=8	0.125		24.81	7.44
N=2	0.5	0.67	11.75	3.58
N=3	0.33		23.26	10.07
N=4	0.25		6.98	3.16
N=5	0.2		17.44	6.27
N=7	0.142		13.95	4.72
N=8	0.125		20.93	8.56

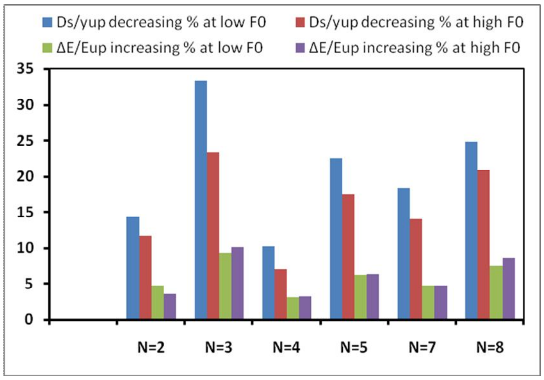


Fig. 8 Percentages of decreasing and increasing in (D_s/y_{up}) and ($\Delta E/E_{up}$)

5.2. Analysis of the Results of Energy Dissipation

Fig. 9 represents our experimental results concerning the energy dissipation from the spillway crest to the sequent depth versus (hw/dc) and those of Chafi et al. (2010) and Outsu et al. (1995) for N=7. The analysis of the data of this figure indicates that the energy dissipation values obtained in our experiments are less than those of Chafi et al. in which the spillway slope is 32° and those of Outsu et al. with a spillway slope of 30°. This because of the convergent stilling basin with θ=2.86°. As the angle of convergence is increased, the width of stilling basin is decreased and velocity is increased. The energy dissipation is decreased and the scour is increased as a result.

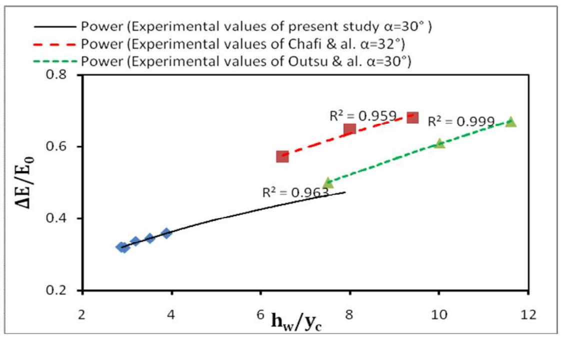
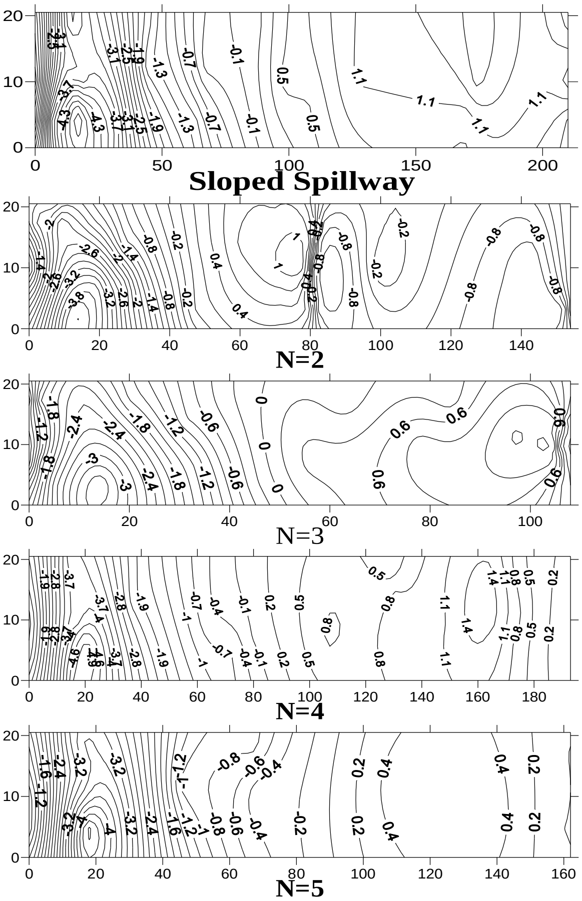


Fig. 9 The relation between ($\Delta E/E_{up}$) and h_w/y_c for N=7

5.3. Contour maps of bed deformation downstream the stilling basin

Fig. 10 shows the contour maps of the deformation downstream the stilling basin of the stepped spillway with different numbers of steps (N= 0, 2, 3, 4, 5, 7 and 8) at F_0 = 0. From these figures, it was noticed that there was a symmetric area in the beginning of the movable bed that was increasing with increasing the Froude number. The scour hole was asymmetric for all different spillway numbers of steps and was taking the right side of the channel. Deposition position was at relative distance of 38-85% from the end of stilling basin.



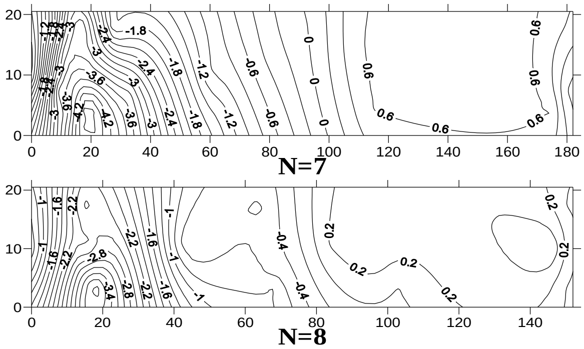


Fig. 10 Contour maps of the deformation downstream the stilling basin at F0= 0.047

Fig. 11 shows the relationship between the relative critical scour depth (D_s/y_c) and the upstream Froude number (F_0) for different number of spillway steps. From this figure, it could be noticed that the relative critical scour depth was increasing with increasing of discharge. At the same flow condition, the relative critical scour depth was decreasing with increasing number of steps. The spillway with N=3 produced the minimum relative critical scour depth. Figure 11 shows the relationship between (D_s/y_c) and (y_2/y_c) for different number of spillway steps. It is observed that (D_s/y_c) was increasing with decreasing of the relative critical sequent depth (y_2/y_c) and was decreasing with increasing number of spillway steps for the same (y_2/y_c). The relative critical scour depth (D_s/y_c) produced the smallest value at N=3 and the greatest value at sloped spillway. From this figure, it was indicated that maximum scour depth was decreasing with increasing of sequent depth (y_2) for the same critical depth. It could be said from this figure that the tail water depth has remarkable effect on scour hole dimensions. In addition, for the same discharge the scour hole dimensions were reversed with the tail water depth.

Fig. 13 shows the relationship between the maximum scour depth (D_s) and the critical depth (y_c). The maximum scour depth (D_s) is directly proportional to critical depth (yc) while critical depth (y_c) is directly proportional to the discharge. This indicates that the maximum scour depth (Ds) is increasing with increasing of the discharge. Again, it could be said from Fig. 11and Fig. 12 that the tail water depth has remarkable effect on scour hole dimensions. In addition, for the same discharge the scour hole dimensions were reversed with the tail water depth.

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Fig. 14 the last remark that the tail water depth had the major effect on scour hole dimensions was fixed. The sequent Froude number (F_2) was a function in the incoming discharge and the sequent depth of water. As the sequent depth of water decreased the velocity increased also for the same discharge. So the scour processing was magnified.

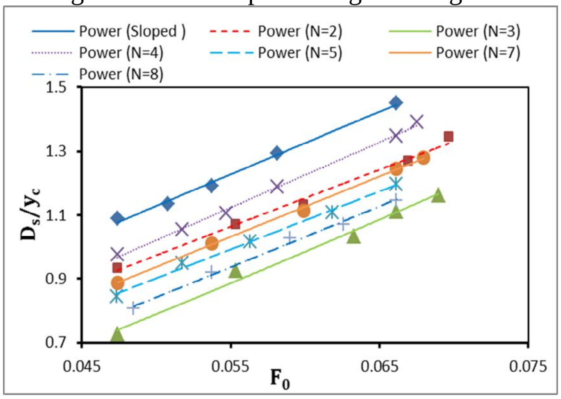

Fig. 11 The relationship between (D_s/y_c) and (F_0) for different number of spillway steps

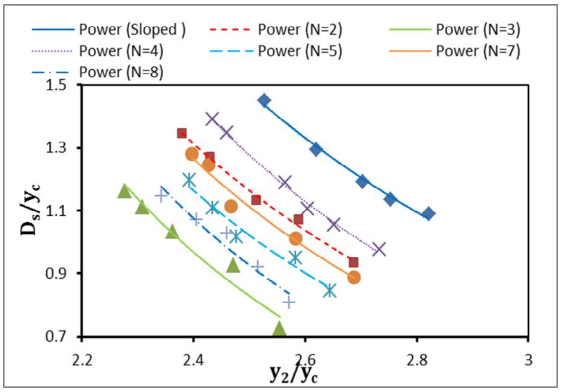

Fig. 12 The relationship between (D_s/y_c) and (y_2/y_c) for different number of spillway steps

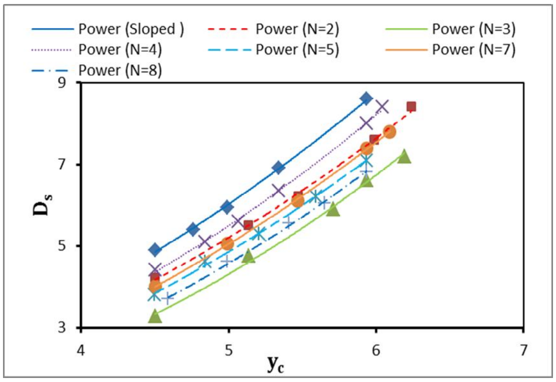

Fig. 13 The relationship between (D_s) and (y_c) for different number of spillway steps

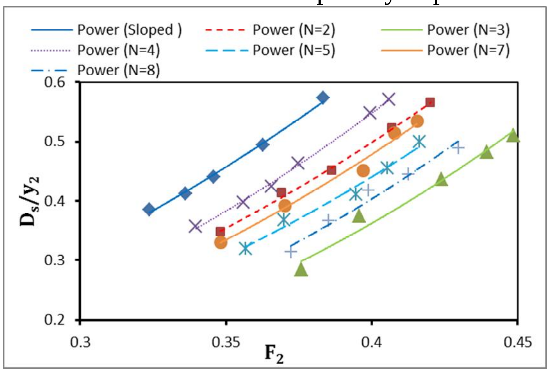

Fig. 14 The relationship between (D_s/y_2) and (F_2) for different number of spillway steps

6. CONCLUSION

An experimental study was carried out to investigate effect of using stepped spillways of different arrangements instead of a sloped one on the scour characteristics D.S a convergent stilling basin. The results of the experimental study are presented. The discussion and analysis of the results highlighted the following conclusions:

1 the maximum scour depth increased with increasing of upstream Froude number (F_0) for all spillways (sloped and of different numbers of steps).

2 At the same upstream Froude number (F_0), the relative maximum scour depth decreased with increasing numbers of steps.

3 The spillway with three steps gave the smallest value of scour depth while the greatest value of maximum scour depth occurred at the sloped spillway

4 for the same upstream Froude number (F_0) the spillway with N=3 produced the maximum relative energy loss while the sloped spillway produced minimum energy dispersion.

5 The scour hole was asymmetric for all investigated spillway and was taking the right side of the water channel.

6 The relative critical scour depth (D_s/y_c) decreased with increasing number of steps. The spillway with N=3 produced the minimum relative critical scour depth and the maximum value was at sloped spillway.

7 The relative critical scour depth (D_s/y_c) increased with decreasing of the relative critical sequent depth (y_2/y_c) and decreased with increasing number of spillway steps for the same (y_2/y_c).

8 Prediction equations were developed using the multiple linear regression (MLR) to model the relative scour depth and the relative energy loss. An acceptable agreement was obtained between the predicted and the measured values.

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