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Laboratory Study for the Local Scour Downstream Drops

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Abstract: *Drops are widely used in many artificial water streams such as open channel drains and flash flood channels to allow for the sudden increase in the discharge and consequently the flow depth. Turbulency associated with flow over drops results in deterioration in the channel bed due to the scour hole that takes place downstream the drop. This paper presents the results of a laboratory study of short duration (5 to 90 min) clear water scour tests downstream drops in erodible bed (medium sand). Experiments examined the effects of time, flow parameters and drop geometry on the dimensions of the scour hole. The dimensions under study are the maximum scour depth, the length of the scour hole, and the scoured volume. The study concentrates on the effect of the drop slope on the scour parameters. Four models with different drop slopes and one model with no drop were tested. It was found that the scour hole dimensions increase with the increase of the discharge factor and time. The relative depth of scour decreases while both the relative length and volume of scour increase as the drop slope gets steeper.*

Key words: *Open Channel, Local Scour, Laboratory Study, Drops, Scour Hole Dimensions.*

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I. Introduction And Literature Review

Scour is the excavation and removal of material from bed and banks of streams because of the erosive action of flowing water. This erosive action may potentially harm the erodible channel boundaries and hydraulic structures, and it is the main cause of failure of these structures. Drop structures are widely used in drains and flash flood channels where the flow discharge increases abruptly due to laterals discharging in the mainstream. Scour holes take place downstream drops due to high turbulence as position head is abruptly converted to velocity head. Due to the wide use of drop structures and the bad effects on the channel sections caused by local scour, the topic has received large attention from researchers all over the world.

Doehring and Abt[5] conducted an experimental study to determine how drop height beneath a culvert outlet affects the dimensions of local scour. They concluded that culverts placed above the bed level result in deeper, wider, and shorter scour holes. **Ojha[10]** studied variation of scour dimensions with drop heights situated downstream pipe outlet. **Lenzi et al.[8,9]** compared sour holes below grade-control structures in mountain rivers located in the eastern Italian Alps with the case of natural steps. They found that the jet thickness and drop height determine the scour hole dimensions. **Adduce and La Rocca[1]** conducted three series of laboratory experiments to investigate local scour downstream of a trapezoidal drop followed by a rigid apron. **Dey and Raikar[4]** studied scour below a high vertical drop where drop height/critical depth >1. **Thomas et al.[11]** studied case of natural steep drops in Colorado. **Ghodsian et al.[7]** developed new equations for the parameters of the scour hole occurred due to free fall jets based on experimental measurements. They found that by increasing the sediment non-uniformity parameter, the scour hole parameters decrease. **Castillo and Carrillo[2]** analyzed the expected depth and scour shape in the Toachi River, Ecuador as a result of the construction of the Toachi Dam using four approaches: 1) laboratory model, 2) 36 empirical formulae, 3) a semi-empirical methodology based on pressure fluctuations-erodibility index, and 4) FLOW-3D numerical simulations. Other attempts may be found in the references given at the end of this paper.

In the present study, the results of laboratory experiments to study the scour hole dimensions downstream sloped drop are presented. The effect of flow parameters, slope geometry, and time are studied. It is hoped to add a new insight to the phenomena.

II. Theoretical Background

In this study, the maximum depth of scour, D, is the dependent variable. It can be expressed as a function of the independent variables as follows:

$$D = f\,(W, H, S, Y, U, Q, D_{50}, \gamma_s, \rho, \nu, g, t, L, V) \qquad (1)$$

Where; W is the width of the channel, H is the drop height, S is the drop slope, Y is flow depth, U is flow mean velocity, Q is rate of flow, D_{50} is the mean sediment diameter, γ_s is the sediment submerged weight, ρ and ν are fluid mass density and kinematic viscosity respectively, g is gravity acceleration, t is time, L is the length of scour hole, and V is the volume of the scoured soil.

In this study, W, H, D_{50}, and γ_s are kept constants, and the viscosity effects are neglected. Applying the Buckingham л-theory, the relative main scour hole dimensions can be expressed as follows:

$$D/Y,\ L/Y,\ \text{or}\ V/Y^3 = f\,(t/t_o,\ Q^2/gY^5,\ S,\ F) \qquad (2)$$

Where D/Y, L/Y, V/Y^3 are the relative depth, length, and volume of scour hole respectively, t/t_o is the time of scour normalized by a characteristic time t_o, Q^2/gY^5 is the discharge factor, and F is the Froude number.

III. Experimental Work

Experiments were conducted in an outdoor concrete flume of the re-circulating type. The length of the flume is 23.2 m. It consists of two identical rectangular concrete sections, 80 cm wide and 90 cm deep, separated by a 30 cm thickness concrete wall. Water is pumped to enter the first section of the flume, then passes to the second section where the test models are located, then finally gets back to the supply ground tank. A drainage system was installed to dry the sand bed before measuring bed configurations. The drainage system consists of 3 perforated UPVC 40 mm diameter pipes equipped with sluice valves to control the rate of bed drying. Water depths and bed configurations were measured using a point gauge fixed on a carriage, and the flow discharge was measured using a pre-calibrated 90° triangular notch.

Five models were used. Four models are shown in Figure no. 1 with the same drop height (H = 24 cm) and different drop slope (S = 0:1, 1:1, 2:1, 3:1) and the fifth model has no drop. The widths of all models were kept constant equal to the width of the channel; 80 cm. Concrete apron of 50 cm long was used downstream of each model. Medium sand (D_{50} = 0.65 mm) was used as bed material. Soil laboratory investigations resulted that the used sand for the flume bed has a specific gravity of 2.65, volume weight of 1.68 t/m^3, and clay and fine dust of 0.76% by weight.

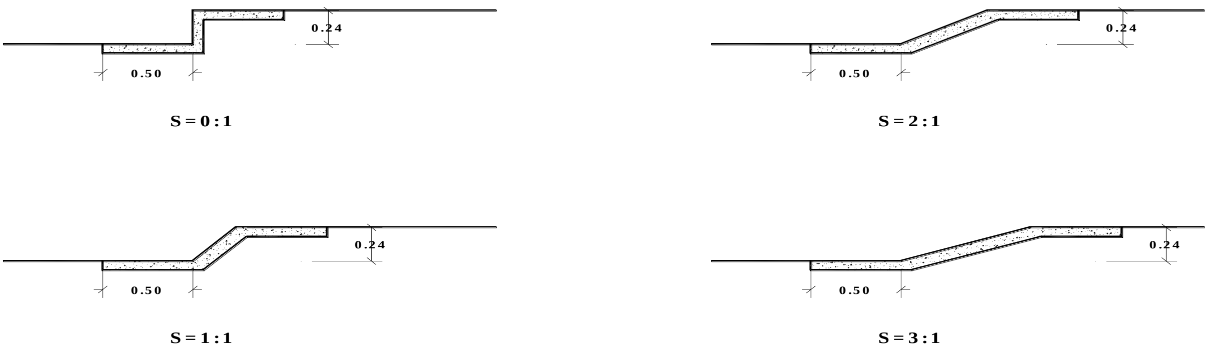

Figure no. 1: The test models

Calibrating preliminary test runs were first conducted to determine the limitations of the test parameters. Then, seventy-five runs were performed. Every model from the five drop models was tested with three different values of flow discharges and five different time steps. In each run, the drop model was constructed using cemented concrete with the required drop angle and the sand bed was leveled to the zero level. Water was allowed to pass with the desired discharge for the required run time. Then, the discharge was cut off and the test section was dried using the drainage system. At times equal 5, 20, 40, 60, 90 min, bed configurations were measured through complete meshes 10 cm × 10 cm. It was observed from the preliminary runs that the scour hole is approximately symmetrical about the center line of the bed width. So, it was decided to measure meshes of only half the flume width. The ranges of the used parameters were 17.17 to 84.95 L/s for discharge, 3.9 to 14.2 cm for water depth, 5 to 90 min for time and 0:1 to 3:1 for the drop slope.

IV. Data Analysis and Discussion

In the coming section, some of the experimental results are presented and discussed based on hydraulic principles to know more about the phenomena.

IV-1. Flow description: Water starts as sheet flow on the chute slope of the drop in a supercritical flow regime. At first, the sheet flow covers the whole flume length but, as the flow accumulates forming a tail water depth, water begins to flow in normal subcritical depth downstream the drop due to the horizontal bed of the flume. The abrupt change of flow from supercritical on the chute slope of the drop to subcritical downstream the drop takes place through some sort of a *hydraulic jump*. Part of this *hydraulic jump* is located on the solid apron and the other part on the sand bed. Due to high turbulency associated with the part of the *hydraulic jump* located on the erodible sand bed, the scour hole is created and develops rapidly.

Changing the drop model to a steeper one, the *hydraulic jump* is pushed away from the solid apron and the part formed on the sand bed gets larger. On the other hand, it was noticed that, as the drop slope gets steeper, the energy lost due to impact of the jet with the horizontal solid apron increases decreasing the turbulence associated with the *hydraulic jump*.

It should be noted that the characteristics of the formed *hydraulic jump* change rapidly with the rapid change of flow characteristics due to the scour hole configurations. So, it is better called *turbulence zone* rather than a *hydraulic jump*.

IV-2. Scour along the centerline and bed configurations: The bed configurations were measured through the center line of the flume downstream of drop each 10 cm for times equal 5, 20, 40, 60, and 90 min as part of the complete 10 cm × 10 cm meshes measured to totally survey the test area after scour effects. Figure no. 2 and Figure no. 3 give samples for the scour along centerline of the flume and bed configurations respectively. The test area may be divided into three main regions.

Region (1) is located just downstream the drop where ripples and dunes are formed due to flow on the mobile bed material. A small scour hole is noticed just downstream the solid apron of the drop. This is due to the change in bed material from concrete to sand resulting in change in roughness coefficient, shear bed stress, and flow carrying capacity. That may be clearer in the case of no drop as the entire scour hole takes place due to the change in bed roughness only.

Region (2) is located just downstream Region (1), where high turbulence and air entrainment occur changing regime of flow from supercritical flow downstream the slope of drop to subcritical flow in the tail section. High turbulence and kinetic energy in this region create the deepest scour hole. This region may be called "The main scour hole region". The upstream slope of the main scour hole is much steeper than the downstream one.

Region (3) is located downstream Region (2) at the end of scour hole, where water section goes back to normal flow conditions (subcritical) and most of water energy is lost through turbulence and air entrainments. It is noticed that this region is the largest with respect to area but has a rather small depth of scour.

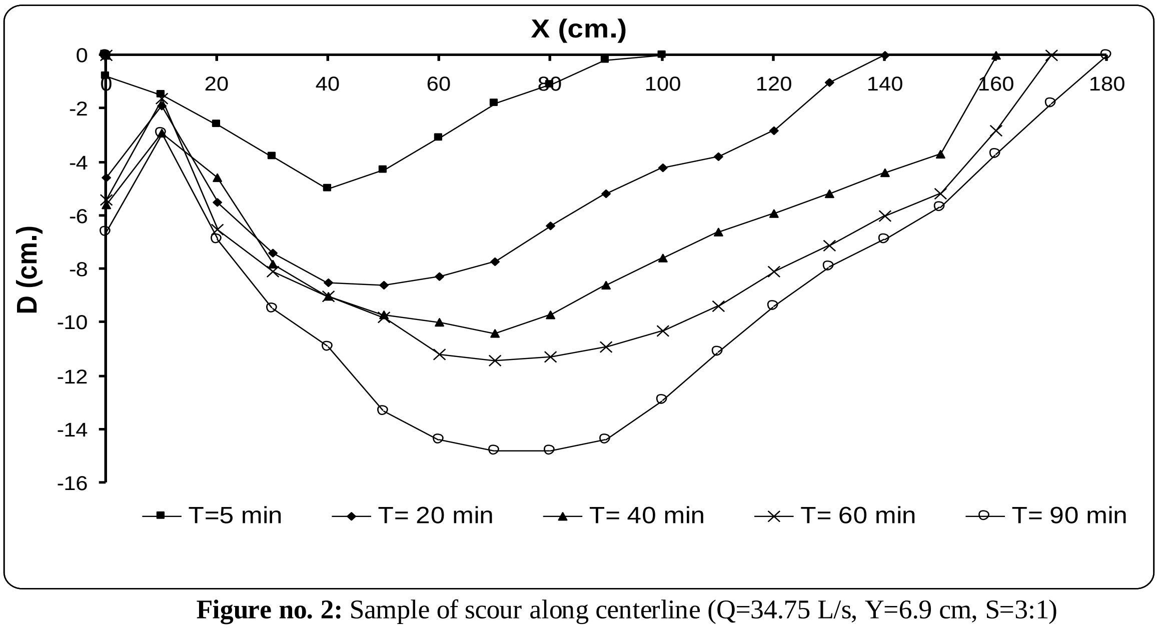

Figure no. 2: Sample of scour along centerline (Q=34.75 L/s, Y=6.9 cm, S=3:1)

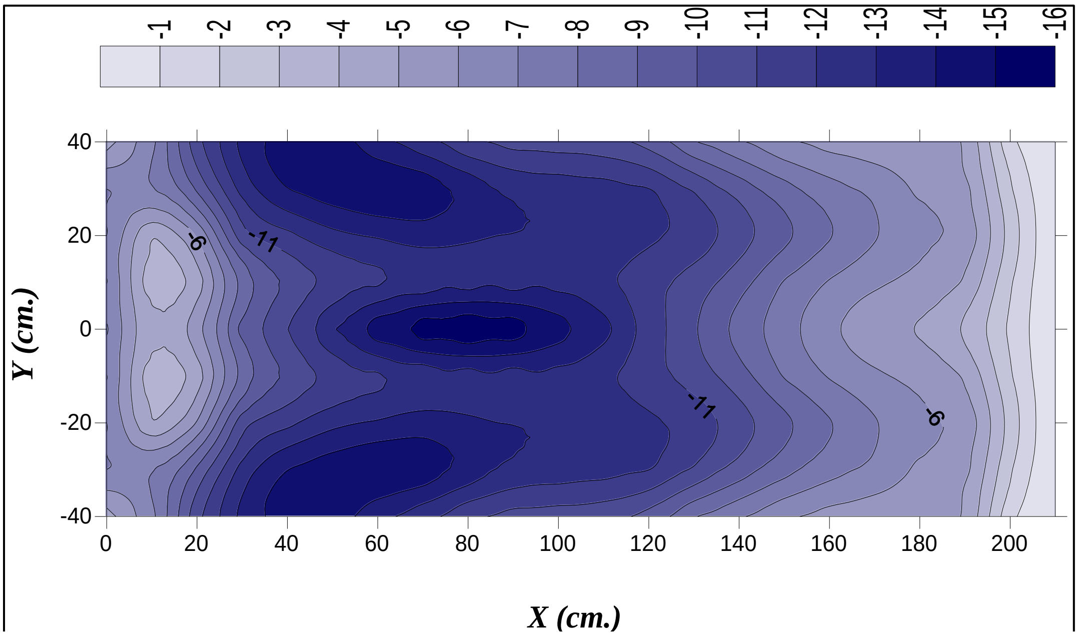

Figure no. 3: Bed configuration after scour (Q=59.12 L/s, Y=9.1 cm, t=90min, S=3:1)

IV-3. Effect of time on scour parameters: Figures no. 4, 5, 6 show samples of the time variation of the relative maximum depth of scour hole (D/Y), the relative length of scour hole (L/Y), and the relative volume of scour hole (V/Y^3) for the case of S=1:1 at different Froude numbers (F). The scour parameters are normalized by the depth of flow and the time is normalized using a characteristic time, t_o. The marks give the measured values, and the solid lines give the best fit.

It can be noticed from the sample figures that the relative scour parameters increase with the increase of time, while the rate of their increase decreases with time. This may be explained as local scour occurs due to the increase of the flow velocity and bed shear stress. With time, and as the scour increases, the flow depth increases, and the flow sectional area increases. Hence, the flow velocity and the bed shear stress decrease. Consequently, the rate of scour decreases with time. Statistical analysis resulted in the following equation for the relation between any relative scour parameter and time:

$$\text{Relative Scour Parameter} = a_1 \, \text{Ln}\left(\frac{t}{t_o}\right) + a_2 \qquad (3)$$

a_1 and a_2 are coefficients that were found to vary with the flow parameters and the drop slope, S.

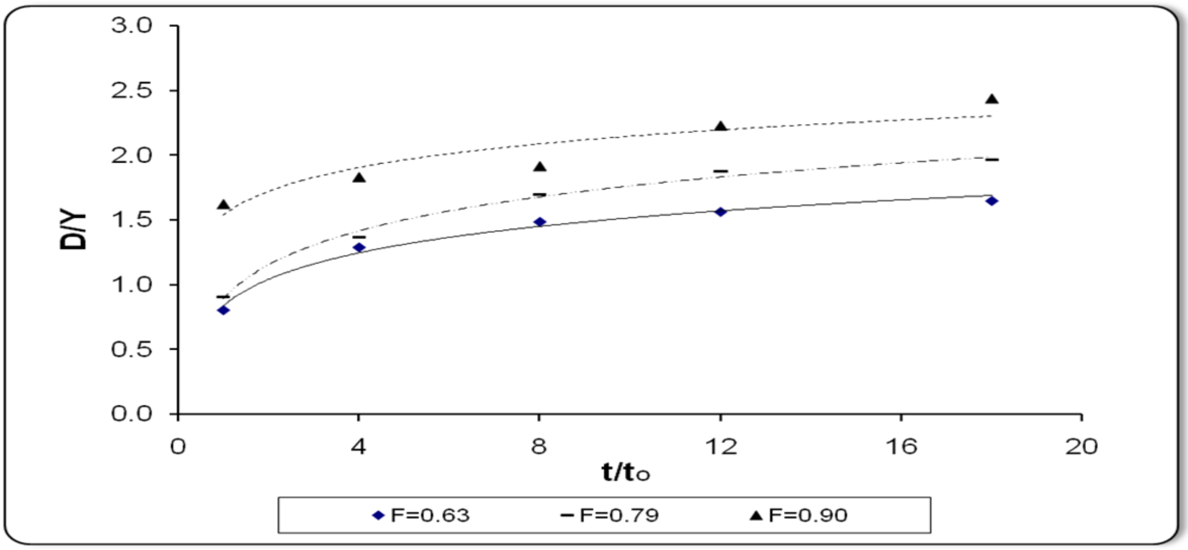

Figure no. 4: Variation of D/Y with t/t_o at different Froude Numbers (S=1:1)

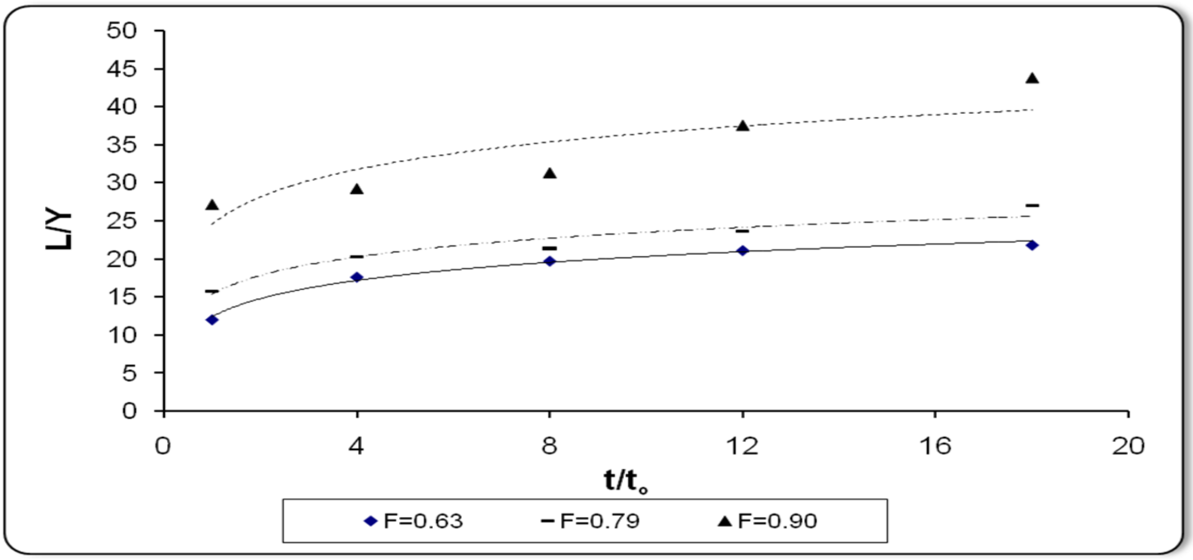

Figure no. 5: Variation of L/Y with t/t_o at different Froude Numbers (S=1:1)

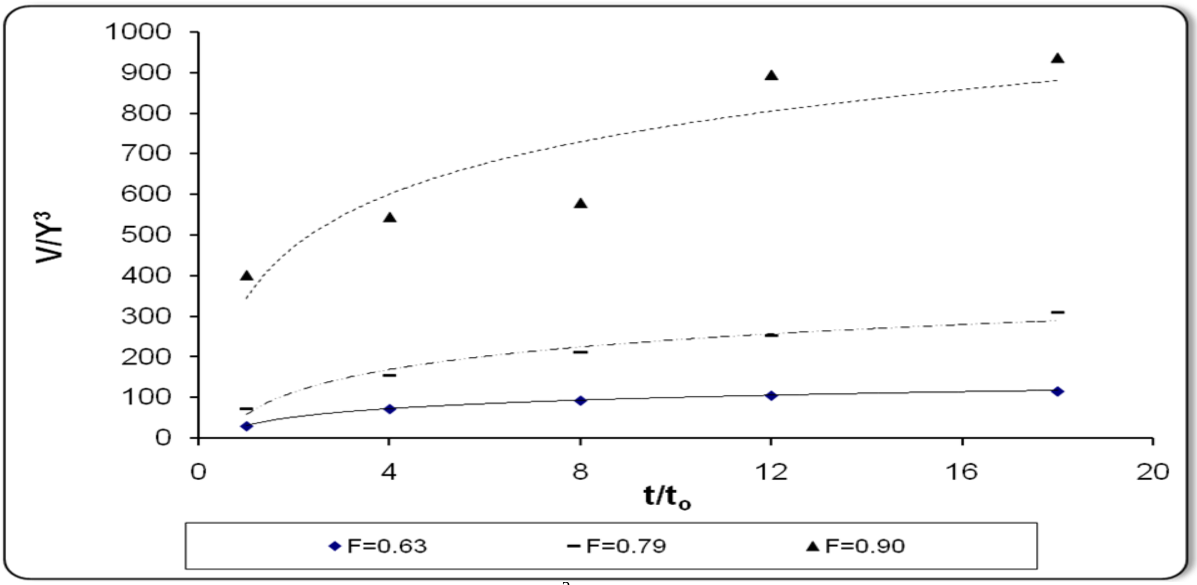

Figure no. 6: Variation of V/Y^3 with t/t_o at different Froude Numbers (S=1:1)

IV-4. Effect of discharge factor on scour parameters: Figures no. 7, 8, 9 demonstrate the relations between the discharge factor that was determined through the theoretical background (Q^2/gY^5), and the three relative scour parameters. The figures are drawn at constant relative time, t/t_o = 18.

In every figure, five different curves are drawn, one for every drop slope namely 0:1, 1:1, 2:1, 3:1, and the case of no drop. It is clear that any of the relative scour parameters increases with the increase of the discharge factor for all the studied drop slopes. This may be easily explained noting that the selected discharge factor is a measure of the carrying capacity through the discharge, Q, the inertia through the gravity, g, and the flow depth, Y. The increase of the discharge factor means increase of the discharge and/or decrease of the flow depth. This results in an increase of the flow velocity, resulting in an increase of the kinetic energy and bed shear stress bringing about an increase in the scour hole dimensions.

IV-5. Effect of drop slope on maximum depth of scour: Referring to Figure no. 7, it is noticed that for the same value of discharge factor, the relative maximum depth of scour (D/Y) decreases as the slope gets steeper from 3:1 to 0:1. This may be explained taking into consideration that the scour hole is affected by the impact of the falling jet and the energy of the moving jet as it leaves the rigid apron and approaches the erosive sand bed in Region (2), which is the main scour hole region. With regards to Figure no. 1, the models used in this study were designed to be as close as possible to the real drop structures used in field where solid aprons are usually constructed just downstream the drop. The existence of this apron vanishes the effect of the impact of the falling jet. Hence, the scour is due to energy of the turbulence zone only. Such energy decreases as the slope gets steeper resulting in less maximum depth of the scour hole.

IV-6. Effect of drop slope on relative Length of Scour and Relative Volume of Scour: Referring to Figures no. 8 and 9, here are two main factors affecting the values of relative length of scour and relative volume of scour. Factor no. 1 is how far the turbulence zone is pushed away from the solid apron. Factor no. 2 is the value of energy in the turbulence zone. The following can be noticed:

- For the model with the steepest slope 0:1, even though a major part of the turbulence zone was pushed away from the solid apron to the sand bed, the relative length and relative volume of the scour hole are less than other models. This is due to the loss of most of the value of energy in the turbulence zone during the hard impact between the falling jet and the solid apron. That is factor no. 2 governs this case.
- For the other three models, the relative length and relative volume of the scour hole increases with the increase of slope sharpness as a greater part of the turbulence zone is pushed away from the solid apron affecting the sand bed. That is factor no. 1 governs these cases.

In all cases, it is also noticed that the relative depth of scour, the relative length of scour, and the relative volume of scour in case of no drop, where scour is due to change in bed roughness only, is much less than the other cases with drops.

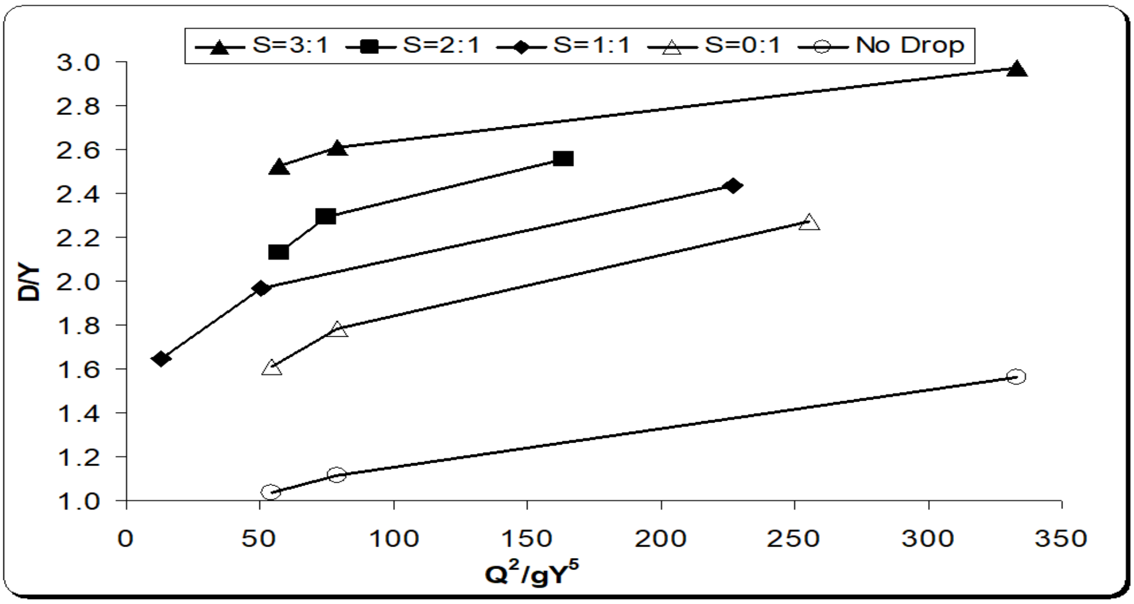

Figure no. 7: Variation of D/Y with Q^2/gY^5 at Different Drop Slopes (t/t_o=18)

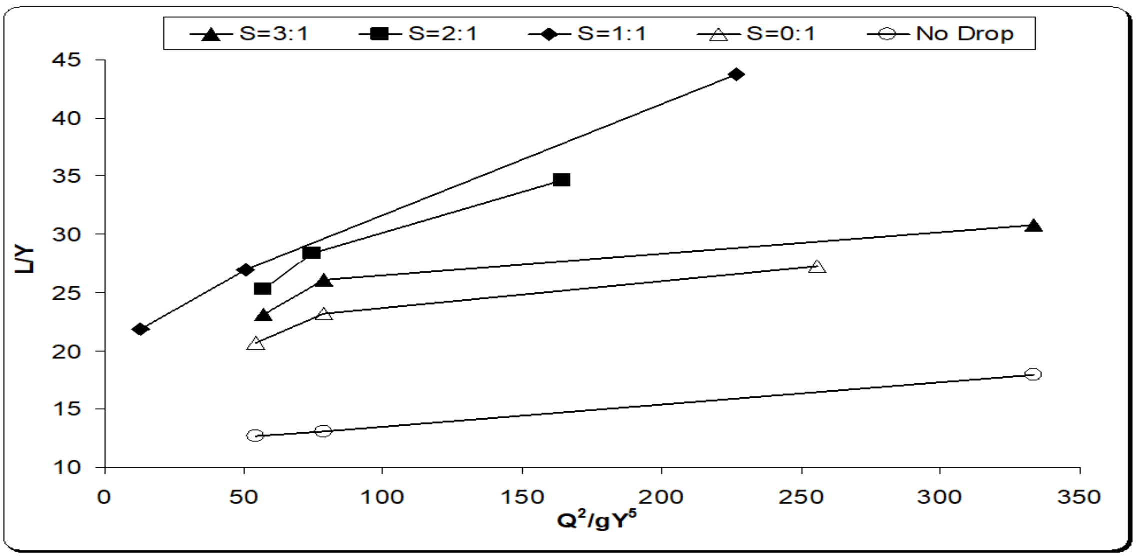

Figure no. 8: Variation of L/Y with Q^2/gY^5 at Different Drop Slopes (t/t_o=18)

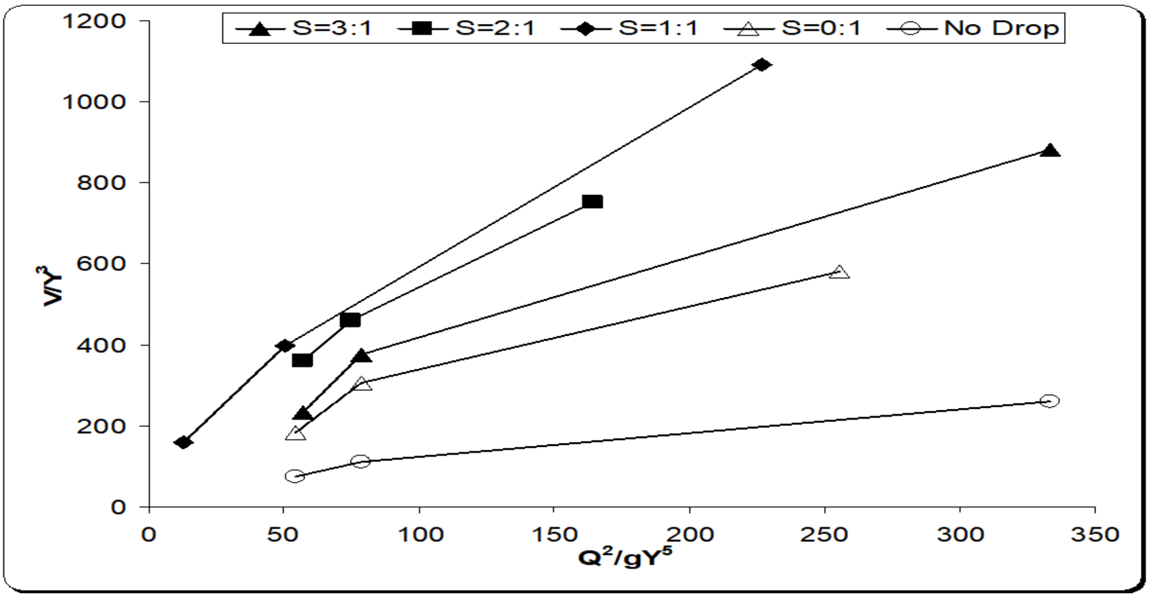

Figure no. 9: Variation of V/Y^3 with Q^2/gY^5 at Different Drop Slopes (t/t_o=18)

V. Conclusions

In this work, the laboratory results of the scour downstream open channel flume were presented. Five models were tested for different discharges and time intervals. Within the study limits, the following could be concluded:

- The sharpness of the drop slope results in pushing the turbulence zone away from the solid apron bringing about scour hole in the erodible flume sand bed.
- The scour effect downstream drops is symmetrical around the flume centerline and consists of three scour hole regions.
- The scour hole relative maximum depth, relative length, and relative volume increase with time in a logarithmic trend with rates that decrease with time.
- The scour hole relative maximum depth, relative length, and relative volume increase with the discharge factor due to the increase in velocity energy and shear stresses.
- The case of no drop gave minimum relative scour hole dimensions that resulted from the change of bed material from cemented concrete to sand.
- The case of drop slope = 0:1 gave minimum relative scour hole dimensions with respect to other drops as most of the velocity energy was lost during the impact between the solid apron and the falling jet.
- The relative maximum scour hole depth increases as the drop slope gets milder.
- The relative scour hole length, and relative scour hole volume increase as the drop slope gets sharper.

Symbols and Abbreviations

a_i	Coefficients defined elsewhere.	D	The maximum depth of scour
D_{50}	The mean sediment diameter	F	Froude number
g	gravity acceleration	L	The length of scour hole
Q	Flow discharge	S	Drop slope
t	Time	t_o	Characteristic time
U	Flow mean velocity	V	Scour hole volume
W	Flume width	Y	Flow depth
γ_s	the sediment submerged weight	ρ	Fluid mass density
ν	Fluid kinematic viscosity		

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