Mansoura Bulletin Vol.8, No.2, December 1983

SCOUR BEHIND SLUICE GATES

Zidan, A.R.[1], Owais, T.[2], Abdel-Moati, M.[3]
and El-Masry A.[4].

ABSTRACT:

The influence of variables which affect the local scour depth and length, downstream irrigation gate structures is investigated in this paper.

Experimental verifications of theoretical analyses of the scour depth and length are given, the effect of discharge per unit length of opening width, which flows under a sluice gate, on the scour phenomena is investigated experimentally.

The combined effect of the gate opening, length of the solid floor downstream the gate, and the downstream water depth is also demonstrated.

Empirical formulae for both scour hole depth and scour hole length in terms of Froude number are presented.

INTRODUCTION:

The phenomenon of local scour is defined as the removal of the material from the bed and banks in a confined reach by the act of the fluid in motion. It includes all phases of sediment movement, traction, entrainment, suspension and deposition Ref.(10).

It is necessary to understand the mechanism of local scour and to be able to calculate the potential scour depths and lengths. This mechanism must be considered in the design of hydraulic structures, to accomodate scour, to eliminate it, or to reduce its magnitude by an acceptable degree of accuracy.

Local scour may occur in conjunction with or in the absence of degradation, aggradation. It may be divided into three groups; (i) stable scour hole where the sediment discharge entering the scour hole is equal to the sediment discharge leaving the scour hole; (ii) clear water scour in which the flow of sediment into the scour hole is zero. The erosion is continuous and the depth of

---

1,4) Irrigation and Hydraulics Dept., Mansoura University.

2) Dean and Head of Water Engg. Dept., Fac. of Engg., Zagazig University.

3) Irrigation and Hydraulics Dept., Alexandria University.

scour increases with time until a limiting value is reached; and (iii) scour with varying sediment inflow in which the flow of sediment from upstream may be smaller or greater than the rate of sediment discharge from the scour hole.

The major causes of local scour are the fluctuations of forces, lift forces and shear forces. A complete theoretical solutions of the scour problem seems to be illusionary as the scour is a function of many variables such as; characteristics of section properties of the channel, characteristics of bed material of the site and the transported sediment, characteristics of flood hydrographs and the history of former and recent floods and characteristics of man made hydraulic structures. Tremendous vast studies have been made to get a better understanding of the scour phenomena such as the works given by Carstens Ref.(16), colemon Ref.(7) Doddiah, et al. Ref.(8), Ismail, et al. Ref.(10) Laursen Ref.(11), Leliavsky Ref.(12) and Valentine Ref.(14).

Atinbilek Ref.(1) and Altinbilek and Okyay Ref.(2) tried to develop an expression capable of relating the characteristics of scour hole to the characteristics of flow. Neil Ref.(13) suggested a trial and error procedure to solve the problem of scour. Carstens Ref.(6) defined a sediment number and tried to explain scour phenomena in terms of this number. The work by Breasers Refs.(3,4) suggested that for non cohesive materials at any fixed distance from the end of apron, the depth of scour would approach a limiting value. The maximum depth of scour occured at a point which was continually moving upstream i.e. the upstream part of the scour hole remained unchanged while the downstream part of the process continued.

The main objectives of the present work is to accomplish the following points:

1) Establishing the interrelationship between the main parameters which affect the tail erosion.

2) Cross correlating the tail erosion against the solid floor length for different flow conditions.

3) Development of empirical relationships between the variables involved for practical use, such as those concerning the depth and length of the scour hole.

DIMENSIONAL ANALYSIS:

The following variables were used in the dimensional analysis to serve the problem of scour as the prediction of scour depth and length should be made by using the known values of hydraulic and sediment characteristics in the section and the geometry of the channel under study.

These variables could be classified into four categories:

1) Variables describing the geometry of the channel in which; B = width of the channel section, L_f = solid floor length, and H_g = sluice gate height.

2) Variables describing the kinematics of flow in which; V = mean velocity of flow immediately behind the sluice gate, D_1 = upstream flow depth, D_2 = downstream flow depth and g = gravitational acceleration.

3) Variables describing the fluid properties in which; ρ = density of water and μ = dynamic viscosity of water.

4) Variables describing the sediment properties such as D_{50} = mean diameter of sediment and ρ_s = density of bed material.

References (1) and (5) deal with similarity laws of the local scour.

If D_s is taken as a dependent variable, then;

$$D_s = f\,(V,\ g,\ \rho,\ \rho_s,\ \mu,\ D_{50},\ H_g,\ L_f,\ D_1,\ D_2,\ L_s) \quad \ldots(1)$$

Using dimensional analysis

$$\frac{D_s}{D_2} = \phi\left(\frac{D_2 \cdot g}{V^2},\ \frac{\mu}{V \cdot \rho \cdot D_2},\ \frac{D_{50}}{D_2},\ \frac{H_g}{D_2},\ \frac{L_f}{D_2},\ \frac{L_s}{D_2},\ \frac{D_1}{D_2},\ \frac{\rho_s}{\rho}\right) \quad \ldots(2)$$

$$\text{or } \frac{D_s}{D_2} = \phi\left(\frac{1}{F^2},\ \frac{1}{R},\ \frac{D_{50}}{D_2},\ \frac{H_g}{D_2},\ \frac{L_f}{D_2},\ \frac{L_s}{D_2},\ \frac{D_1}{D_2},\ \frac{\rho_s}{\rho}\right) \quad \ldots(3)$$

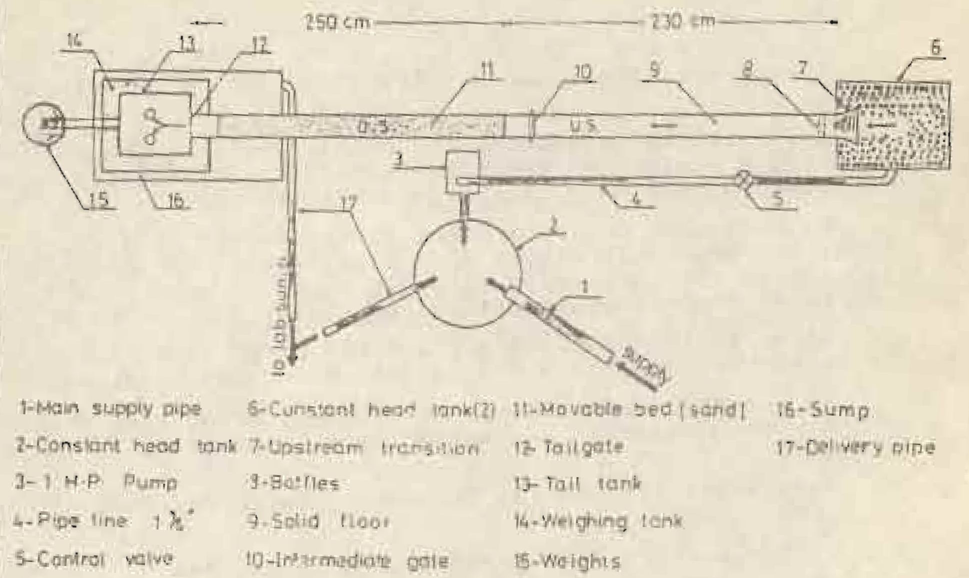
in which; F = Froude number and R is Reynold's number.

With certain manipulations within the theory of dimensional analysis by assuming that the parameter $1/R$ is of secondary importance in estimating the depth of scour as the flow is mainly gravitational flow. Also the term ρ_s/ρ was excluded from the analysis as all experiments were conducted for sand with the same density ρ_s. Each of the main parameters in equation (3) were plotted against the relative scour depth D_s/D_2 and the relative scour length (L_s/D_2).

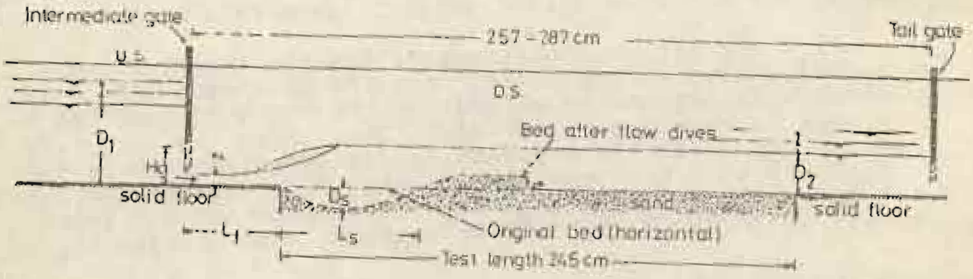
EXPERIMENTAL WORK:

1) Experimental Apparatus.

The experiments were conducted in the hydraulic laboratory at Mansoura University. The general arrangement of the apparatus is shown in Fig.(1). The experiments were carried out in a horizontal rectangular prespex walled flume 480 cm long, 150 mm depth and 75 mm wide with upstream transition (7). Water was supplied to the system from a constant head tank (2). The intermediate gate(10)



FIG(1) GENERAL ARRANGEMENT OF EXPERIMENTAL EQUIPMENT



FIG(2) Lay out of under test section

mounted on the apparatus that could slide along rails above the horizontal surface of the side walls of the flume. The water surface level in the flume downstream the gate could be controlled by adjusting a vertical tail gate(12) at the downstream end of the flume. The water then discharged under the tail gate and returned to the sump (16).

The discharge was controlled by a valve 1¼" (5) in the pipe line, and was measured by a weighing tank (60 x 45 x 60 cm^3)(14). The water passed through upstream transition (7)which was provided by a series of baffles (8). Elevations of water surface and sand bed were measured by a point gauge mounted on a carriage. This instrument could slide on rails above the horizontal surface of the side walls of the flume. The artificial bed in upstream region of the gate was made of a smooth painted wooden plank (9) with 230 cm long, 75 mm wide, and 55 mm depth. The bed of the flume downstream of the gate was filled with sand Fig.(2).

A sample of bed material was taken from the eroded region and analysed mechanically as shown in Fig.(3).

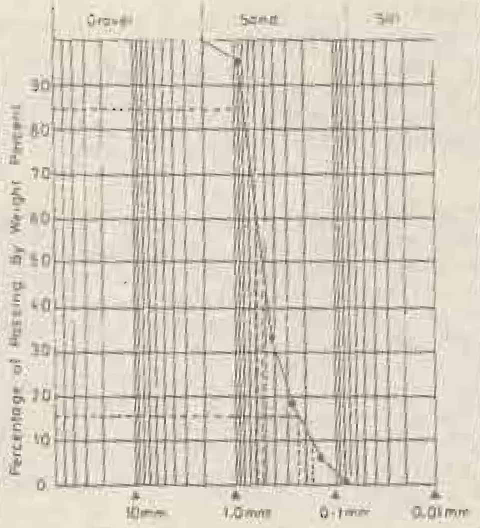
ii) Experimental Procedure:

Experimental tests were started by adjusting the slope of the flume and its artificial bed (sand) horizontally. The bed was formed for everyrun, by falling sand from a constant height to be sure that the bed material of bed has the same compaction, in all runs. The artificial bed was adjusted horizontally by using a water balance device, the intermediate gate height was changed to 0.9 cm, 1.3 cm and 1.5 cm for every discharge under consideration Fig.(2).

Three groups of experimental tests were made, each group was conducted under a certain discharge $q_1 = 72.73$ cm^3/Sec./cm, $q_2 = 57.14$ cm^3/Sec./cm and $q_3 = 42.1$ cm^3/Sec./cm). These discharges were measured by using a weighing tank (3) Fig.(1).

The development of scour hole depth and length was recorded with time, for every run, until the scour hole reached to steady state. Fig.(4), then the scour hole profile was recorded by using a point gauge. At the end of each run the upstream and downstream water depths were measured.

Each group has 54 runs, for each gate opening, three tail water depths were made. With every depth, the length of apron was changed from 5 cm to 30 cm. with a step 5 cm.



Uniformity coefficient : 3.4

Effective diameter 0.38 mm

D_{50} 0.54mm

Standard deviation σ_g = 1.75

FIG(3) Size Distribution Curve

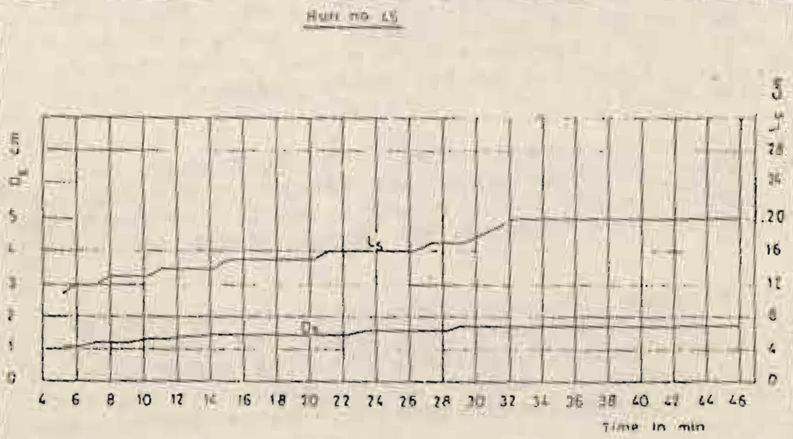


FIG (4) Scour hole development

ANALYSIS OF RESULTS:

Each test has the following dimensionless parameters which were drawn in the following figures.

Relationships between D_s/D_2 and D_1/D_2 for L_f/D_2:

Figures (5,6,7) show the variation of D_s/D_2 with D_1/D_2 for different values of relative floor length L_f/D_2. It is clear that the depth of scour hole being affected by the downstream water depth, i.e. increasing of the tail water depth decreases the scour depth. It is observed in the same figures, increasing the ratio D_1/D_2 for the same floor length gives a bigger value of the scour depth.

Relationships between Floor length (L_f) and Scour Depth (D_s) for Different values of Froude Number (F):

Figures (8,9,10) show the influence of rear apron length, with various values of Froude number, on the scour hole depth. The figures demonstrate the increase of scour hole depth due to the decrease of the tail length of the solid floor, for the same Froude number, as the flow momentum has a stronger effect on short length of relative rear apron $L_f/D_2 < 2.78$. Also it is clear that for the same length of rear apron, the scour hole depth increases with the increase of Froude numbers.

For arelative length of solid floor $L_f/D_2 < 2.78$ (short floor) there were no steady scour hole for a considerable length of time.

Relationships between Scour Length (L_s) and Floor Length L_f for Various Froude Numbers:

Figures (11,12,13) show the variation of scour length (L_s) and rear apron length (L_f), for different values of Froude number for downstream depth (D_2) = 2.4 cm, 3.0 cm and 3.6 cm.

For supercritical flows the relationship between L_s and L_f has a positive linear correlation, i.e. the increase of L_s corresponds to the increase of L_f. On the contrary for subcritical flows the relationship between L_s and L_f has a negative linear correlation, i.e. the increase of L_f gives a decrease in L_s.

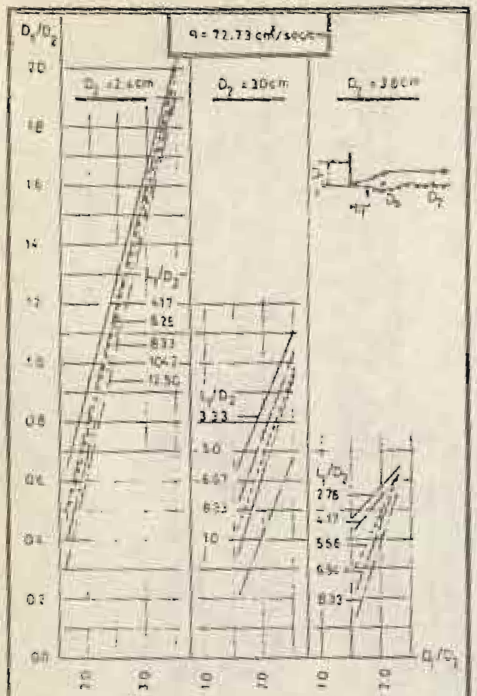


FIG (5) variation of (D_s/D_2) with (D_1/D_2) for (L_1/D_2)

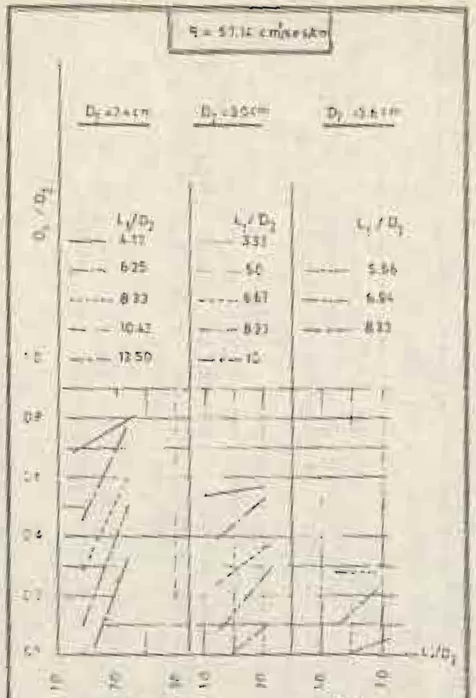


FIG (6) variation of (D_1/D_2) with (D_1/D_2) for (L_1/D_2)

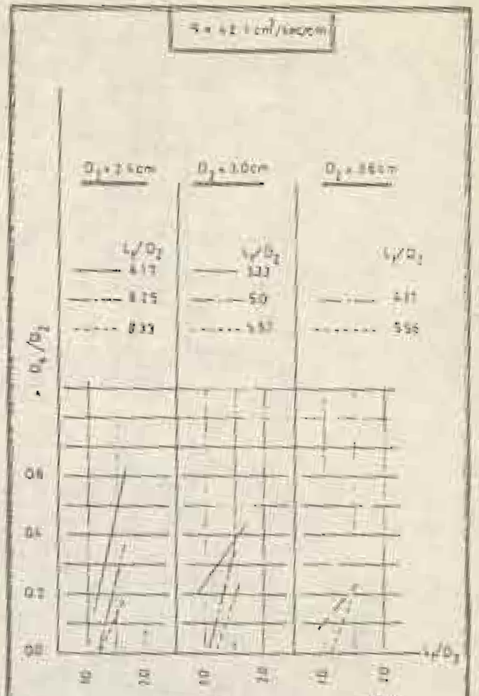


FIG (7) variation of (D_1/D_2) with (D_1/D_2) for (L_1/D_2)

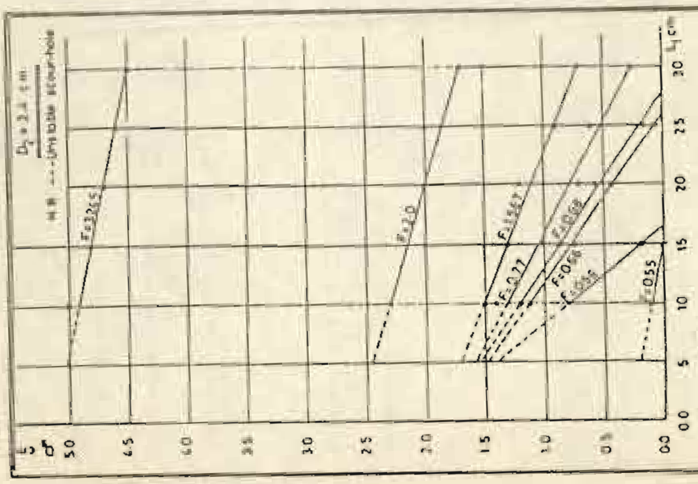


FIG (8) Variation of D_s with L_1 for F Values

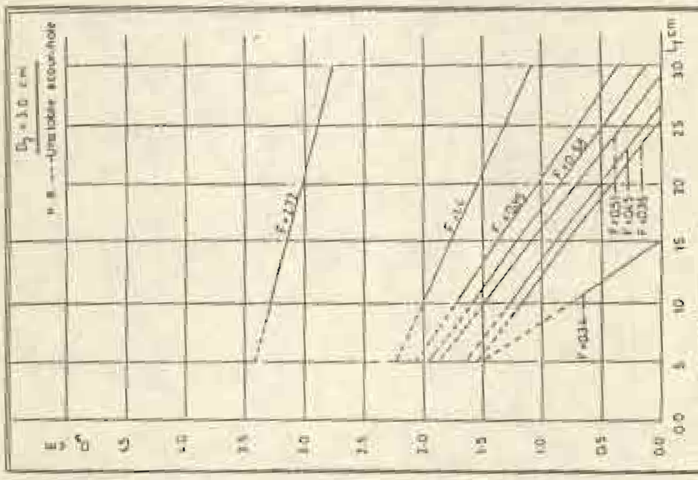


FIG (9) Variation of D_s with L_1 for F Values

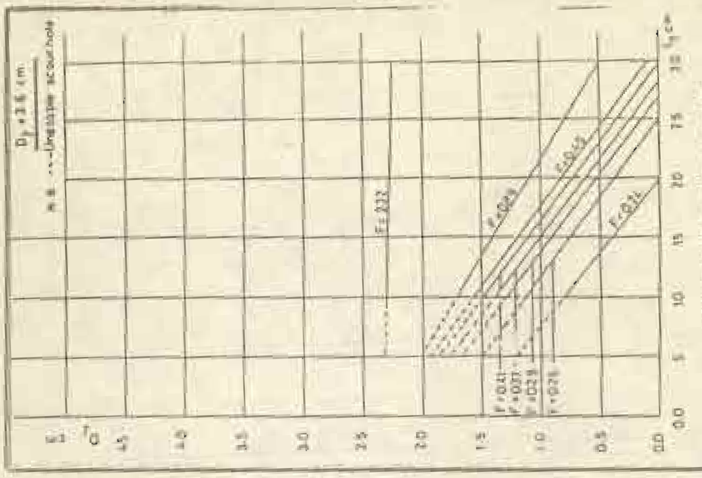


FIG (10) Variation of D_s with L_1 for F Values

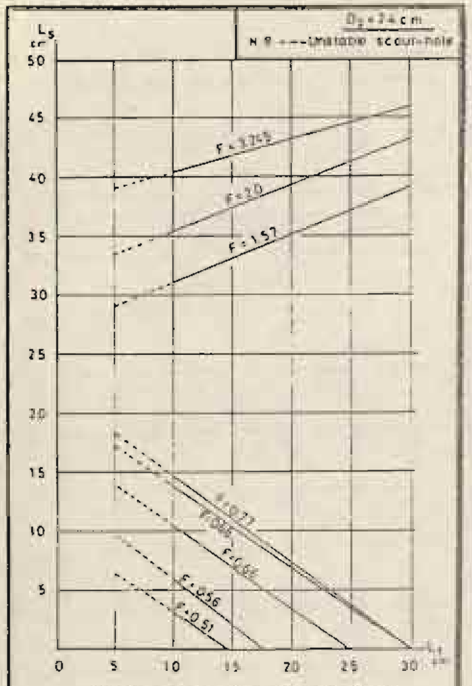


FIG (11) Variation of L_s versus L_1 for F

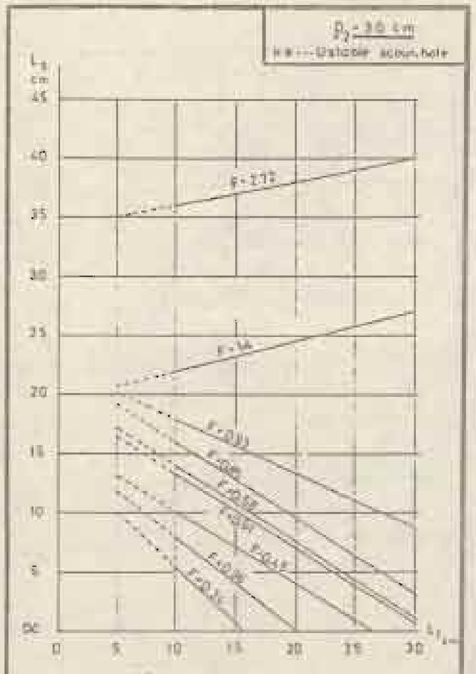


FIG (12) Variation of L_s versus L_1 for F

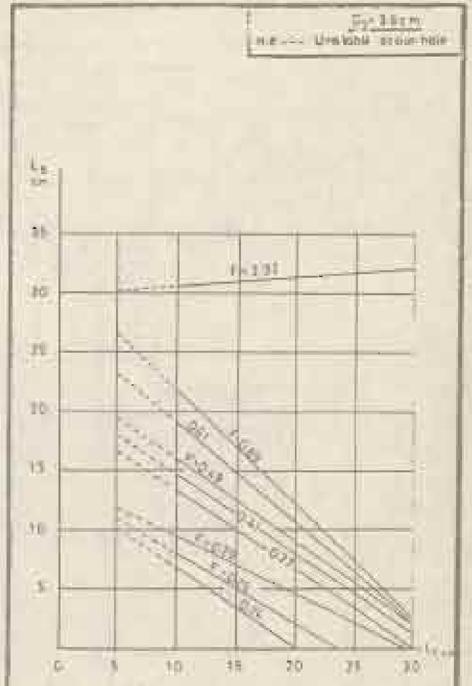


FIG (13) Variation of L_s versus L_1 for F

Relationships between Relative Depth of Scour Hole D_s/D_2 and Relative Length of Rear Apron L_f/D_2, for Various Values of Froude Numbers:

Figures (14,15,16) show the relationship between D_s/D_2 and L_f/D_2 for gate height equals to 0.9 cm, 1.3 cm and 1.5 cm respectively. In these cases, for supercritical flow, there is a negative linear correlation.

For subcritical flow, the relationship between D_s/D_2 and L_f/D_2 takes a higher order correlation with a max. value of relative depth of scour hole occurs between (2-3) times the floor length i.e. behind the edge of the solid floor the length from (2-3) L_f must be protected with concrete blocks or pitching to diminish the influence of the scour phenomenon.

Relationships between Relative Length of Scour L_s/D_2 and Relative Floor length L_f/D_2 for Different Froude Numbers:

Figures (17,18,19) show the relationships between L_s/D_2 with L_f/D_2 for different cases of flow under gate opening 0.9cm, 1.3 cm and 1.5 cm. In these cases, for supercritical flows there is a positive linear correlation. On the other hand, for subcritical flow there is a negative linear correlation with a higher order.

Empirical Formula for Scour Hole Depth D_s:

From dimensional analysis for scour hole depth.

$$\frac{D_s}{D_2} = \phi\left(\frac{1}{F^2}, \frac{1}{R}, \frac{D_{50}}{D_2}, \frac{H_g}{D_2}, \frac{L_f}{D_2}, \frac{D_1}{D_2}\right)$$

Under the same working conditions and for the same diameter of sand.

$$\frac{D_s}{D_2} = \phi\left(\frac{1}{F^2}, \frac{H_g}{D_2}, \frac{L_f}{D_2}, \frac{D_1}{D_2}\right) \qquad .....(4)$$

From observation $D_s/D_2 \propto D_2/L_f$, then;

$$\frac{D_s}{D_2} = K_d\left(\frac{1}{F^2} \cdot \frac{H_g}{D_2} \cdot \frac{D_1}{L_f}\right) \qquad .....(5)$$

in which; K_d is a coefficient of scour hole depth which could be obtained from Fig.(20).

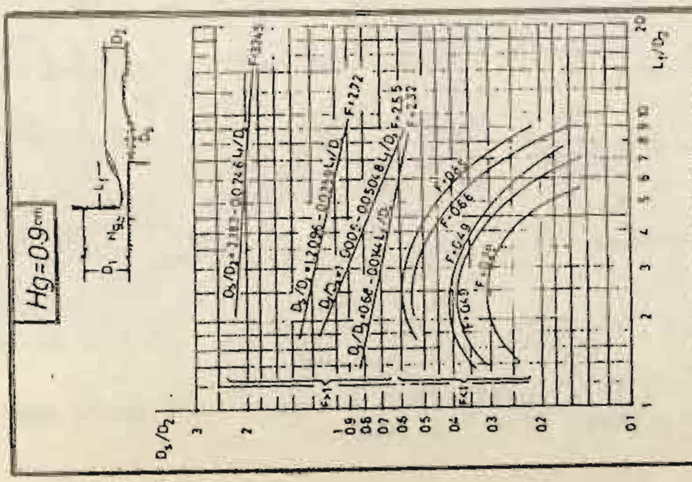


FIG (14) Variation of (D_s/D_2) with (L_1/D_2) for F

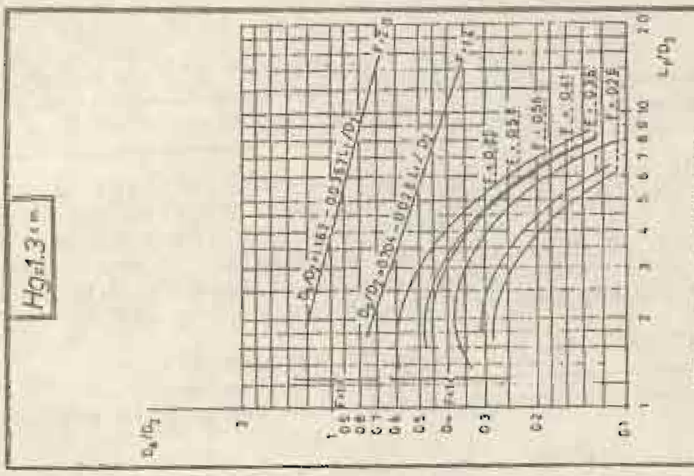


FIG (15) Variation of (D_s/D_2) with (L_1/D_2) for F

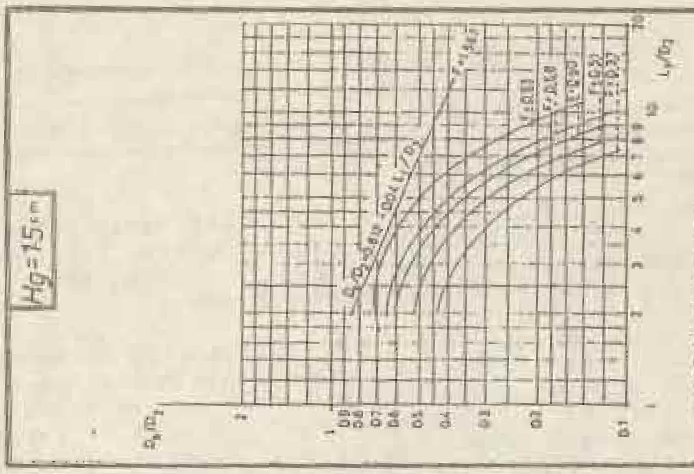
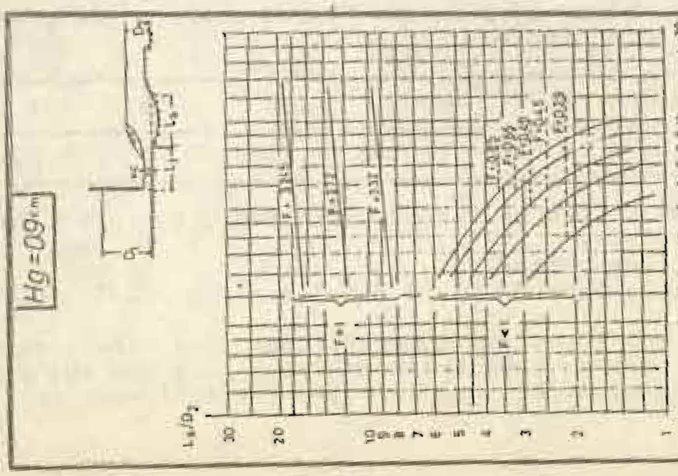
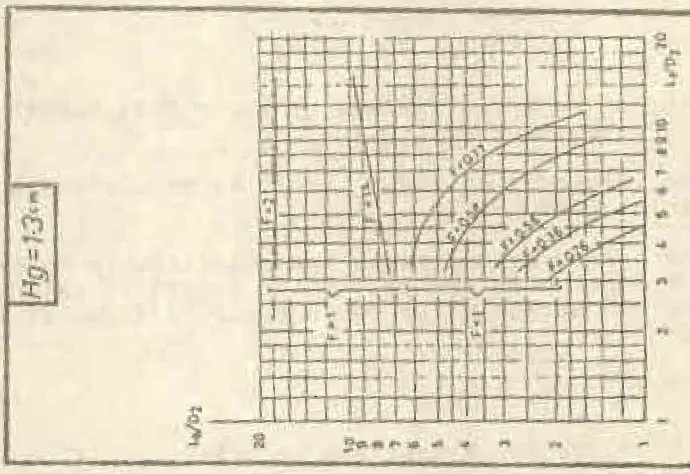


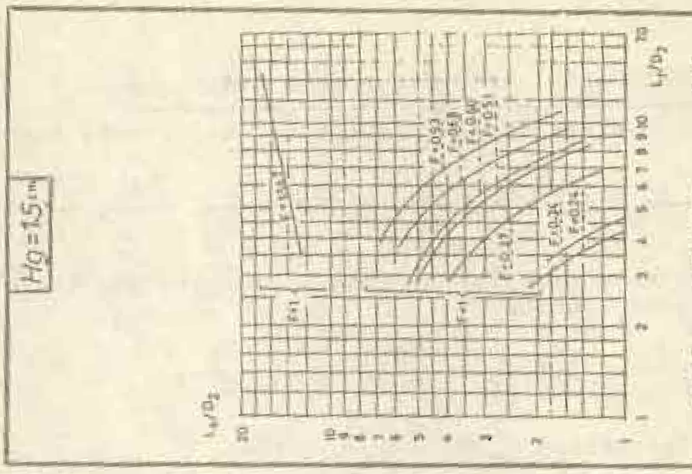
FIG (16) Variation of (D_s/D_2) with (L_1/D_2) for F



FIG(17) Variation of (L_s/D_2) with (L_j/D_2) for F



FIG(18) Variation of (L_s/D_2) with (L_j/D_2) for F



FIG(19) Variation of (L_s/D_2) with (L_j/D_2) for F

Empirical Formula for Scour Hole Length L_s:

From dimensional analysis for scour hole length;

$$\frac{L_s}{D_2} = \varnothing \left(\frac{1}{F^2}, \frac{1}{R}, \frac{D_{50}}{D_2}, \frac{H_g}{D_2}, \frac{L_f}{D_2}, \frac{D_1}{D_2}\right)$$

for the same diameter of sand and neglecting the effect of Reynold's number

$$\frac{L_s}{D_2} = \oint \left(\frac{1}{F^2}, \frac{H_g}{D_2}, \frac{L_f}{D_1}, \frac{D_1}{D_2}\right) \qquad .....(6)$$

From observation $L_s/D_2 \propto D_2/L_f$, then:

$$\frac{L_s}{D_2} = K_L \left(\frac{1}{F^2} \cdot \frac{H_g}{D_2} \cdot \frac{D_1}{L_f}\right) \qquad .....(7)$$

in which, K_L is a coefficient of scour hole length which could be obtained from Fig.(21).

The values of K_d and K_L could be tabulated in convenient tables Ref.(9).

For supercritical flow, the relationship between the depth of scour hole and rear apron length of solid floor with the downstream water depth could be formulated in the following form

$$q = \frac{V_d}{\alpha} (D_s + \beta L_f) \qquad .....(8)$$

in which; V_d is the downstream velocity.

The values of β versus Froude numbers are given in the following table.

F	3.245	2.72	2.55	2.00	1.567	1.4
β	0.0246	0.0359	0.0505	0.0363	0.040	0.028

values of α can be deduced from Fig.(**22**) in the following formula.
number, from which;

$$\alpha = 0.87 F - 0.55 \text{ for } 1.4 \leqslant F \leqslant 3.245 \qquad .....(9)$$

Also it was found for supercritical flow, the interrelationship between the length of scour hole and the other variables could be formulated in the following way

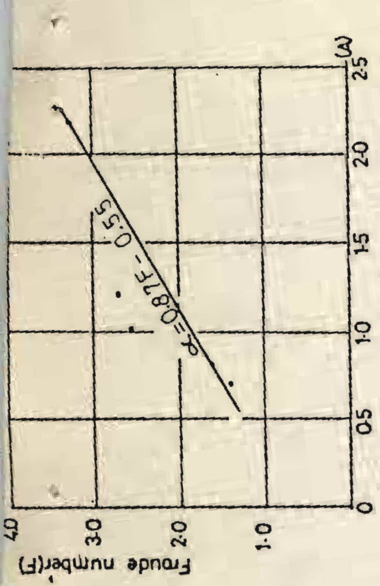


Fig.(22) Froude Number Versus (α) Values

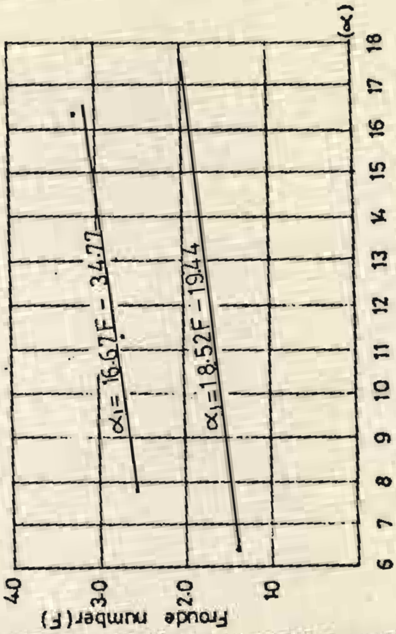
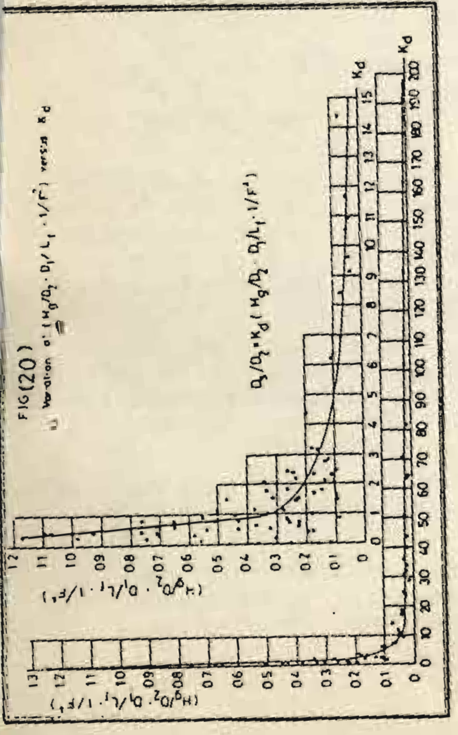
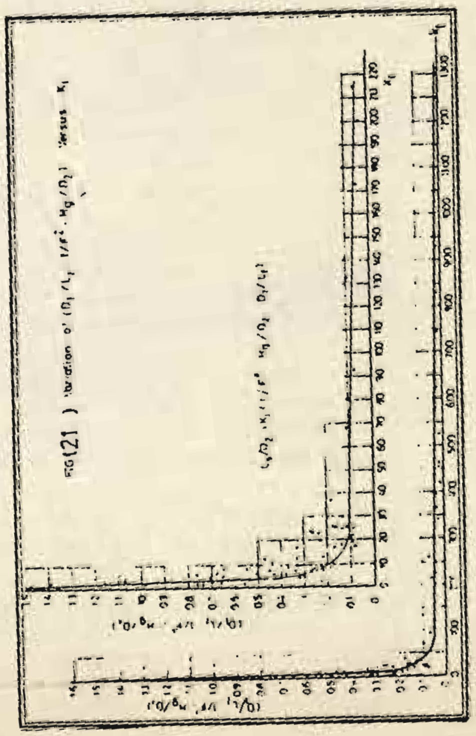


Fig.(23) Froude Number Versus (α) Values

FIG(20) Variation of (Hg/D2 · D1/L1 · 1/F²) versus Kd



FIG(21) Variation of (D1/L1 · 1/F² · Hg/D2) versus K1



$$q = \frac{V_d}{\alpha_1} (L_s - \beta_1 L_f) \qquad .....(10)$$

The values of β_1 versus Froude numbers are given in the following table

F	3.245	2.720	2.55	2.0	1.567	1.40
β_1	16.280	11.334	7.78	17.5	10.72	6.44

Values of α_1 can be deduced from Fig.(23) and are given in the following two formulae

$$\alpha_1 = 18.52\ F - 19.44 \text{ for } 1.4 \leqslant F \leqslant 2.0 \qquad .....(11)$$

$$\alpha_1 = 16.67\ F - 34.77 \text{ for } 2.55 \leqslant F \leqslant 3.24 \qquad .....(12)$$

CONCLUSIONS:

The problem of local scour behind sluice gate has been studied experimentally using sand modeling having a mean diameter $D_{50} = 0.54$ mm. In addition to the empirical formulae which have been formulated, the following points could be concluded.

1) The volume of scour hole has been affected by the depth of uniform flow at upstream and downstream of the gate location.

2) For subcritical flow, the maximum depth of scour occurs on a position far from the edge of the floor in a distance varies between two and three times the rear apron length.

3) The relationship between the scour depth and the length of rear apron, for different values of Froude number, indicated a negative linear correlation, an increase or decrease in the length of floor resulting in a decrease or increase of scour depth with a rate ranges from 0.16 to 0.01 depending on the value of Froude number.

4) For supercritical flows, the increase of rear apron length causes a bigger length of scour hole with a positive linear correlation on the other hand for subcritical flows the increase of rear apron length decreases the length of scour hole with higher order of correlation.

5) For short floor $L_f/D_2 < 2.78$, there were no stable scour hole for that reason it is important to avoid these short aprons to protect hydraulic structures from failure.

6) A bigger value of downstream water depth would exhibit a more quantity of bed material to be transported from the scour hole with corresponding slower value of velocity and vice versa.

7) From experimental observations, frequently the depth of scour hole is established earlier than the length of scour hole.

8) The influence of both the viscosity, represented by Reynold's number $V.L/\nu$, and the surface tension, represented by Weber's number $V/\sqrt{\sigma/\rho L}$, was neglected in this study. These two water properties may play a considerable part in the analysis due to the narrow width of the channel (75 mm).

9) Further studies could be carried out using different sizes of bed materials, the study could also be extended to include the bed slope especially an adverse slope. In this case empirical formulae could be formulated including these effects.

APPENDIX (I)

REFERENCES

1. Altinbilek, H.D., "Similarity Laws for Local Scour With Special Emphasis on Vertical Circular Pipe in Oscillatory Flow", XIV Congress of IAHR, Paris, 1971.
2. Altinbilek, H.D. and Okyay, S., "Localised Scour in a Horizontal Sand Bed Under Vertical Jets", XV Congress of IAHR, Istanbul, 1973.
3. Breasures, H.N.C., "Scour Around Drilling Platform" Bulletin, Hydraulic Research 1964 and 1965 IAHR, Vol. 19, P 276, 1965.
4. Breasers, H.N.C., "Conformity and Time Scale in Two Dimensional Local Scour" Proc of the Symposium on Model and Prototype Conformity, Hydraulic Research Laboratory, Poona, India, 1966, pp. 1-8.
5. Breusers, H.N.C., "Time Scale of Two Dimensional Local Scour", Proc. 12th Congress, I A H R, pp. C32-1-8.
6. Carstens, M.R., "Similarity Laws for Localised Scour" J. of Hydr. Div., ASCE, Vol. 92, No. HY3, Proc. Paper 4818, May, 1966, pp. 13-36.
7. Colamon, N.L., "Analysing Laboratory Measurements of Scour at Cylinderical Piers in Sand Beds" Proc., IAHR, XIV Congress, Paris, Vol, III, 1971.
8. Doddiah, D., Albertson, M. and Thomas, R., "Scour From Jets", IAHR Proc, Minnesota, International Hydr. Convention, Sept., 1953.
9. El-Masry, A., "Scour behind Irrigation Structures", M.Sc. Thesis Fac. of Engg., Mansoura University, 1984.
10. Ismail, H., El-Assiuti, I. and Abdel Aal, F., "Use of Filters as Bed Armour", the Bulletin of the Faculty of Engg., Cairo University, 1968.
11. Laursen, E.M., "Scour at Bridges Crossings", Transaction, ASCE, Vol. 127, Part I, Paper No. 3294, 1962, pp. 166-180.
12. Leliavsky, S., "Design of Dams for Percolation and Erosion", Chapman & Hall Ltd, London, Vol. III, 1965.
13. Neil, C.R., "Guide to Bridge Hydraulics", Road and Transportation Association of Canada, Univ. of Tronto Press, 1973.
14. Valentine, F., "Considerations Concerning Scour in the Case of Flow under Gates", IAHR, Fort Collins, Colorado, 12th Congress, 1967.

APPENDIX (II)

NOTATION

The following symbols are used in this paper.

D_1 = Upstream water depth;
D_2 = Downstream water depth;
D_{50} = Mean diameter of sand;
D_s = Depth of scour hole;
F = Froude's number;
g = Acceleration due to gravity;
H_g = Height of gate opening;
K_d = Coefficient of scour hole depth;
K_L = Coefficient of scour hole length;
L = Characteristic length;
L_f = Length of rear apron;
L_s = Length of scour hole;
q = Water discharge per unit width;
R = Reynold's number;
V = Velocity of flow at vena contracta;
V_d = Downstream water velocity;
y = Depth of flow;
α = Coefficient;
β = Coefficient;
ρ = Water density;
ρ_s = Soil density;
μ = Dynamic viscosity of water;
ν = Kinematic viscosity of water; and
σ = Surface tension coefficient.