LOCAL SCOUR DOWNSTREAM DROP STRUCTURES

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ABSTRACT

Equilibrium scour hole downstream drop structures was theoretically and experimentally studied. A sum of 27 experiments was performed to examine the effect of the angle of inclination of the sloping face of the drop structure, the difference between the upstream and downstream water level and Froude number of the downstream flow on the dimensions of the equilibrium scour hole. Using the experimental data, a semi-empirical equation was developed to express the maximum equilibrium scour hole depth and length. It was found that the dimensions of the scour hole decreases with the increase of the tailwater depth and increases with the increase of the angle inclination of the sloping face of the drop structure, Froude number, the height of the drop structure and the impinge jet velocity.

Keywords: Drop structures, Local scour, Jet diffusion, Local bed shear stress.

Notations

C	jet diffusion coefficient
ds	Maximum equilibrium scour hole (cm)
d_{50}	Median diameter of the bed mixture (mm)
E_c	Erosion parameter
Fr	Froude number
g	gravitational acceleration (cm/sec^2)
L_j	Length of the diffused jet (cm)
Ls	Length of the scour hole (cm)
Q	Rate of flow (Liter/sec)
s	Specific gravity of sediment
T_{*c}	Dimensionless critical shear stress (Shields number)
v_i	Impinge average jet velocity (cm/sec)
$V_{D.S.}$	Average velocity of flow downstream the drop structure (cm/sec)
v_s	Average jet velocity at the bed level (cm/sec)
Y_c	critical depth (cm)
Y_D	Difference between the upstream and downstream water levels of the drop structure (cm)
$Y_{D.S.}$	Depth of flow downstream the drop structure (cm)
Y_i	Thickness of the jet at the tailwater level (cm)
Z	Height of the drop structure (cm)
α	Angle of inclination of the sloping face of the drop structure
γ	Specific gravity of fluid (gm/cm^3)
σ_g	Geometric standard deviation of bed mixture
τ_b	Local shear stress at the bed level (gm/cm^2)
τ_c	Critical shear stress of the bed mixture (gm/cm^2)

INTRODUCTION

Drop structures are constructed in alluvial streams either to reduce its longitudinal slope or to prevent excessive channel bed degradation. The fall velocity downstream drop structures causes significant local scour downstream the drop structures, which may undermine these structures. Therefore, it is important to determine the value of the maximum equilibrium scour depth and its location to protect the drop structures from failure. During the past four decades several experimental attempts have been carried to study the hydraulics of drop structures and the relationship between the height of the drop structure and the local scour occurred downstream it. Laursen [5] stated that local scour occurred when the sediment transport capacity of an eroded section is greater than the rate of supply of material to that area and the rate of erosion will decrease as the flow section is enlarged.

N. Rajaratnam and R. Macdougal [8] studied experimentally erosion of sand bed by plane turbulent wall jets. They concluded that the maximum equilibrium scour depth is function of density metric Froude number "F_o" which is *defined as* $\frac{v_i}{\sqrt{g d_{50}(s-1)}}$. *Where "$v_i$" is the jet* velocity, d_{50} the median diameter of the bed mixture and "s" is the specific gravity of the bed sediments. Their experiments showed that the location of the maximum scour depth moved to downstream direction as the tail water increased.

F. Blaisdell, C. Anderson and G. Hebaus [2] compared the growth of local scour dimensions caused by baffles, piers, spillway apron and pipe outlets. They developed a relationship between the logarithm of the average velocity of scour and the logarithm of time. Their equation has a hyperbolic form which means that the progress of local scour will never stop with time but it slow down with the increase of time.

N.E. Bormann and P.Y. Julien [4] studied theoretically and experimentally local scour downstream grade control structures. They found that local scour downstream grade structures depend on impinging jet velocity, the inclination angle of the jet and the diffusion length. Empirical relationships were developed to express the position of maximum local scour in term of jet diffusion in a plunge pool.

O.R. Stein, C.V. Alonso and P.Y. Julien [10] investigated the mechanics of jet scour downstream of a headcut. They developed empirical equations to determine the equilibrium scour depths of scour hole as a function of critical shear stress of bed mixture.

N.R. Rajaratnam and O. Aderibigbe [9] investigated erosion of loose submerged circular impinging vertical turbulent jets. They developed a so called erosion parameter "E_c" which is defined as the ratio of the force exerted by circular jet on a bed particle located directly under the jet at original bed level to its resistive force. They classified the circular jets into two regimes: Strongly deflected jet for E_c greater than 0.35 and weakly deflected jet when E_c less than 0.35.They developed empirical equations to estimate the maximum equilibrium scour depth and the scour hole radius in term of relative submerged unit weight of sediment and erosion parameter.

The aim of this study is to investigate the effect of the drop structure geometry, the flow conditions upstream and downstream the drop structure on the equilibrium scour hole dimensions and to develop an empirical equation to estimate the *dimensions of the scour hole.*

THEORETICAL ANALYSIS

When there is a significant abrupt drop in bed channel level and the downstream flow level is less than the upstream bed level, the flow will leave the upstream bed forming a jet. This jet will impinges the downstream channel with a velocity "v_i" and angle of inclination equals the angle of inclination of the upstream face of the drop structure"α". The jet velocity will be diffused in the tailwater depth and intrude the downstream bed level with a velocity "v_s". Figure (1) shows a definition sketch of drop structure. The diffused jet velocity will produce bed shear stress "τ_b" which can be expressed as follows:

$$\tau_b = C_f \rho v_s^2 \tag{1}$$

Where ρ is the mass density of water and C_f is the local friction coefficient. Bogardi [3] expressed the C_f as follows:

$$C_f = 0.3448 T_{*c} \left(\frac{d}{Y_i}\right)^{0.19} \tag{2}$$

In which T_{*c} is Shields number for noncohesive particles having mean diameter "d" and "Y_i" is the thickness of the jet.

If the developed bed shear stress is greater than the critical shear stress of the bed mixture "τ_c", local scour will take place at this spot and the downstream water depth at the same spot will be enlarged. This means the length of the diffusion jet will be increased and the jet velocity on bed "v_s" will be decreased and consequently the shear stress will be reduced. Therefore, the scour rate is gradually decreased till it is completely stopped when the bed shear stress equals the critical shear stress of the bed material.

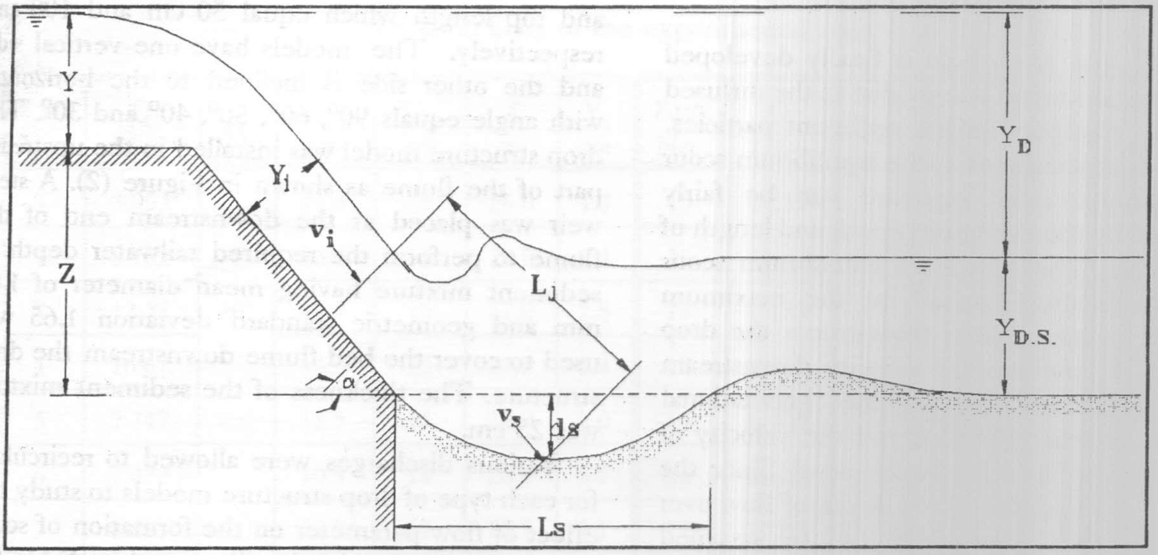


Figure 1. Definition sketch.

Albertson et al [1] obtained the following formula for the diffused jet velocity in the scour hole boundary:

$$v_s = C_j v_i \left(\frac{Y_i}{L_j}\right)^{0.5} \tag{3}$$

Where C_j is the jet diffusion coefficient depends mainly on inlet conditions. Albertson [1] and Rajaratnam [7] suggested that the C_j range from 2.0 → 2.4, v_i is the impinge velocity, and Y_i and L_j are the jet thickness and the length of jet diffusion, respectively (Figure 1). Substituting equation (3) into equation (1), equation (1) can be written as follows:

$$\tau_b = C_f C_j^2 v_i^2 \left(\frac{\gamma}{g}\right)\left(\frac{Y_i}{L_j}\right) \tag{4}$$

Equating the critical shear stress of the bed mixture to the bed shear stress to get the equilibrium condition, the length of diffused jet can be obtained from equation (4) as follows:

$$L_j = C\left(\frac{\gamma}{\tau_{cr}}\right)\left(\frac{v_i^2 Y_i}{g}\right) \tag{5}$$

Where C is constant and equals $C_f C_j^2$.

According to the definition sketch shown in Figure (1), the length of diffused jet can be expressed as follows:

$$L_j = \frac{Y_{D.S.} + ds}{\sin\alpha} \tag{6}$$

In which $Y_{D.S.}$ and "α" is the angle of inclination of the surface face of the drop structure.

Substituting equation (6) into equation (5), the maximum scour depth "*ds*" can be estimated as follows:

$$ds = C\left(\frac{\gamma}{\tau_{cr}}\right)\left(\frac{v_i^2 Y_i}{g}\right)\sin\alpha - Y_{D.S.} \tag{7}$$

The value of "C" is evaluated from the experimental runs and it is called in the present study jet diffusion coefficient.

DIMENSIONAL ANALYSIS

The equilibrium scour hole is finally developed when the excess kinetic energy due to the diffused jet could not transport further sediment particles. Therefore, the dimensions of the equilibrium scour hole downstream drop structure can be fairly characterized by the maximum depth and length of the scour hole. The maximum equilibrium scour hole length depends mainly on the maximum scour depth, depth of flow downstream the drop structure"$Y_{D.S.}$", the average velocity downstream the drop structure "$V_{D.S.}$", the gravitational acceleration "g", the thickness and the velocity of the jet "Y_i" and "v_i" at the tailwater level. Since the value of "v_i" is a function of the depth of flow over the drop structure edge which can be assumed equals the critical depth "Y_c", the difference of the upstream and downstream water levels "Y_D" and the height of the drop structure "Z".

The maximum equilibrium scour length can then be expressed as follows:

$$Ls = f\left(ds, Y_i, Z, V_{D.S.}, Y_{D.S.}, Y_D, Y_c, g, \sin\alpha\right) \quad (8)$$

Applying the Buckingham theory (π- theory) on equation (8), the following normalized equation is developed:

$$\frac{Ls}{ds} = f_1\left(Fr, \frac{Y_c}{Y_D}, \frac{Y_i}{Z}, \sin\alpha\right) \quad (9)$$

Where Fr is Froude number of the flow downstream the drop structure $= \dfrac{V_{D.S.}}{\sqrt{g Y_{D.S.}}}$

EXPERIMENTAL SETUP

For the purpose of observing the effect of the surface slope of the drop structures, a set of 27 experimental runs was conducted in the hydraulic laboratory, Faculty of Engineering Alexandria University. The experiments were conducted in a glass walled tilting flume of width 86 cm and length 12.0 m. Five different drop structure models were constructed having the same height and top length which equal 50 cm and 100 cm, respectively. The models have one vertical side and the other side is inclined to the horizontal with angle equals 90°, 60°, 50°, 40° and 30°. The drop structure model was installed in the upstream part of the flume as shown in Figure (2). A steel weir was placed at the downstream end of the flume to perform the required tailwater depth. A sediment mixture having mean diameter of 1.65 mm and geometric standard deviation 1.65 was used to cover the bed flume downstream the drop structure. The thickness of the sediment mixture was 25 cm.

Various discharges were allowed to recirculate for each type of drop structure models to study the effect of flow parameter on the formation of scour hole, a details of which are illustrated in Table (I).

In order to prevent the formation of local scour at the unsteady flow experimental period, the downstream the drop structure was filled with water to a depth equals the height of the weir. Water was then allowed to circulate with the required discharge for a sufficient period of time till equilibrium stage is practically attained. The flow was then gradually reduced and the flume was slowly drained. During each run the discharge, the depth of flow over the drop structure, along the sloping surface and downstream the drop structure were measured. At the end of each run, the bed levels along the center line of the downstream reach was measured.

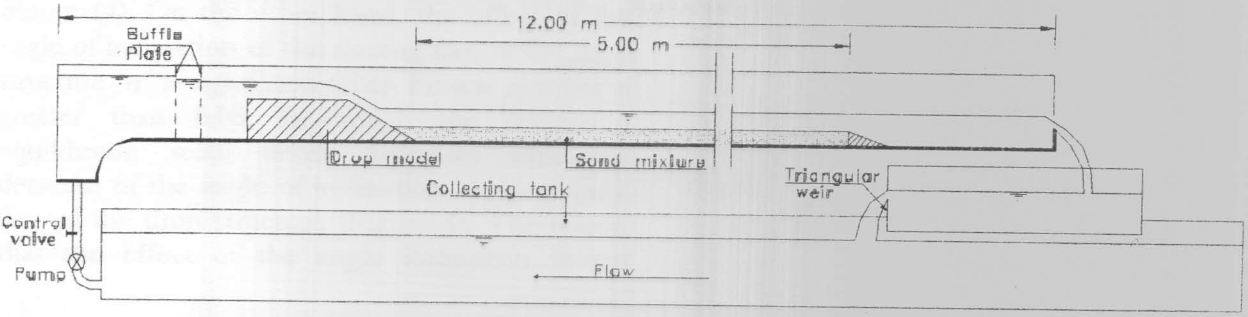
ANALYSIS OF THE RESULTS

As the design discharge was allowed to circulate, the scour downstream drop structure takes place and increases rapidly in the first hour of the experimental time. After that the rate of increase of the scour hole dimensions gradually decreases with time till it is practically stopped. All experiments show that the equilibrium scour hole downstream drop structures have the same shape and is not affected by the sloping face of the drop structure as shown in figure (3). The value of the maximum equilibrium scour hole was then determined for each run.

Table I. Data of the experimental runs.

Run No.	Q L/sec	α	$Y_{D.S.}$ cm	Y_D cm	Z cm	Y_i cm	Run No.	Q L/sec	α	$Y_{D.S.}$ cm	Y_D cm	Z cm	Y_i cm
1	3.993	90°	11.4	16	26.0	1.3	15	12.57	50°	12.2	16.8	26.4	3.2
2	9.762		13.2	16	27.0	2.4	16	16.31		12.4	16.6	26.0	3.2
3	12.57		13.7	16	27.0	2.8	17	1.183	30°	8.7	18.6	26.0	2.3
4	16.67		14.5	15	27.0	3.4	18	4.217		9.3	17.4	25.6	0.7
5	7.747		12.5	16	27.0	2.0	19	6.405		8.7	18.3	25.0	1.2
6	7.472	60°	10.5	18	26.6	5.7	20	13.23		10.1	17.5	24.9	1.1
7	9.613		11.2	18	26.7	4.1	21	17.03		11.1	17.0	25.0	1.2
8	17.39		13.3	16	27.3	5.3	22	5.152		8.4	18.7	24.8	0.5
9	2.937		11.2	18	28.1	4.3	23	4.217	40°	9.0	18.5	25.5	1.8
10	4.445		11.9	18	28.1	4.9	24	6.405		10.2	18.3	25.7	2.2
11	1.038		10.6	18	28.1		25	10.06		11.1	18.3	25.5	2.2
12	3.993	50°	10.3	18	26.6	3.0	26	12.57		10.6	18.4	25.6	3.3
13	7.472		10.7	17	26.5	2.2	27	17.39		11.5	17.3	25.6	2.8
14	8.591		11.5	17	26.5	3.0							

Figure 2. Schematic sketch of the experimental setup.



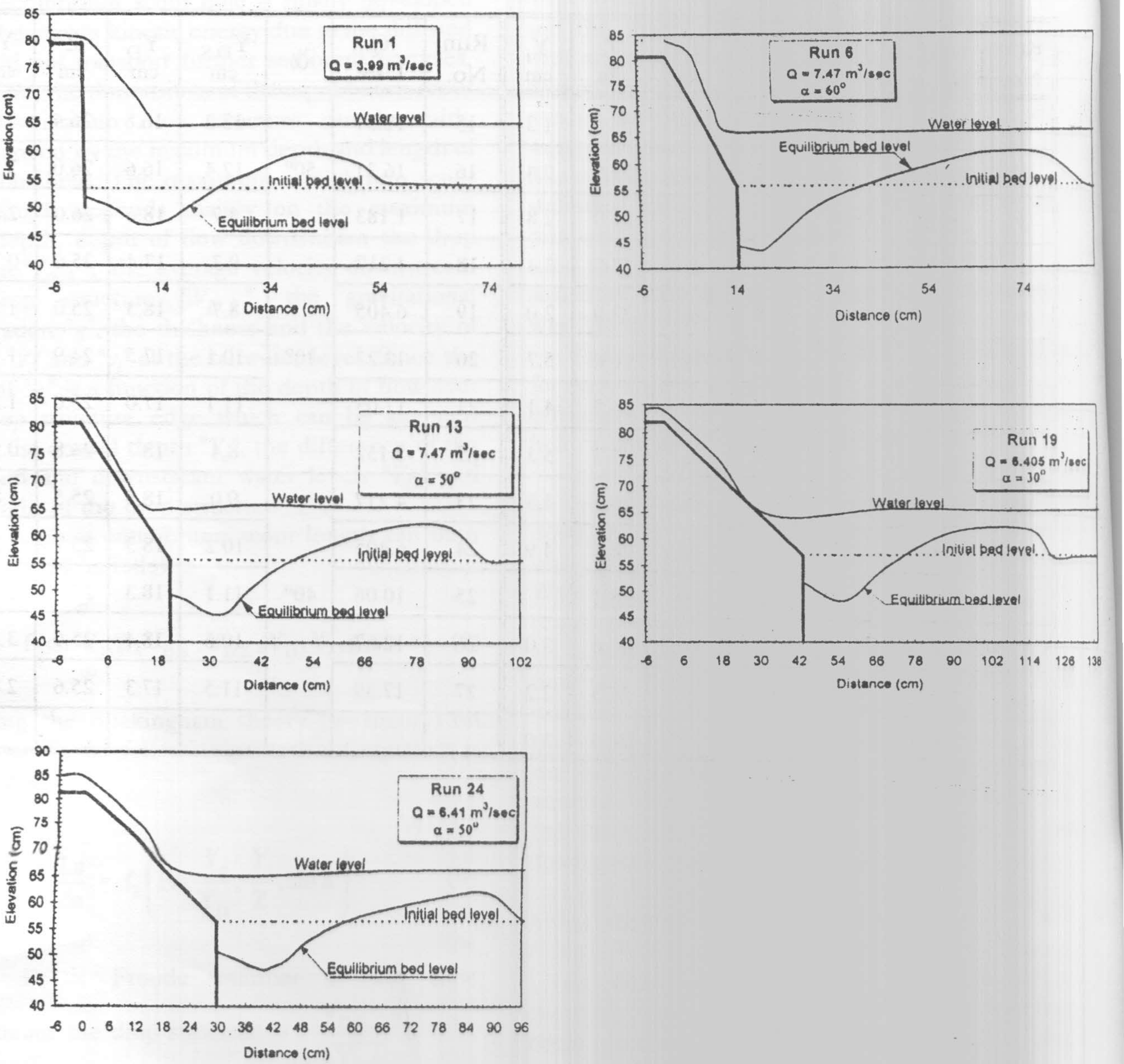


Figure 3. Water surface profile and equilibrium scour hole profile downstream the five models of drop structure.

Table 2. Results of the experiments.

Run No.	Fr	ds (cm)	Ls (cm)	C	Run No.	Fr	ds (cm)	Ls (cm)	C
1	0.039	6.3	24.30	0.03766	15	0.110	16.1	36.53	0.01953
2	0.076	13.3	38.90	0.01712	16	0.139	18.5	47.80	0.01267
3	0.092	16.4	49.70	0.01388	17	0.017	3.0	9.21	0.66519
4	0.112	20.2	60.00	0.01098	18	0.055	5.5	21.00	0.03127
5	0.065	10.5	34.10	0.02022	19	0.093	8.9	31.46	0.02567
6	0.082	12.1	26.80	0.06971	20	0.153	14.7	47.70	0.00843
7	0.095	15.6	33.50	0.03579	21	0.171	18.8	64.00	0.00649
8	0.133	20.9	54.00	0.01818	22	0.079	7.2	22.38	0.01626
9	0.029	8.1	16.40	0.29192	23	0.058	6.5	17.80	0.06232
10	0.040	9.6	19.23	0.16185	24	0.073	9.3	26.87	0.04328
11	0.011	3.7	8.90		25	0.101	11.3	36.53	0.01968
12	0.045	6.8	18.36	0.11082	26	0.135	17.6	50.58	0.02379
13	0.079	10.4	26.90	0.02840	27	0.166	22.7	67.50	0.01308
14	0.082	10.9	29.28	0.03112					

Using the measured values of the discharge and the water depths along the flume and over the drop structure, the values of the critical depth, the average impinge velocity and Froude number downstream the drop structure were calculated. The details of which is illustrated in Table (II). The results of the experiments show that for each drop structure model, the maximum equilibrium scour depth increases with the increase of Froude number of the downstream channel as shown in Figure (4). On the other hand, the effect of the angle of inclination of the sloping face of the drop structure "α" is significant when Froude number is greater than 0.08. In which the maximum equilibrium scour depth decreases with the decrease of the angle of inclination of the sloping face of the drop structure (Figure 4). The reason that the effect of the angle inclination is not significant at low Froude number because the jet is deflected when it impinges the tailwater with angle of inclination greater than α.

The maximum equilibrium scour depth also increases with the increase of the ratio of the critical depth to the difference between the water level upstream and downstream drop structures $\frac{Y_c}{Y_D}$. The relationship between the ratio of the critical depth to the difference between the water level upstream and downstream drop structures $\frac{Y_c}{Y_D}$ and the relative maximum equilibrium scour depth $\frac{ds}{d_{50}}$ is given in Figure (5).

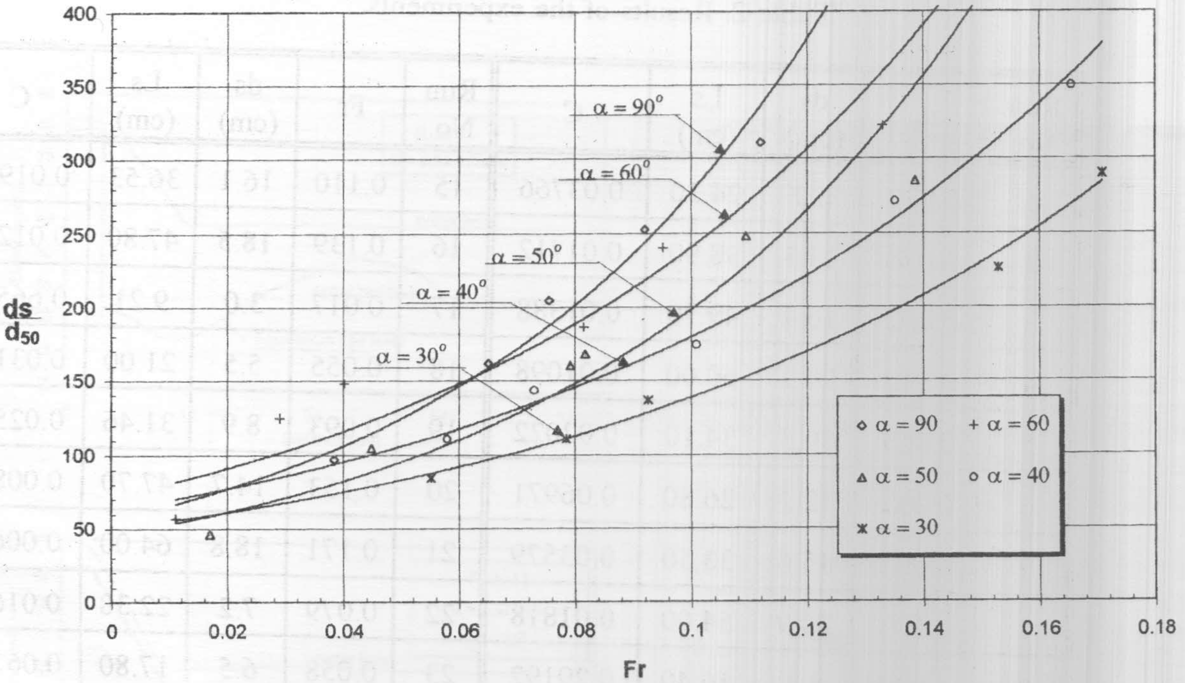


Figure 4. Relationship between froude No. and relative maximum scour depth.

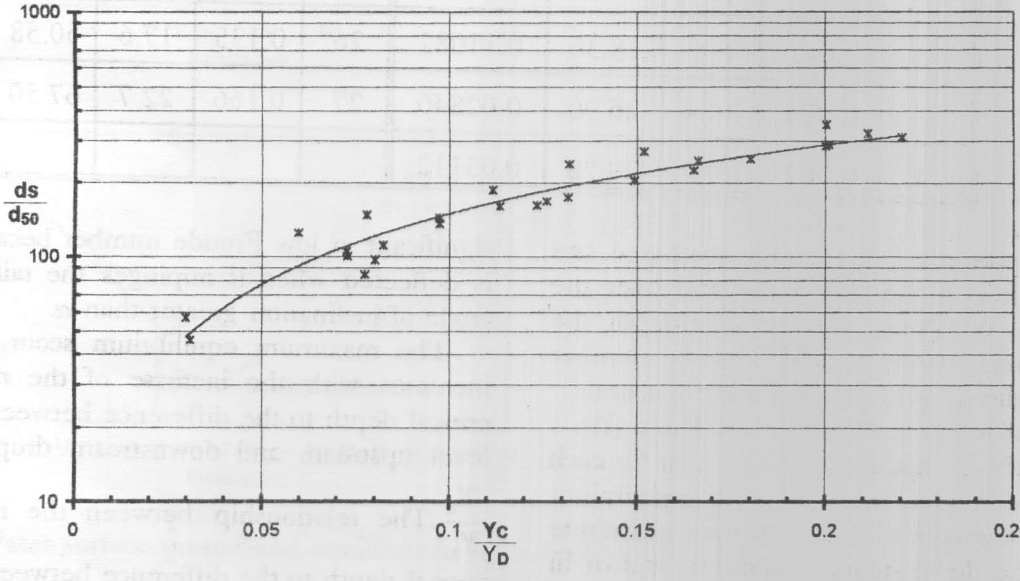


Figure 5. Variation of the ratio of the critical depth to the difference of U.S. and D.S water levels versus the relative maximum scour depth.

The value of the jet diffusion coefficient *"C"* driven from equation (7) was evaluated from the experimental results. Analyzing the experimental data, it was found that the jet diffusion coefficient *"C"* decreases with the increase of $\frac{v_i^2 Y_i}{g}$ as shown in Figure (6).

Applying the least square method on the obtained values of the $\frac{v_i^2 Y_i}{g}$ and the constant "*C*", the following empirical equation expresses this relationship:

$$C = 0.0853\left(\frac{v_i^2 Y_i}{g}\right)^{-0.7949} \qquad (10)$$

The correlation coefficient of equation (10) equals 0.98.

Substituting equation (10) into equation (7), the maximum equilibrium scour depth *"ds"* will then be expressed as follows:

$$ds = 0.8503\left(\frac{\gamma}{\tau_{cr}}\right)\left(\frac{v_i^2 Y_i}{g}\right)^{0.205} \sin\alpha - Y_{D.S.} \qquad (11)$$

Comparing the values of the maximum equilibrium scour depth obtained from the experiments with that estimated from equation (11), it was found that the percentage average standard error of estimate equals 21%. The plot showing the relationship between the average and estimated value of ds obtained from equation (11) is shown by Figure (7).

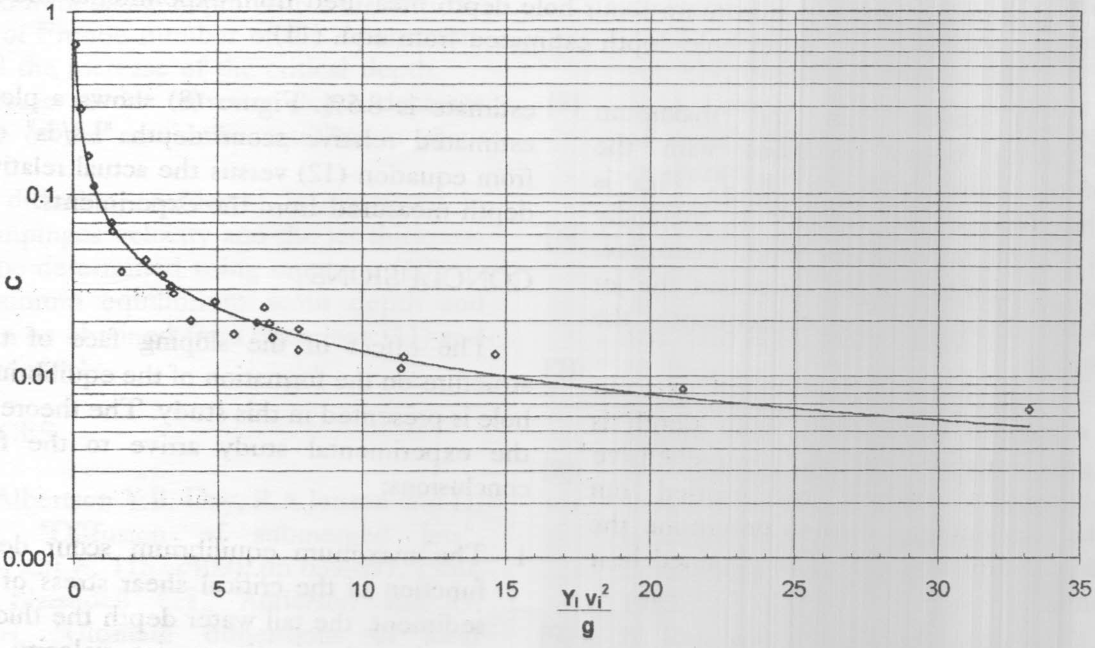


Figure 6. Relationship between diffusion coefficient and $(Y_i\, v_i^2/g)$.

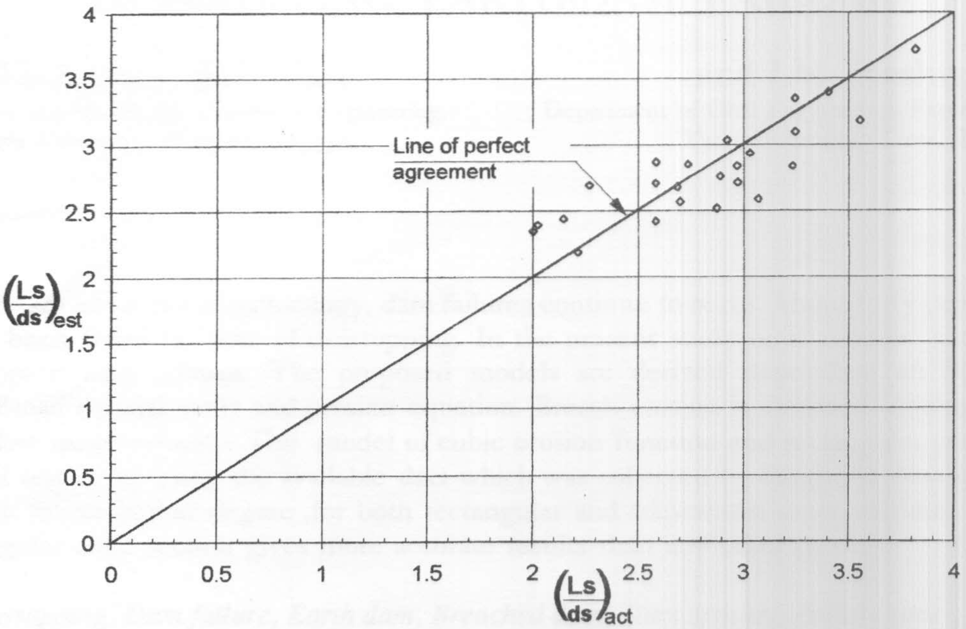


Figure 8. Plot of actual relative scour hole depth length versus relative hole length estimated from equation (12).

3- The maximum scour depth increases with the increase of Froude number of the downstream flow, and the increase of the critical depth.

4- The increase of the tailwater depth decrease the value of the maximum equilibrium scour depth.

5- The jet diffusion coefficient is expressed in term of impinges velocity and the jet thickness and can be determined using equation (10).

6- The maximum equilibrium scour depth and length can be obtained from equations (11) and (12), respectively.

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