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Experimental Investigation of Bed Variations due to Circular Culvert Jet with Different Angles

Mohammad Reza Pirestani[1]*, Mehrdad Kaviani[2]

1.Assistant Professor, Islamic Azad University - South Tehran Branch, Dept. of Civil Engineering, Tehran, Iran

2.M.SC. in Hydraulic Stuctures, Islamic Azad University - South Tehran Branch, Dept. of Civil Engineering, Tehran, Iran

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ABSTRACT

Downfall flows from different outlet hydraulic structures such as culverts and jets throwing to the erodible downstream bed cause scour hole and changes in the downstream bed topography. Therefore, by performing some physical modeling tests on culvert jet flow under different angles, changes in the downstream bed topography under the effect of different parameters such as flow rate, depth of the tail water and the important factor of falling jet angle of the culvert were studied in this paper. Water jet was modeled using a plastic pipe with a circular section throwing on a Silica bed material with a uniform grading in three different culvert angles of 80, 90 and 100 degrees relative to the vertical axis. The results showed that by increasing the jet angle from 80 to 100 degrees, depth of the scour hole increased and the place where the maximum scour hole depth occurs changed. Besides, by using the Non-dimensional Analysis, a relationship for measuring the maximum depth of the scour hole and maximum height of the scour mound was presented in this paper.

Keywords

Falling jet, throwing angle, culvert, depth of the scour hole, height of the scour mound, depth of the tail water

1. Introduction

Every year expensive costs are spent to control and prevent damages caused by the scour phenomenon downstream of the hydraulic structures during flood and non-flood phases. Therefore, scour hole is an important phenomenon in such structures and its occurrence prediction before constructing a structure is essential. Development of the scouring can threaten the stability of structures, while gathering downstream deposited sediments by changing the tail water depth can affect the performance of the structure outlet. On the other hand, scour phenomenon is a two-phase water-sediment flow that the theoretical approach has been less studied and analyzed and generally field or laboratory studies for simulating specific conditions have been used.

Shafaei Bajestan (2008) guaranteed safe long term performance of the hydraulic structures dependent upon a full stabilized protection of the river beds and also expressed that the correction costs due to scour phenomenon is about 50 percent of the construction cost of a hydraulic structure. Abt et al. (1985) investigated the effect of slope on dimensions of the scour hole caused by culverts and concluded that for slopes over 10 percent, depth of the scour hole almost increased up to 15 percent. Meilan et al. (2000) tested falling jet angles of 45 to 90

*Corresponding author email: mrpirestani@azad.ac.ir

degrees, nozzle diameters of 1 and 2 mm and sediment material diameter of 0.5 to 0.7 mm in the submerged conditions in their experiments. They observed that if the speed of the nozzle jet is low, scour volume increased with increasing the jet angle. Rajaratnam and mazurek (2002) tested a diagonal air jet with various impinging distances on erodible bed with two different air jet diameters (12.6 and 6.35 mm), jet approach to bed angles (θ) between 7.5 to 60 degrees, and Polystyrene bed material with the mean particle diameter (d50) of about 1.4 mm. The researchers concluded that the scour hole depth was dependent upon the impinging jet angle, but the length and width of the scour hole were not so. United States Department of Transportation (DOT) (2006) presented a method for estimating the scour at the output culverts in non cohesive soils. In this method, scouring is estimated based on the peak flow duration. Experiments indicated that approximately $^2/_3$ to $^3/_4$ of maximum scour depth occurs at the first 30 minutes of the test. Analysis of the non-submerged falling jets is much more complicated because of the aeration. Ervin (1976) considered the effect of the impinging jets on the scour hole and indicated that with the growth of the jet angle, the amount of air entrance into the jet decreased. According to Mason (1989) the amount of entered air to the jet will affect the scour hole depth, so the more air entering to the jet, the size of the scour hole depth increased. If only the air entering to the jet parameter is considered, it should be expected that by the growth of the jet angle, the amount of air entered into the jet decreased, so the depth of the scour hole will decrease and this indicates the difference between the scours caused by the non-submerged and submerged jets. Ghodsian et al. (2006) found that the tail water has a dual effect on the scour hole dimensions so that dimensions of the scour hole reduced by increasing and decreasing tail water depths from a specific value. Mehraein et al. (2010) experimentally studied the effect of the non-uniform materials on dimensions of the scour hole downstream of the free falling jets and concluded that by using d90 instead of d50 as the diameter of the material, a better correlation is obtained between the Froud Densimetric number and dimensions of the scour hole. Azamathulla et al. (2005 and 2008) presented a model to estimate the maximum scour depth using neural networks and Genetic Programming (GP) and compared it with the experimental methods (Azamathullah et al., 2005 and 2008). Pagliara et al. (2006) investigated hydraulics of Plunge Pool scour due to a circular jet. Jet angles, the air entered to the jet, material grain size and tail water depths were studied. Momeni Vesalian et al. (2008) experimentally studied the local scour due to a rectangular jet downstream of flip-bucket spillways and for predicting the maximum scour hole and height of point bar upstream and downstream of scour hole, an extensive experimental program was conducted [10]. Jueyi Sui et al. (2008) studied the effect of channel width and tail water depth on local scour caused by square jets. Results showed that the expansion ratio (channel width-to-nozzle size ratio) can be important and needs to be considered in the interpretation of laboratory results. Pagliara and Palermo (2008) experimentally studied the plane plunge pool scour with protection structures to understand the hydraulics of plane plunge pool scour in presence of basin protection structures. It was indicated that the scour hole due to jet impact depends on several parameters (i.e. jet discharge, jet angle, tail water depth, Densimetric Froude number and grading properties of the basin material).

In this paper, the effect of falling jet culvert angle with changes in flow rate and depth of tail water at a constant height of falling jet on a physical model has been investigated and since less attention has been paid to the impinging jet angle in the past researches, the main emphasis in this study is on the jet angle falling from the culvert.

2. Physical Model Descriptions

Laboratory equipment included sediment basin, which was made with a boundary constraint of Plexiglas wall and water flowed from a culvert installed directly at the end of a flat flume with the dimensions of 2m×0.5m×0.55m. Sediment basin was about 2 m long, 1.5 m wide and to prevent the side effects, a 0.7 m height was considered. Culverts were embedded to full the profile section of water from 80, 90 and 100 degrees relative to the vertical axis. Experimental model prepared based on the dimensional analysis presented in section 4.

To study bed topographic changes, sediment basin was filled with uniform silica sediments up to 40 centimeters of the basin height according to the following specifications.

$$d_{16} = 0.8\,mm,\ d_{50} = 0.92\,mm,\ d_{84} = 1.32\,mm,$$

$$\gamma_s = 2.65\ {}^{gr}/_{cm^3},\ \sigma = \sqrt{\frac{d_{84}}{d_{16}}} = \sqrt{\frac{1.32}{0.8}} = 1.28$$

After leveling the bed sediments surface smoothly at the start of each experiment, tail water depth was stabilized by means of a gate available at the end of the stilling basin and the falling jet was finally released to the basin. Bed topographic variations of the scour hole measured at the end of each experiment using a point gauge of 0.01 mm precision, which moved on the rails along the longitudinal and transverse directions. In addition, flow rate in the test was controlled by an Electro-magnetic flowmeter during the test and water head behind the culvert in the flume was kept constant. Figure 1 shows the equipment used in this study.

Then, the pump was turned on and the arbitrary flow rate was adjusted by the control valve available on the electromagnetic flow meter. In addition, to prevent the error caused by the preliminary strike of the falling flow to the bed sediments, jet was deviated to the end of the basin by using a moderator and the falling jet finally released to the basin. At the end, the whole volume of water in the basin discharged gently and the bed topographic variations of the scour hole were measured by the point gauge. Then, the surface was smoothened again and the next test with specific characteristics conducted. At the end of each experiment, maximum depth of the scour hole (h_s), maximum height of the scour mound (h_c), and distance between the maximum height of the scour mound and water surface level (F_h) was investigated.

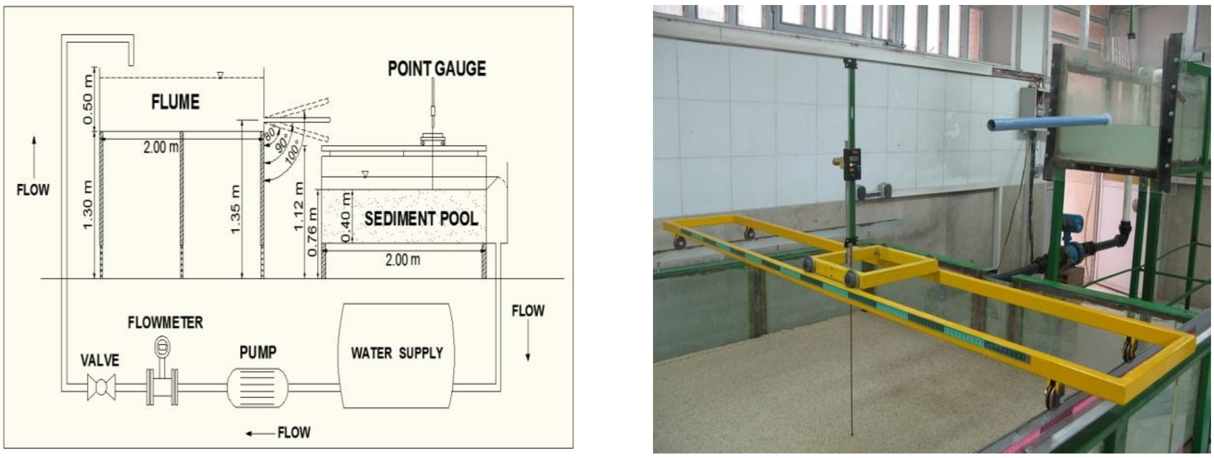

Fig. 1. Schematic view of the physical model and equipment

The important point was to determine the equilibrium time of the test. Because of omitting the time factor from the test, point gauge must measure the bed topographic changes in scouring phenomenon when the scour hole was in equilibrium condition. To this aim, three tests with 15 cm of tail water depth and a maximum flow rate of about 1.9 lit/s with all different angles of falling jet culvert were performed and maximum depth of the scour hole and maximum height of the scour mound were measured at some specific times.

After continuing the experiments for 30 hours and by drawing equilibrium time curves, as shown in Fig. 2, time duration of 360 minutes was considered as the time needed for the formation of 88% of the total scour hole depth for the experiments.

3. Assumptions and imitations of the tests

For the tests, hydraulic conditions were set as follows:

1) Water at all angles of the culvert pipe flows in the bank full condition.
2) Sediment movement as a result of the local scour was mainly as bed load.
3) Scouring in the sediment pool was not mostly influenced by the side walls.
4) All the tests were carried out in clear water condition.

4. Dimensional Analysis

Considering the parameters affecting the scour phenomenon induced by impinging jets, dimensional analysis was performed to determine the dependence of the parameters to each other and finally, a non-dimensional relationship was presented. Therefore, if ψ indicates the dimensions of scour hole and downstream mound height, it can be writte

$$\psi = f(V, T_w, \rho_w, g, d_{50}, \Delta\rho, H_w, \theta) \quad (1)$$

where v is flow velocity in flume, T_w is tail water depth, ρ_w is fluid density, g is acceleration due to gravity, d_{50} is bed particles specific or mean diameter, H_w is water head at the flume behind the culvert, θ is slope or falling angle of impinging jet and $\Delta\rho = \rho_s - \rho_w$ in which ρ_s is sediment density.

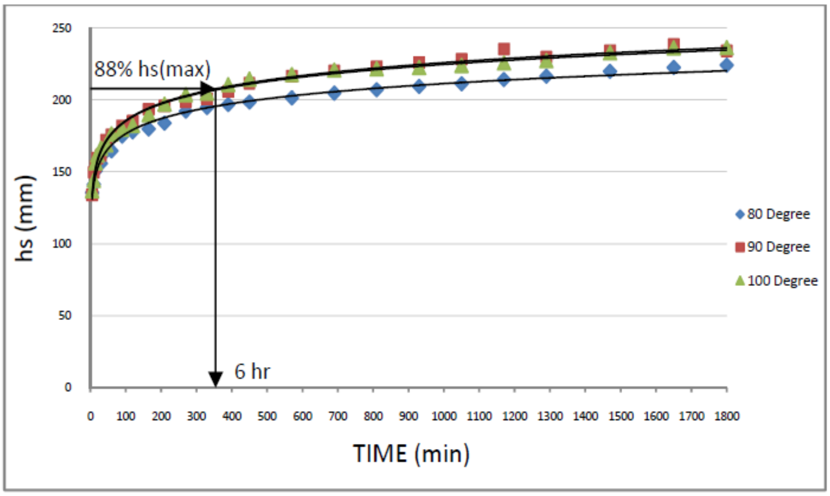

Fig. 2. Equilibrium curves for the scour hole depth and all three angles of falling jet culvert.

In this paper, to investigate the effect of different parameters for the hydraulic studies, dimensional analysis provided by Buckingham (*Π* method-1951) was conducted and the following relation was finally obtained:

$$\frac{\psi}{H_w} = f\left(\frac{T_w}{H_w}, \theta, Fr_d\right) \quad (2)$$

In Eq. (2), Fr_d is the Froud Densimetric parameter defined as follows:

$$Fr_d = \frac{V}{\sqrt{g \times d_{50} \times (\frac{\Delta\rho}{\rho_w})}} \quad (3)$$

Rates and the relations between the parameters in Eq. (2) will be determined by the data collected by the laboratory tests.

5. Results and Analysis

5.1. Longitudinal profiles of the scour hole

In Fig. 3, longitudinal profiles of the scour hole and downstream mound heights where the maximum hole depth occurs are shown to study the falling angle of the impinging jet from the culvert.

Evaluation of the longitudinal profiles revealed that by increasing the falling jet angle from 80 to 100 degrees, length of the longitudinal profile increased. In addition, by increasing the falling jet angle, the depth of scour hole increased and its occurrence location changed, and the scour hole and mound shifted to the downstream of the sediment basin so that for 100 degree in comparison to 80 and 90 degrees, this was more evident.

Furthermore, increase in scour hole depth for 100 degree angle was more than that for 80 and 90 degrees, because in this condition, culvert flow falls upward and acts as a throwing jet and finally, the falling jet came down at a more distant location in comparison to two other cases in the sediment basin. Therefore, the scour hole and mound shifted to the downstream of the sediment basin.

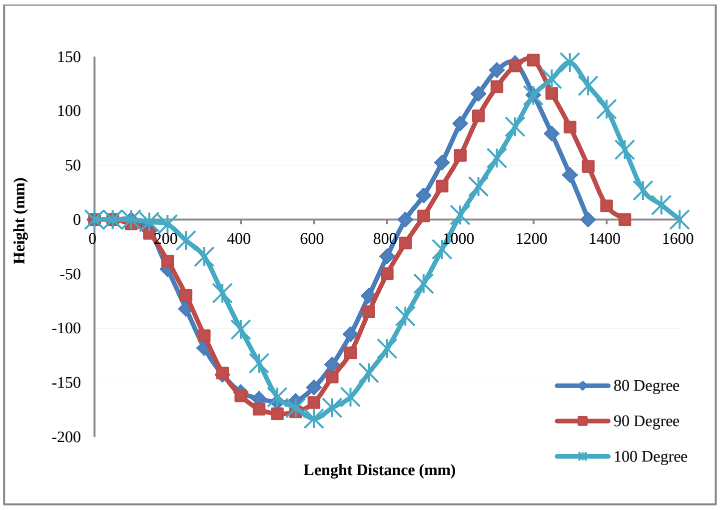

Fig. 3. Longitudinal profiles of scour hole where the maximum hole depth occurs for Q=1.9 lit/s and tail water depth of 15 cm.

5.2.Transverse profiles of the scour hole

In Fig. 4, transverse profiles of the scour hole and downstream mound height where the maximum hole depth occurs are shown to study the falling angle of the impinging jet from the culvert.

Evaluation of the transverse profiles revealed that by increasing the falling jet angle from 80 to 100 degrees, for a specific flow rate and a constant tail water depth, the depth and width of the scour hole increased and also, the place where the maximum scour hole depth occurs changed. Similar to the previous case, scour hole depth and width increase for 100 degree angle was more than these values for 80 and 90 degrees, because in this condition, culvert flow falls upward and acts like throwing jets and there is no control for measuring the general movements of the jet.

5.3.Effect of non-dimensional parameters on the scour dimensions

Based on Eq. (2), declining the effect of non-dimensional parameters on the depth of scour hole and the height of sediment mound in scouring phenomenon, with the help of final data collected from each experiment, the effect of non-dimensional geometric and hydraulic parameters on the depth of scour hole and the height of sediment mound will be considered.

First, ($Fr_d \times \theta$) factor was achieved that is shown in Figs. 5 and 6.

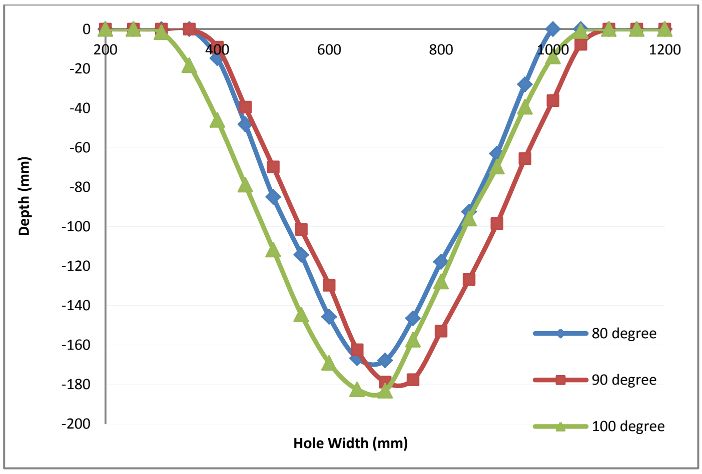

Fig. 4. Transverse profiles of the scour hole where the maximum depth of the scour hole occurs for Q=1.9 lit/s and tail water depth of 15 cm

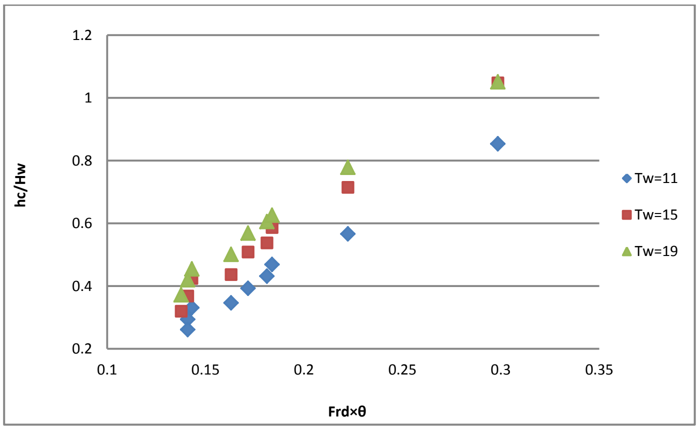

Fig. 5. Effect of $Fr_d \times \theta$ factor on the non-dimensional ratio of $\frac{h_c}{H_w}$

According to the graphs, it was observed that for all the three angles and tail water depths, by increasing the Froud Densimetric dimensionless parameter (Fr_d), both the non-dimensional ratios of $\frac{h_s}{H_w}$ and $\frac{h_c}{H_w}$ increased. In addition, for a specific Froud Densimetric dimensionless parameter and a constant angle of the falling jet, by increasing the tail water depth, the non-dimensional ratio of $\frac{h_s}{H_w}$ decreased, but the non-dimension ratio of $\frac{h_c}{H_w}$ increased. This pattern showed that by increasing the tail water depth, the depth of the scour hole decreased, but the height of the downstream scour mound increased. The effect of $Fr_d \times \frac{T_w}{H_w}$ factor is shown in Figs. 7 and 8.

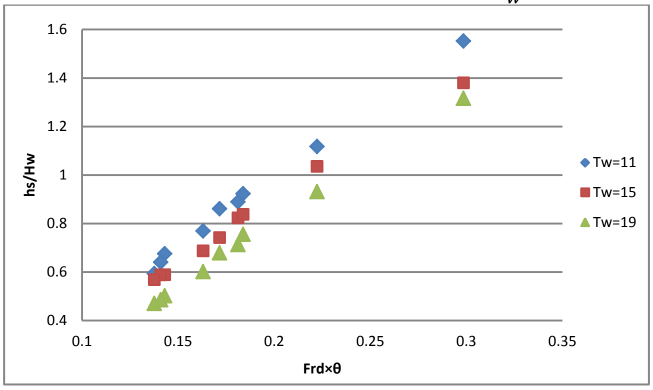

Fig. 6. Effect of $Fr_d \times \theta$ factor on the non-dimensional ratio of $\frac{h_s}{H_w}$

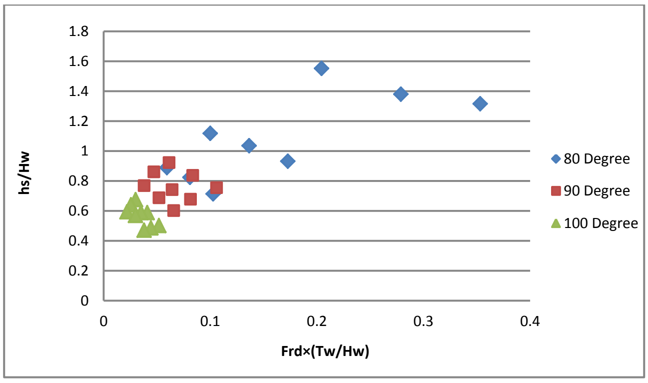

Fig. 7. Effect of $Fr_d \times \frac{T_w}{H_w}$ factor on the non-dimensional ratio of $\frac{h_s}{H_w}$

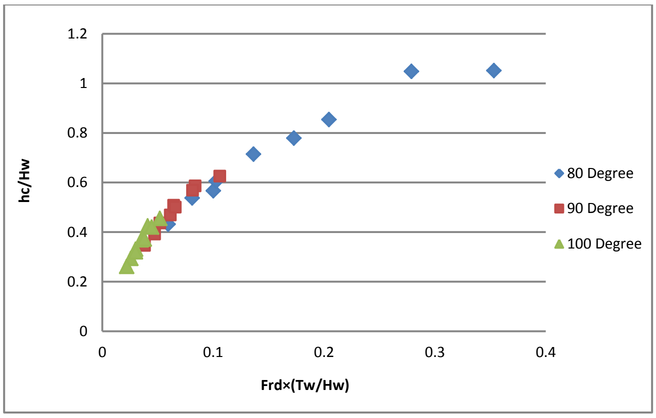

Fig. 8. Effect of $Fr_d \times \frac{T_w}{H_w}$ factor on the non-dimensional ratio of $\frac{h_c}{H_w}$

According to the Figs. 7 and 8, three separate curve groups resulted each belonging to a specific falling jet culvert angle. By increasing the $Fr_d \times \frac{T_w}{H_w}$ factor for each curve group, the non-dimensional ratio of $\frac{h_s}{H_w}$ decreased, but the non-dimensional ratio of $\frac{h_c}{H_w}$ increased. However, an ascending general pattern of both the non-dimensional factors of $\frac{h_s}{H_w}$ and $\frac{h_c}{H_w}$ was observed by increasing $Fr_d \times \frac{T_w}{H_w}$. Another point considering Figs. 7 and 8 was that the changes of $Fr_d \times \frac{T_w}{H_w}$ factor vary with the change in the falling jet angle. In other words, by increasing the falling jet angle from 80 to 100 degrees, the range of $Fr_d \times \frac{T_w}{H_w}$ factor on the horizontal axis miniaturized and data became closer to each other, while for 80 degree and for both the non-dimensional scour hole parameters, a wider range of data was observed. This was attributed to the impact of the Froud Densimetric dimensionless parameter (Fr_d), i. e. by increasing the falling jet angle from 80 to 100 degrees for a constant flow rate, Froud Densimetric dimensionless parameter (Fr_d) decreased. The reason is that in $Fr_d = \frac{Q}{A\sqrt{g \times d_{50} \times (G_s - 1)}}$, by increasing the falling jet angle from 80 to 100 degrees, *Hw* increased, so *A* increased. Because the other parameters are constant in the relation, by increasing the falling jet angle, Froud Densimetric dimensionless parameter decreased.

The effect of $Fr_d \times \frac{T_w}{H_w}$ on the non-dimensional ratio of $\frac{h_s}{h_c}$ is shown in Fig. 9.

According to Fig. 9, it is clear that by increasing $Fr_d \times \frac{T_w}{H_w}$ for all three falling jet angles, non-dimensional ratio of $\frac{h_s}{h_c}$ has a descending pattern, and it was also concluded that by increasing the falling jet angle from 80 to 100 degrees, the range of $Fr_d \times \frac{T_w}{H_w}$ on the horizontal axis miniaturized and for 80 degrees, a wider range of results were obtained. It was also clear that the depth of the scour hole (h_s) for all the experiments was greater than the height of sediment mound (h_c) and usually the value of $\frac{h_s}{h_c}$ was more than one.

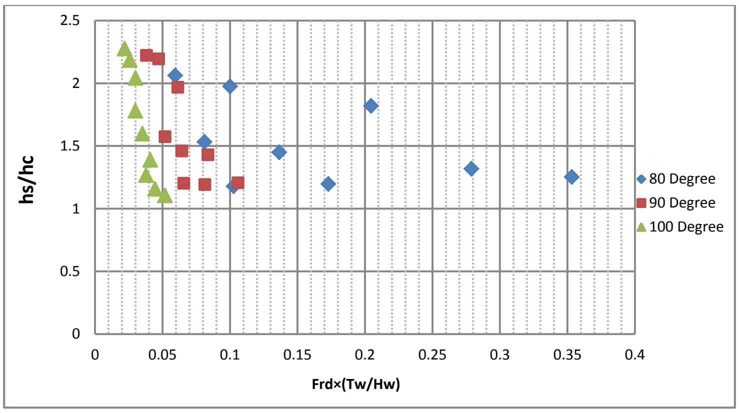

Fig. 9. Effect of $Fr_d \times \frac{T_w}{H_w}$ factor on the non-dimensional ratio of $\frac{h_s}{h_c}$ for all the three falling jet angles

Another studied parameter was the distance between the maximum height of scour mound and the water surface level (F_h) and in this section, the effect of $Fr_d \times \frac{T_w}{H_w}$ factor on the non-dimensional ratio of $\frac{h_s}{F_h}$ is investigated. Figure 10 shows a comparison between F_h in mm for the three falling jet angles.

According to Fig. 10, a specified uniform procedure for F_h for all the three falling jet angles from the culvert was observed. By increasing tail water depth, for all the three falling jet angles and for all flow rates F_h increased. In addition, for Q=1.5 lit/s and a constant tail water depth, by increasing the falling jet angle, F_h decreased and the reduction rate of F_h by increasing the tail water depth was ascending, i. e. by increasing the falling jet angle, the reduction slope of F_h for a higher tail water depth was steeper than a lower tail water depth. This procedure was not observed for flow rates of 1.7 and 1.9 lit/s.

The first point discovered from the above charts was the specified uniform procedure for all the three falling jet culvert angles. According to Fig. 11, by increasing the tail water depth for a constant flow rate, F_h increased and h_s decreased. However, for each falling jet angle, by increasing flow rate for a constant tail water depth, F_h decreased and h_s increased.

As mentioned before, the effect of $Fr_d \times \frac{T_w}{H_w}$ factor on the non-dimensional ratio of $\frac{h_s}{F_h}$ is investigated here and results are shown in Fig. 12. According to Fig. 12, there was a specified uniform procedure for all the three falling jet culvert angles and it is clear that by increasing $Fr_d \times \frac{T_w}{H_w}$ for all the three angles, the non-dimensional ratio of $\frac{h_s}{F_h}$ showed a descending procedure. In addition, it was concluded that by increasing the falling jet angle from 80 to 100 degrees, the range of $Fr_d \times \frac{T_w}{H_w}$ on the horizontal axis was miniaturized and for 80 degree, a wider range of data was observed that as explained before, it is attributed to the Froud Densimetric dimensionless parameter.

In each curve group for each falling jet angle, by increasing the tail water depth a constant flow rate happened, because at $Fr_d \times \frac{T_w}{H_w}$ factor, Froud Densimetric dimensionless parameter and Hw were constant and only Tw increased. Evaluation of the horizontal axis in Fig. 12 showed that by increasing $Fr_d \times \frac{T_w}{H_w}$, the non-dimensional ratio of $\frac{h_s}{F_h}$ decreased. By increasing the tail water depth, h_s showed a decreasing pattern, so the non-dimensional ratio of $\frac{h_s}{F_h}$ had a decreasing pattern, and F_h ratio must increase.

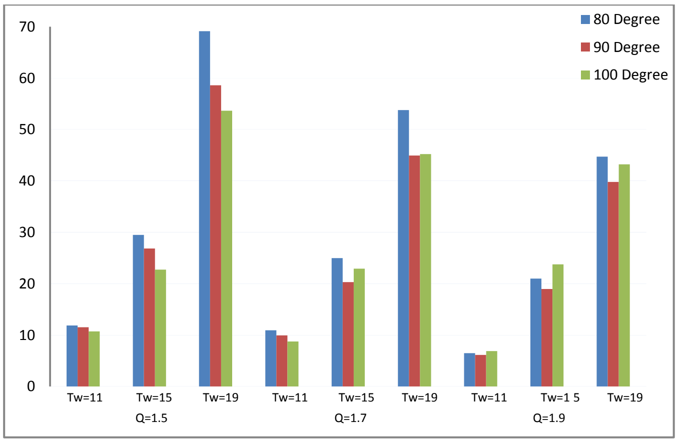

Fig. 10. Comparison between F_h values (in mm) for all the three falling jet angles

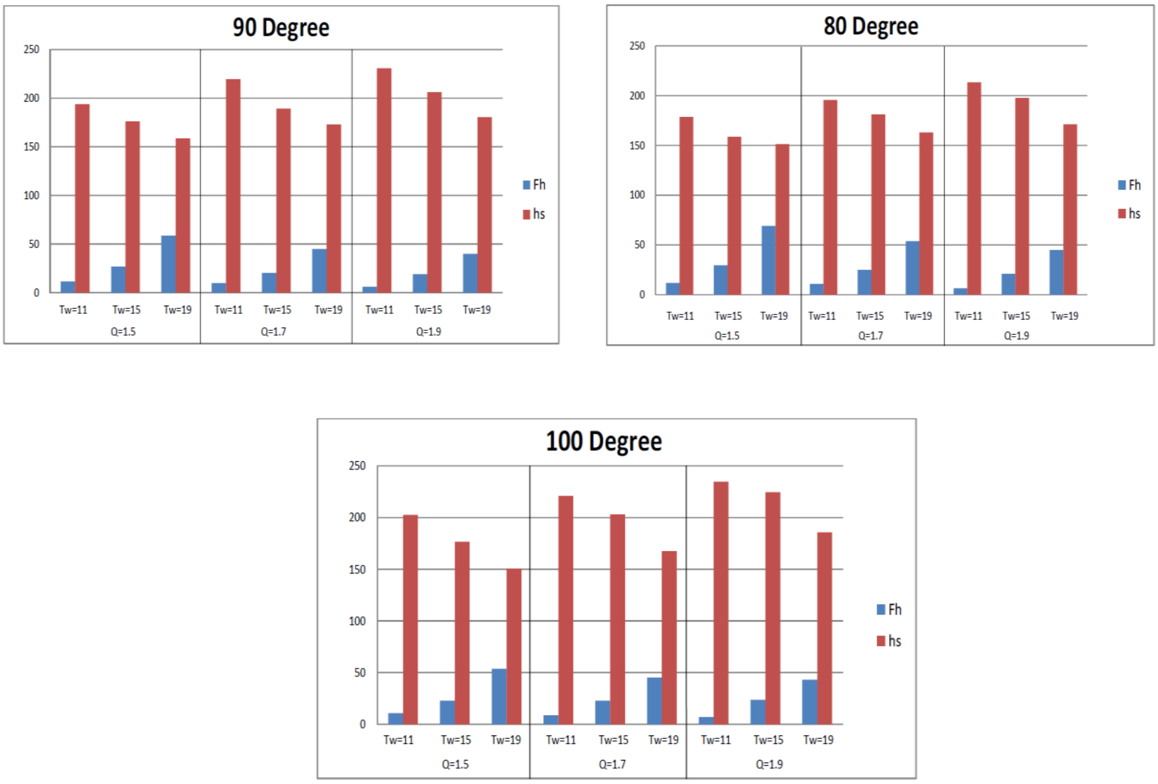

Fig. 11. Comparison between F_h and h_s values (in mm) for all the three falling jet culvert angles

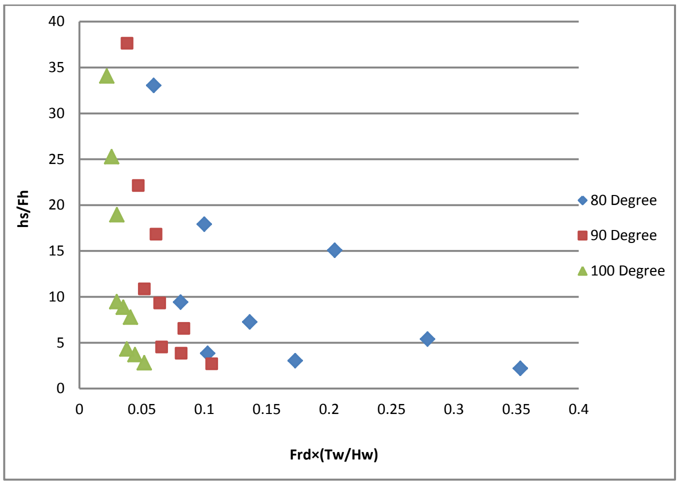

Fig. 12. Effect of $Fr_d \times \frac{T_w}{H_w}$ factor on the non-dimensional ratio of $\frac{h_s}{F_h}$ for all the three falling jet angles

5.4.Estimated relationships to predict the extent of scour hole

Using the statistical analysis, the correlation between different parameters using a multi-variable regression was estimated. A dimensionless equation based on Eq. (4) was obtained by applying dimensional analysis and Eq. (2) on experimental results to estimate the maximum depth of the scour hole (h_s) and the maximum height of the scour mound (h_c) as below:

$$\frac{\psi}{H_w} = K \times \left(\frac{T_w}{H_w}\right)^a \times \theta^b \times (Fr_d)^c \qquad (4)$$

where $\frac{\psi}{H_w}$ is a dimensionless parameter related to the scour hole and downstream mound dimensions in this study, K is a coefficient and a, b and c are values dependent upon the bed topography variations.

According to the experimental data, maximum depth of the scour hole (h_s) and maximum height of the scour mound (h_c) were calculated by using the Solver modules of Excel software and to verify the results, these values were compared with the results of Data-Fit version 9.0.59 software. These values were determined by comparing the experimental and calculated values so that the sum of squares (LSSE=Least Sum of Square Error) would be the least.

In order to determine the relationships presented in Table 1 quantitatively, statistical parameters related to the estimated models were measured according to Table 2 in which E was obtained using $E(\%) = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{Y_{obs}-Y_{cal}}{Y_{obs}}\right|$, where Y_{obs} is the experimental value and Y_{cal} is the calculated value and n is the number of data. This parameter shows the accuracy of the estimated values using models compared to the experimental ones. Min Residual and Max Residual represent the minimum and maximum differences between the experimental and calculated values (using the obtained model), respectively. A lower value indicates a more certainty in estimation of variation dimensions.

The correlation coefficient (R Square) indicates the change percentage of the dependent variable by the estimated models and changes were in the range of 0 to 1. Closer values to 1 indicate the suitability of the estimated models.

To indicate the accuracy of the relations presented in Table1, Figs. 13 and 14 were plotted. These figures show the obtained experimental versus calculated values using the relations presented in Table 1. In these figures, depicted lines are in fact the bisector of the first quarter of the coordinate axis (y=x). Concentration of the experimental and calculated values around these lines indicates the accuracy of the estimated models.

Table 1. Presented relationships for dimensions of the scour

maximum depth of scour hole	$\frac{h_s}{H_w} = 0.043 \times \left(\frac{T_w}{H_w}\right)^{-0.336} \times \theta^{1.388} \times Fr_d^{1.618}$
maximum height of scour mound	$\frac{h_c}{H_w} = 0.8 \times \left(\frac{T_w}{H_w}\right)^{0.553} \times \theta^{0.177} \times Fr_d^{0.458}$

Table 2. Statistical accuracy of the presented relationships in Table1

Dimensions of scour phenomenon	E (%)	Min Residual	Max Residual	R Square
maximum depth of scour hole	4.1	-0.0662	0.0691	0.9825
maximum height of scour mound	3.31	-0.0702	0.0594	0.9869

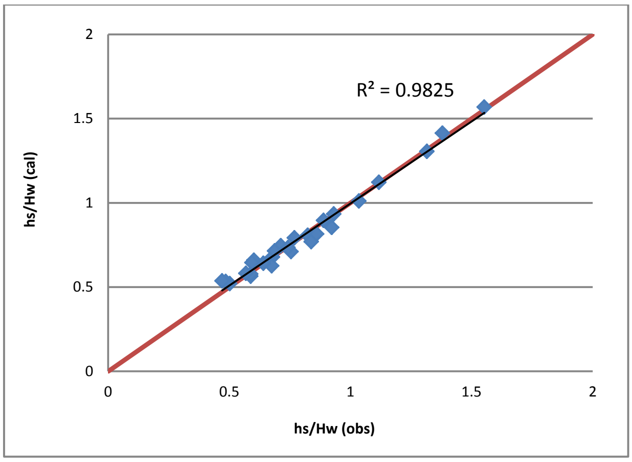

Fig. 13. Correlation between the experimental and calculated values of $\frac{h_s}{H_w}$

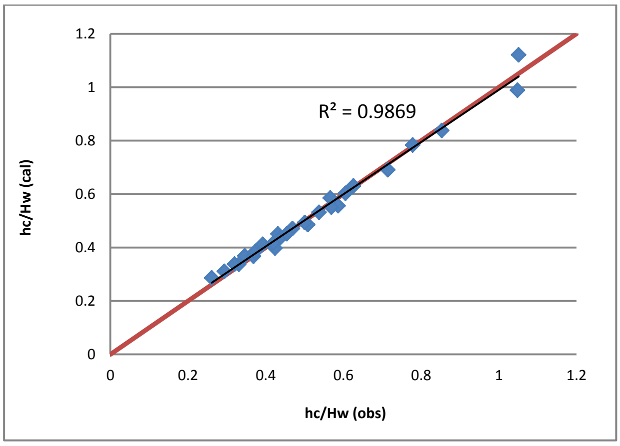

Fig. 14. Correlation between the experimental and calculated values of $\frac{h_c}{H_w}$

6. Conclusions

The following points were concluded from the present study:

By increasing the falling jet angle from 80 to 100 degrees, depth of the scour hole increased and its occurrence place changed. In addition, the entire scour phenomenon including scouring hole and mound shifted to the downstream of the sediment basin.

The flow rate showed a direct relationship with the depth of the scour hole and the height of scour mound, i. e. by increasing the flow rate, these parameters increased and vice versa.

By increasing the tail water depth, the depth of the scour hole decreased, but the height of the downstream mound increased.

Increasing rate of the scour hole depth during the experiment followed a logarithmic pattern and by time, the growth rate reduced but never stopped.

By increasing the Froud Densimetric dimensionless parameter (Fr_d), both the non-dimensional ratios of $\frac{h_s}{H_w}$ and $\frac{h_c}{H_w}$ increased.

The general equation format for predicting dimensions of the scour presented as follows:

$$\frac{\psi}{H_w} = K \times \left(\frac{T_w}{H_w}\right)^a \times \theta^b \times (Fr_d)^c$$

Distance between the maximum height of the scour mound and the water surface level (F_h) for all the three falling jet culvert angles increased by tail water depth and decreased by the flow rate.

Acknowledgments

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