ANALYTICAL STUDY OF LOCAL SCOUR

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by

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FOREWORD

Since July 1957, the Bureau of Public Roads, U. S. Department of Commerce, has sponsored a research project on local scour in alluvial channels at the Hydraulics Laboratory at Colorado State University under leadership of the late Dr. H. K. Liu. A report which assembled three years' of study was submitted to the sponsor in February 1961. Since that time, the first author, who was also second author of the first report, has continued the analytical study of local scour under the supervision of Dr. V. M. Yevdjevich.

The current report is in effect an addendum to the report, "EFFECT OF BRIDGE CONSTRICTION ON SCOUR AND BACKWATER, " previously submitted to the Bureau of Public Roads. This addendum includes review of additional pertinent literature not included in the previous report; discusses further the results presented in the earlier report from dimensional considerations; describes the physical hydrodynamic aspects of local scour; and prepares a logical outline of future research procedures into the study of the local scour phenomenon.

At one time a theoretical analysis of the scour phenomenon was prepared for inclusion in this report. However, after much discussion between engineering research staff members at Colorado State University it was decided that a physical description of the mechanics of local scour would be more meaningful and valuable in this report, especially since development of theoretical expressions were based on fundamental assumptions which require further study.

I. INTRODUCTION

Local scour in an alluvial channel, caused by obstructions in the stream or constriction of the banks, is a subject which has attracted many researchers. Much of the results from various studies are empirical and qualitative in nature with little theoretical clarification of the mechanics of scour, thus the results have limited applicability to field design problems. Generally, a specific empirical relationship, describing in some manner location and geometry of scour, is limited to stream channels having very similar characteristics to the laboratory conditions from which the relationship was developed. Also, lack of fundamental knowledge of model-prototype relationships for alluvial channels creates some doubt as to satisfactory field application of even these specific cases.

Local scour, by its nature of development, is a three-dimensional problem and because of constantly changing boundary conditions, occurs under unsteady flow conditions. Differential equations describing the mechanics of fluid and sediment motion under these conditions, are complex and it is for this reason that past research has been largely empirical and researchers who have attempted analytical solutions have imposed such simplifying assumptions as to limit general applicability of the results. Nevertheless, these studies provide valuable insight to visualization of local scour phenomena and must not be overlooked in future studies.

II. REVIEW OF PREVIOUS STUDIES

There have been several interesting approaches to the problem of local scour. Some, like Lacey (7)*, Inglis (8), Blench (9), and Ahmad (10) have applied general regime transport formulae for alluvial channels, along with dimensional considerations for channel obstructions and contractions, and empirically developed scour depth relationships. Laursen (6) used a total sediment transport relationship between a contracted and uncontracted stream channel to develop a formulation for scour depth from known physical stream and contraction geometrics. From experiences in the laboratory he concluded that the depth of scour was controlled mainly by depth of flow and was nearly independent of sediment size and average stream velocity. A discussion of these studies is included in the parent report. Other researchers have observed similarity in changes of stream flow lines caused by obstructions and contractions to flow around river bends. They reasoned that development of secondary flow and associated changes in the vertical velocity distribution were the principal cause of scour and developed scour relationships accordingly.

A. Keutner (3), experimentally showed the existence of a lateral water surface profile when a pier was placed in a stream channel. He reasoned that the secondary flow was generated because of the existence of the lateral water surface slope and that the secondary flow, together with the normal flow, scoured the bed. The intensity of scouring action he found, was firmly related to the magnitude of the lateral water surface slope. Scour at the nose, or upstream side of the pier, was affected by the shape of the nose, and determined the magnitude of the lateral water surface slope. He erroneously thought that the slope of the water surface, normal to the pier, to be the cause of scour, rather than the effect from changes in flow pattern.

B. Tison (5), reasoned that local scour resulted from development of secondary circulation due to curvatures in the stream lines around a pier. It is interesting to follow his development. When a pier of arbitrary shape is located in a stream channel the curvature of the stream lines in the vicinity of the pier can be described at any point as having a center of curvature 0 with a radius ρ as shown in Fig. 1.

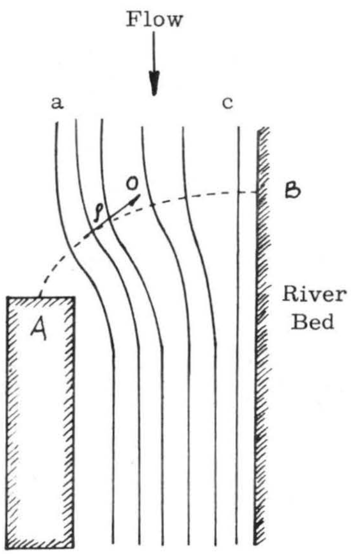

Figure 1. Flow around a bridge pier.

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* The numbers in parentheses refer to the list of references at the end of this report.

Near the river bank, the pier is assumed to exert no change in the direction of the stream line c-d. He divided the stream flow into horizontal layers, recognizing the existence of changing point velocities along a vertical line. By applying the Bernoulli equation along a line A-B , in a layer of flow near the water surface, Tison developed the following relationship:

$$z_B + \frac{p_B}{\gamma} + \frac{1}{g}\int_A^B \frac{V^2}{\rho}\, ds = z_A + \frac{p_A}{\gamma} , \tag{2-1}$$

in which

z = a point in depth of flow above the bed,

p = pressure,

γ = specific weight of the fluid,

V = point velocity of flow,

s = distance from A to B .

Similarly for flow near the bed of the stream he derived:

$$z_{B'} + \frac{p_{B'}}{\gamma} + \frac{1}{g}\int_{A'}^{B'} \frac{(V')^2}{\rho}\, ds = z_{A'} + \frac{p_{A'}}{\gamma}, \tag{2-2}$$

where V' is a point velocity near the stream bed, and A' and B' are in the same vertical lines as A and B respectively.

The variation of pressure between B and B' follows the hydrostatic law, so that

$$z_B + \frac{p_B}{\gamma} = z_{B'} + \frac{p_{B'}}{\gamma} . \tag{2-3}$$

By combining Eqs. (2-1), (2-2) and (2-3),

$$z_A + \frac{p_A}{\gamma} - \left(z_{A'} + \frac{p_{A'}}{\gamma}\right) = \frac{1}{g}\left[\int_A^B \frac{V^2}{\rho}\, ds - \int_{A'}^{B'} \frac{V'^2}{\rho}\, ds\right] , \tag{2-4}$$

in which V is greater than V' .

From Eq. (2-4) it follows that the water surface cannot be parallel to the bed surface thus vertical velocity components are developed to create a diving motion which attacks the stream bed. Tison concluded that local scour depends on the magnitude of the vertical velocity component as described by the right-hand term of Eq. (2-4). If ρ is small, which means curvature of the stream line is large, greater components of vertical velocity will be developed and a greater scour hole will result.

Tison experimentally confirmed his analysis with different shapes of piers but with the same cross-sectional pier lengths and widths. He found that streamlined pier noses produced less scour than a square-cornered pier.

C. Ishihara (4), approached the problem from a viewpoint similar to Tison's; that secondary circulation created by obstructions in a stream channel was related to local scour around the obstruction. By defining the intensity of secondary flow in terms of centrifugal force and lateral water surface slope developed in the vicinity of the obstruction, and by accounting for variations of point velocities in a vertical section of the flow, he developed an expression for scour force per unit of stream width at the outer edge of curvature.

When a particle of unit mass moves with a velocity, V , along a curved stream line of radius ρ , the particle receives a centrifugal force having a magnitude of $\frac{V^2}{\rho}$. In general, flow in an open channel has a vertical velocity distribution similar to that shown in Fig. 2. Hence the centrifugal force exerted on finite particles along a vertical line differs with elevation because velocity varies.

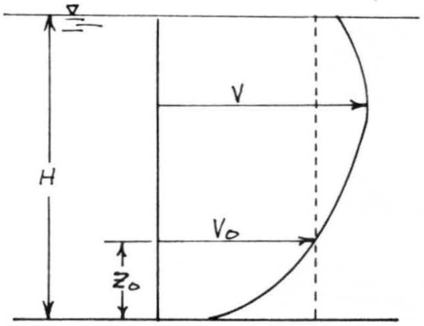


Figure 2. Typical vertical velocity distribution in open channel flow.

If the lateral water surface slope in the zone of curvilinear flow is defined by

$$S_r = \frac{V_o^{\,2}}{g\rho} , \tag{2-5}$$

where

S_r = lateral water surface slope,
V_o = average velocity of approach,
g = gravitational acceleration,
ρ = fluid density,

and if the velocity along a vertical line normal to the flow is constant, each unit mass of fluid would follow a curved stream line. However, since a vertical velocity distribution does exist, a unit mass of fluid (or particle) above elevation $z = z_o$ is acted upon by a force of $(\frac{V^2}{\rho} - \frac{V_o^2}{\rho})$ and since V is greater than V_o, the particle moves outward from the center of curvature. A particle below level $z = z_o$ moves toward the center of curvature because of the force $(\frac{V_o^2}{\rho} - \frac{V}{\rho})$. The upper layer of flow, above $z = z_o$, moves inward, or towards the center of curvature. In order to satisfy the continuity of mass, a secondary circulation is created and the flow turns downward at the outer bank and upward at the inner bank. Ishihara related the intensity of secondary flow to an arbitrary quantity dC defined as follows:

$$dC = \frac{\gamma}{g} \int_{z_o}^{H} \left(\frac{V^2}{\rho} - \frac{V_o^2}{\rho} \right) dz + \frac{\gamma}{g} \int_{0}^{z_o} \left(\frac{V_o^2}{\rho} - \frac{V^2}{\rho} \right) dz , \qquad (2\text{-}6)$$

which dimensionally is force per length squared. By applying Laval-Rapp's equation for the vertical velocity distribution (12):

$$\left. \begin{aligned} V &= V_s \left(\frac{Z}{H} \right)^{1/\alpha} \\ V_o &= V_s \left(\frac{\alpha}{\alpha - 1} \right) \\ Z_o &= H \frac{\alpha}{\alpha + 1} \end{aligned} \right\} \qquad (2\text{-}7)$$

Equation (2-6) can be transformed to

$$dC = \frac{\left(\frac{8}{g} \right) \left(\frac{V_o^2}{\rho} \right) H}{\alpha \; (\alpha + 2)} \qquad (2\text{-}8)$$

where

H = depth of flow,
α = constant dependent upon the nature of the bed material,
V_s = velocity of flow at the water surface.

Ishihara further assumed the scour force measured along the outer bank of the stream to be proportional to the quantity:

$$C = \int_{\rho_1}^{\rho_2} dC , \qquad (2\text{-}9)$$

whence the scour force per unit of width, K, at the outer bank can be expressed as

$$K = \phi_1 \frac{\gamma}{g} \frac{1}{\alpha(\alpha + 2)} \int_{\rho_1}^{\rho_2} \frac{V_o^2 \; H}{\rho} d\rho , \qquad (2\text{-}10)$$

where

K = the scour force,
ϕ_1 = an experimental coefficient.

Tison's and Ishihara's viewpoints agree that the main cause of scour is the secondary flow developed by curvature of the stream lines. Tison assumed an ideal fluid in comparing the total energy content in the upper and lower layers of the flow. He might well have integrated vertically through the flow as well as laterally across the flow to arrive at the total energy in the seconday circulation. If Ishihara had used a more precise definition of the water surface slope,

$$S_r = \frac{1}{g H} \int_{0}^{H} \frac{V^2}{\rho} dz , \qquad (2\text{-}11)$$

he would have arrived at a scour force of

$$K = \phi_1 \frac{\gamma}{g} \frac{1}{\alpha(\alpha + 2)} \int_{\rho_1}^{\rho_2} \int_{0}^{H} \frac{V^2}{\rho} dz \; d\rho . \qquad (2\text{-}12)$$

It is rather interesting to discuss the possibility of integrating Eq. (2-4) and Eqs. (2-10) or (2-12). In order to define the value, $\frac{V^2}{\rho}$, it is necessary to define the function of a stream line by considering two-dimensional potential flow. Flow in the vicinity of the scour hole, however, is three dimensional, moreover, the flow is unsteady since the boundary changes with time. Thus, solutions to the problem of local scour which assume two-dimensional potential flow is not valid once scour begins.

III. DIMENSIONAL CONSIDERATIONS OF LIU'S EXPERIMENTAL RESULTS

Liu and his associates (11) approached the problem of local scour using dimensional analysis and developing as a result of experimental studies, an empirical relationship describing the rate of scour. In general form, depth of scour was related to several variables associated with properties of the fluid and sediment, flow characteristics and geometrics of the channel and constriction as follows:

$$d_s = \psi_1(h_n, V_o, B, d, \Delta\gamma_s, \omega, \rho_o, g, \mu, a, \theta, G, t) \qquad (3\text{-}1)$$

where in corresponding dimensions,

d_s = depth of scour measured from the original bed surface,
h_n = depth of approach flow,
V_o = mean velocity of approaching flow,
B = channel width,
d = characteristic size of bed material,
$\Delta\gamma_s$ = difference of specific weight between sediment and fluid,
ω = fall velocity of the bed material,
ρ_o = fluid density,
g = gravitational acceleration,
μ = dynamic viscosity of the fluid,
a = width of obstruction measured normal to the approach flow direction,
θ = skew angle of the obstruction with respect to the flow direction,
G = shape factor of the obstruction,
t = time.

By combining the variables in dimensionless π-terms they arrived at the following form:

$$\frac{d_s}{h_n} = \psi\left(\frac{tV_o}{d}, \frac{a}{h_n}, \theta, G, \frac{V_o^2}{gh_n}, \frac{B}{a}, \frac{d}{h_n}, \frac{\omega}{V_o}\right) \qquad (3\text{-}2)$$

Experimentally, Liu, et al, found that scour depth could be related to time by:

$$d_s = d_{sM}\left[1-e^{-\frac{ct}{t_o}} \Big/ 1-\frac{t}{t_m}\right], \qquad (3\text{-}3)$$

where

d_{sM} = maximum depth of scour,
e = base of natural logarithm,
c = empirical coefficient,
t_o = time factor determined empirically,
t_m = time required for d_s to reach d_{sM}.

Equation (3-3) applies to channels with "appreciable" bed loads. If the stream does not transport significant bed load, t_m is infinite and Eq. (3-3) changes its form to

$$d_s = d_{sL}\left[1 - e^{-\frac{ct}{t_o}}\right], \qquad (3\text{-}4)$$

in which

d_{sL} = ultimate scour depth.

Equation (3-4) satisfies the initial and final boundary conditions, this is, when $t = o$, $d_s = o$ and $d_s = d_{sL}$ when $t = \infty$, and gives satisfactory results at intermediate times if proper values are assigned to coefficients c and t_o. From experimental results it was found that c could be expressed in the following exponential form:

$$c = e^{-A_o y^{1/2}}, \qquad (3\text{-}5)$$

where

A_o = coefficient dependent upon channel and constriction geometrics, flow conditions, and characteristics of the bed material,
y = $\frac{d_s}{d_{sL}}$.

The value of t_o, having the dimensions of time, t, is generally small and can be adequately expressed by:

$$t_o = e^{-B_o}, \qquad (3\text{-}6)$$

where

B_o = experimental coefficient.

Should a constricted stream be conveying essentially clear water, the depth of scour would asymptotically approach the limiting scour depth, d_{sL}, as time approaches infinity.

In the experimental studies limiting scour depths were determined in both the 4- and 8-foot flumes for vertical wall, wing wall and spill-through abutment models. In the 4-foot flume, tests were made with clear water while in the 8-foot flume sediment was recirculated and some general bed movement prevailed. The technique applied in both flumes involved preshaping a scour hole to known dimensions as determined from previous runs and gradually varying the flow conditions in the flumes until movement of sediment particles in the preshaped scour hole was observed. The basic data for these runs are tabulated in Table I (Ref. 11) as runs 101-165 and 166-287. The analysis which follows, however, includes only data from runs 101-114 because (a) these runs were considered to yield consistent and reliable data, and (b) because of the similarity in geometry and flow patterns.

The vertical wall abutment model data of runs 101-114 are plotted in Fig. 3 as $\frac{d_{sL}}{h_n}$ vs. $F\left(\frac{a}{B}\right)^{1/2}$. The basic data from reference 11 are reproduced and computed values are shown in Table II. From Fig. 3 it can be seen that for a constant Froude number, F, of the approach flow,

$$\frac{d_{sL}}{h_n} \propto \left(\frac{a}{B}\right)^{1/2} \tag{3-7}$$

A straight line which is drawn through the data by "eye" can be represented by the equation

$$\frac{d_{sL}}{h_n} = 33\,F\left(\frac{a}{B}\right)^{1/2}, \tag{3-8}$$

and by rearrangement

$$d_{sL} = \frac{33\,V_o\sqrt{h_n\,a}}{\sqrt{g\,B}}\;. \tag{3-9}$$

The total momentum force, F_M, against the upstream face of the vertical abutment is

$$F_M = \rho_o\,V_o^2\,h_n\,a\,. \tag{3-10}$$

Thus, d_{sL} is proportional to $(F_M)^{1/2}$. The effect of sediment size on d_{sL} was not determined from these studies as the experimental tests were conducted with only one size of sediment, $d_{50} = 0.56$ mm.

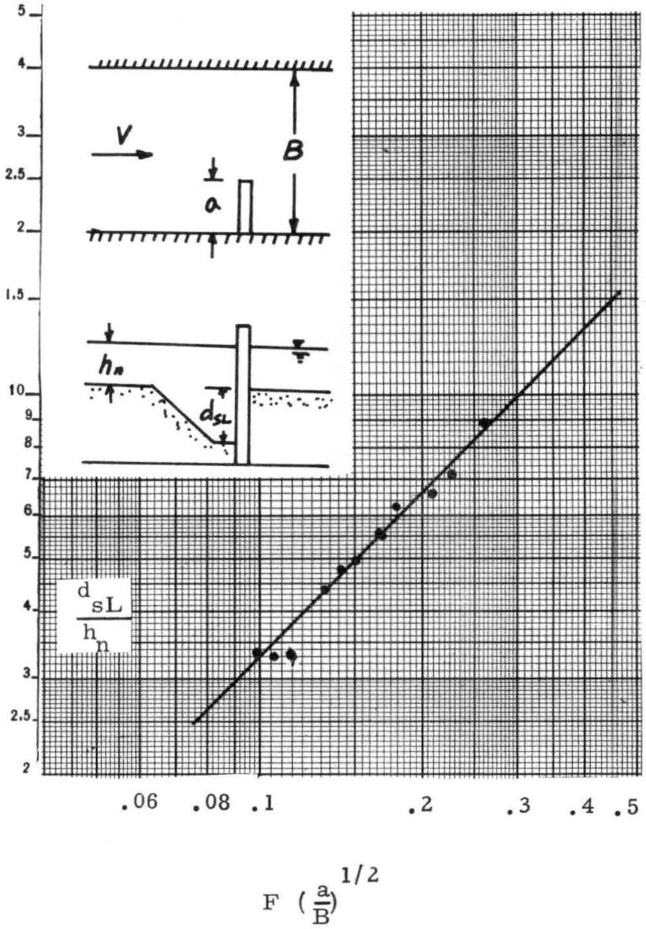


Figure 3. Relationship of limiting scour depth to stream geometry.

The coefficients A_o and B_o in Eqs. (3-5) and (3-6) can be expressed by the relationships,

$$A_o = \psi_{A_o}\left[F^{1.8}\left(\frac{a}{B}\right)^{0.75}\left(\frac{h_n}{B}\right)^{0.25}\left(\frac{h_n}{d_{50}}\right)^{1.35}\right] \tag{3-11}$$

and

$$B_o = \psi_{B_o}\left[F^{1.8}\left(\frac{a}{B}\right)^{0.8}\left(\frac{h_n}{B}\right)^{0.2}\left(\frac{h_n}{d_{50}}\right)^{1.4}\right], \tag{3-12}$$

as shown in Figs. 4 and 5 respectively.

TABLE I. BASIC DATA FROM REFERENCE 11

Fixed Data For All Runs in This Table

Vertical Wall Model. Medium Size Bed Material $d_{50} = 0.56$ mm.

Run No.	Model Length a (ft)	Number of Models p	Width of Flume B (ft)	Total Discharge Q (cfs)	Slope of Bed S	Normal Depth of Flow h_n (ft)	Opening Ratio $M = \frac{B-pa}{B}$	Mean Velocity of flow V (ft/sec)	Froude Number F
1	0.50	2	8	4.5	0.00250	0.43	0.875	1.310	0.353
2	0.75	"	"	6.6	0.00253	0.46	0.812	1.795	0.467
3	1.00	"	"	"	"	"	0.750	"	"
4	1.25	"	"	"	"	"	0.687	"	"
5	1.50	"	"	"	"	"	0.625	"	"
5A	"	"	"	"	"	"	"	"	"
6	1.75	"	"	"	"	"	0.562	"	"
6A	"	"	"	"	"	"	"	"	"
7	2.00	"	"	"	"	"	0.500	"	"
8	2.25	"	"	"	"	"	0.437	"	"
9	2.50	"	"	"	"	"	0.375	"	"
10	0.50	"	"	13.0	0.00230	0.77	0.875	2.110	0.424
11	0.75	"	"	"	"	"	0.812	"	"
12	1.00	"	"	"	"	"	0.750	"	"
13	1.50	"	"	"	"	"	0.625	"	"
14	2.00	"	"	"	"	"	0.500	"	"
15	3.00	1	"	"	"	"	0.625	"	"
16	1.50	"	"	"	"	"	0.812	"	"
17	1.00	2	"	10.0	0.00270	0.62	0.750	2.015	0.452
18	1.50	"	"	"	"	"	0.625	"	"
33	1.00		"	8.5	0.00370	0.50	0.875	2.130	0.531
33R	1.00		"	8.4	0.00340	"	"	2.100	0.524
34	2.00		"	"	0.00335	"	0.750	2.100	0.524
36	2.00	"	"	4.8	0.00044	"	0.750	1.200	0.297
38	1.50	"	"	"	0.00068	"	0.812	1.210	0.302
39	2.50	"	"	4.0	0.00046	"	0.687	1.000	0.250
40	3.00	"	"	"	"	0.54	0.625	0.925	0.222
41	2.00	"	"	5.0	0.00069	0.52	0.750	1.201	0.294
43	3.00	1	8	5.0	0.00069	0.52	0.625	1.201	0.294
47	"	"	"	"	"	"	"	"	"
54	2.00	"	"	"	"	"	0.750	"	"
55	"	"	"	7.0	0.00038	0.70	"	1.250	0.264
56	1.00	"	"	"	0.00050	"	0.875	"	"
73	"	"	4	1.2	0	0.25	0.750	1.200	0.424
74	"	"	"	"	0.00100	"	"	"	"
75	"	"	"	2.1	"	0.46	"	1.130	2.940
76	"	"	"	1.7	0.00250	0.24	"	1.810	0.657
76R	"	"	"	"	"	"	"	"	"
77	"	"	"	1.5	0.00200	"	"	1.562	0.562

TABLE II. BASIC DATA FROM REFERENCE 11 CLEAR WATER STUDY

Fixed Data For All Runs in This Table

Vertical Wall Model.
Number of Models $p = 1$.
Width of flume $B = 4$ ft.
Slope of $S = 0$.
Medium Size Bed Material $d_{50} = 0.56$ mm .

Run No.	Model Type	Model Length a (ft)	$\frac{d_{SL}}{h_n}$	Total Discharge Q (cfs)	$F\left(\frac{a}{B}\right)^{\frac{1}{2}}$	Normal Depth of Flow h_n (ft)	Limiting Scour Depth d_{SL} (ft)	Opening Ratio $M = \frac{B-pa}{B}$	Mean Velocity of flow V (ft/sec)	Froude Number F
101	VW	1.00	4.40	0.8	.132	0.25	1.10	0.750	0.750	0.264
102	"	"	3.33	0.9	.099	0.33	"	"	0.644	0.198
103	"	"	5.50	0.7	.168	0.20	"	"	0.850	0.332
104	"	"	4.77	1.1	.141	0.30	1.43	"	0.875	0.282
105	"	"	4.77	1.0	.141	"	"	"	0.842	0.271
106	"	"	7.15	0.9	.227	0.20	"	"	1.150	0.454
107	"	"	7.15	"	.227	"	"	"	1.125	0.443
108	"	"	6.22	"	.178	0.23	"	"	0.968	0.356
109	"	1.50	3.33	0.7	.115	0.30	0.99	0.625	0.583	0.188
110	"	"	4.95	0.5	.151	0.20	"	"	0.625	0.247
111	"	"	3.30	0.7	.106	0.30	"	"	0.541	0.174
112	"	"	6.60	0.5	.208	0.15	"	"	0.750	0.342
113	"	"	5.52	0.8	.166	0.25	1.38	"	0.770	0.272
114	"	"	8.96	0.6	.262	0.15	"	"	0.957	0.430

TABLE III. COMPUTATION OF A_o, B_o, and d_{sL}

Run	b	h_n	V	B	d_{50}	a	F	$F(b/B)^{\frac{1}{2}}$	$\frac{d_{SL}}{h_n}$	d_{sL}	ψ_{A_o}	A_o (Fig. 4)	ψ_{B_o}	B_o (Fig. 5)
2	1.5	.46	1.795	8.0	.56	.75	.467	.202	6.6	3.04	1.57	18.0	1.93	5.1
3	2.0	"	"	"	"	1.0	"	.233	7.6	3.49	1.98	25.2	2.44	9.0
4	2.5	"	"	"	"	1.25	"	.261	8.6	3.95	2.36	30.0	2.93	11.6
5	3.0	"	"	"	"	1.50	"	.286	9.5	4.37	2.68	33.0	3.32	12.9
5A	3.0	"	"	"	"	1.50	"	.286	9.5	4.37	2.68	33.0	3.32	12.9
6	3.5	"	"	"	"	1.75	"	.309	10.5	4.83	3.01	35.4	3.83	13.8
6A	3.5	"	"	"	"	1.75	"	.309	10.5	4.83	3.01	35.4	3.83	13.8
7	4.0	"	"	"	"	2.00	"	.330	11.0	5.05	3.33	37.1	4.27	14.2
8	4.5	"	"	"	"	2.25	"	.350	11.5	5.30	3.63	38.4	4.69	14.3
9	5.0	"	"	"	"	2.50	"	.368	12.1	5.67	3.92	39.4	5.10	14.4
10	1.0	.77	2.110	"	"	.50	.424	.146	4.8	3.70	2.30	29.4	2.69	10.4
11	1.5	"	"	"	"	.75	"	.184	6.0	4.62	3.03	35.5	3.74	13.7
12	2.0	"	"	"	"	1.00	"	.212	7.0	5.39	3.84	39.1	4.74	14.3
13	3.0	"	"	"	"	1.50	"	.260	8.6	6.62	5.18	42.0	6.45	14.4
14	4.0	"	"	"	"	2.00	"	.300	9.9	7.62	6.45	43.0	8.28	14.4
15	3.0	"	"	"	"	3.0	"	.260	8.6	6.62	8.73	43.0	11.38	14.4
16	1.5	"	"	"	"	1.5	"	.184	6.0	4.62	5.18	42.0	6.45	14.4
17	2.0	.62	2.015	"	"	1.00	.452	.226	7.4	4.59	3.08	36.0	3.80	13.8
18	3.0	"	"	"	"	1.50	"	.277	9.2	5.71	4.16	40.1	5.16	14.4
33	1.0	.50	2.13	8.0	.56	1.0	.531	.188	6.2	3.10	2.92	34.9	3.60	13.5
33R	1.0	"	2.10	"	"	1.0	.524	.186	6.1	3.05	2.87	34.5	3.54	13.4
34	2.0	"	"	"	"	2.0	.524	.262	8.7	4.35	4.81	41.4	6.19	14.4
36	2.0	.51	1.20	"	"	2.0	.297	.149	4.9	2.50	1.78	22.2	2.28	8.0
38	1.5	.50	1.21	"	"	1.5	.302	.130	4.3	2.13	1.41	14.5	1.76	3.4
39	2.5	"	1.00	"	"	2.5	.250	.139	4.6	2.28	1.47	16.5	1.93	5.4
40	3.0	.54	.925	"	"	3.0	.222	.136	4.7	2.40	1.55	17.7	2.02	5.9
41	2.0	.52	1.20	"	"	2.0	.294	.147	4.8	2.50	1.78	22.1	2.29	8.0
43	3.0	"	"	"	"	3.0	"	.180	5.9	3.07	2.41	30.5	3.13	12.3
47	3.0	"	"	"	"	3.0	"	.180	5.9	3.07	2.41	30.5	3.13	12.3
54	2.0	"	"	"	"	2.0	"	.147	4.8	2.50	1.78	22.1	2.29	8.0
55	2.0	.70	1.25	"	"	2.0	.264	.132	4.3	3.01	2.37	30.1	3.04	12.0
56	1.0	"	1.25	"	"	1.0	"	.094	3.1	2.17	1.40	14.3	1.73	3.0
73	"	.25	1.20	4.0	"	1.0	.424	.212	7.0	1.75	1.28	11.0	1.58	1.0
74	"	"	1.20	"	"	1.0	"	.212	7.0	1.75	1.28	11.0	1.58	1.0
75	"	.46	1.13	"	"	1.0	.294	.147	4.8	2.22	1.76	22.0	2.17	7.0
76	"	.235	1.81	"	"	1.0	.657	.329	10.7	2.52	2.58	32.2	3.18	12.4
76R	"	"	"	"	"	1.0	.657	.329	10.7	2.52	2.58	32.2	3.18	12.4
77	"	"	1.56	"	"	1.0	.562	.281	9.7	2.27	1.97	25.0	2.43	9.0

The curves in these figures were established from experimental data and the experimental forms in Eqs. (3-11) and (3-12) were determined by trial and error to best fit the data. Rather than to develop complex mathematical expressions, A_o and B_o , should be determined from Figs. 4 and 5 with computed values of ψA_o and ψB_o from known flow, and geometric variables and median sediment size.

Scour depths at various times (scour rates) were computed using the relationships discussed in the preceding paragraphs for runs Nos. 38, 39, 40, 41, 73, 75, 76, and 77 (11) and when compared to measured experimental data a satisfactory correlation was noted. The comparisons between computed and measured results for these runs are shown in Figs. 6a through 6h inclusively. Scour depths were computed for other test runs, including both clear-water and sediment-laden flow, specifically for time t = 60 minutes and when compared to measured data a satisfactory correlation was noted. The computed and measured values of d_s for the runs are tabulated in Table IV. A graphical comparison of the calculated and measured scour depths in terms of d_s/h_n is shown in Fig. 7. The majority of the points lie within a 10 percent variation band about the computed line.

The empirical relationships derived from this study, although satisfactory when applied to model conditions, cannot be used with confidence in situations which deviate from the experimental conditions with respect to geometry, flow characteristics or sediment properties. A more basic understanding of the mechanics of local scour is necessary before a general formula can be developed which would be equally applicable to laboratory and field conditions.

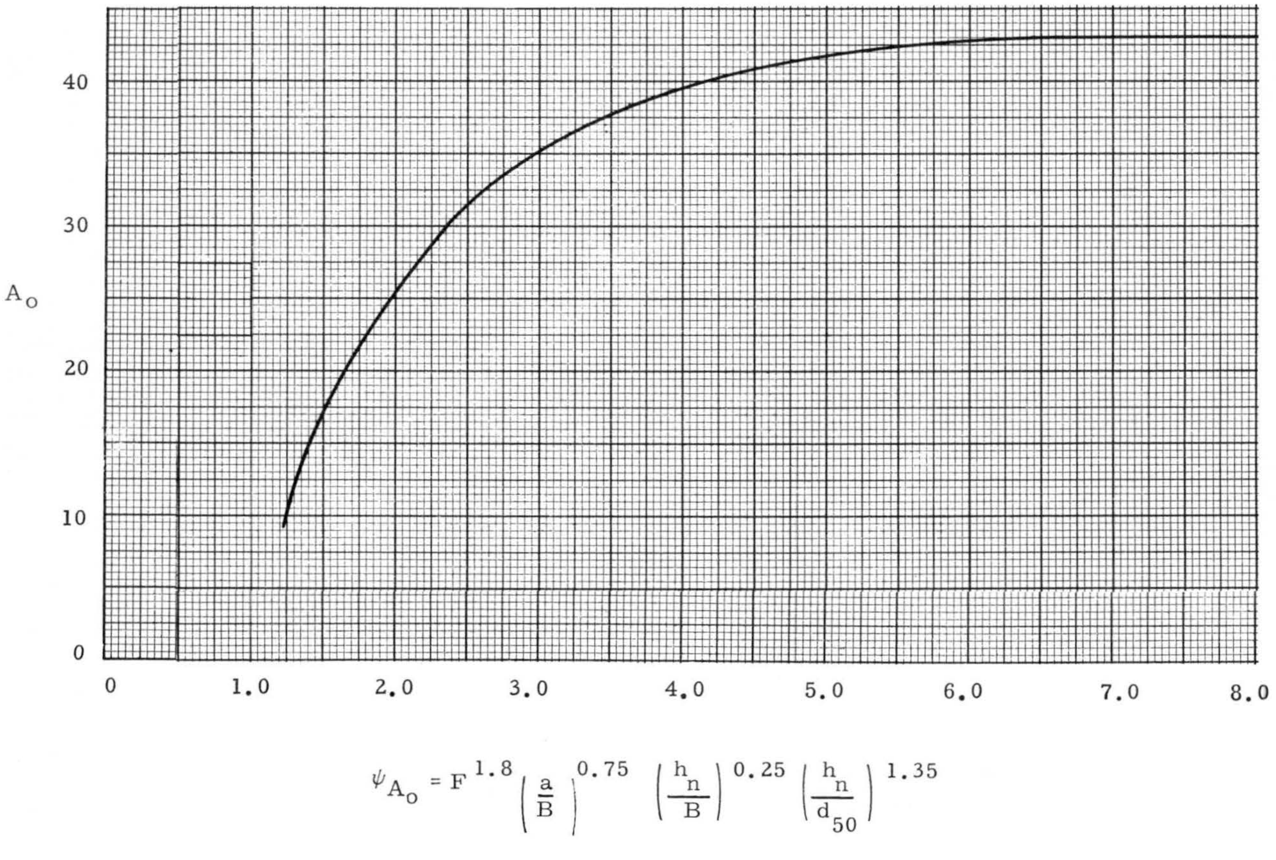
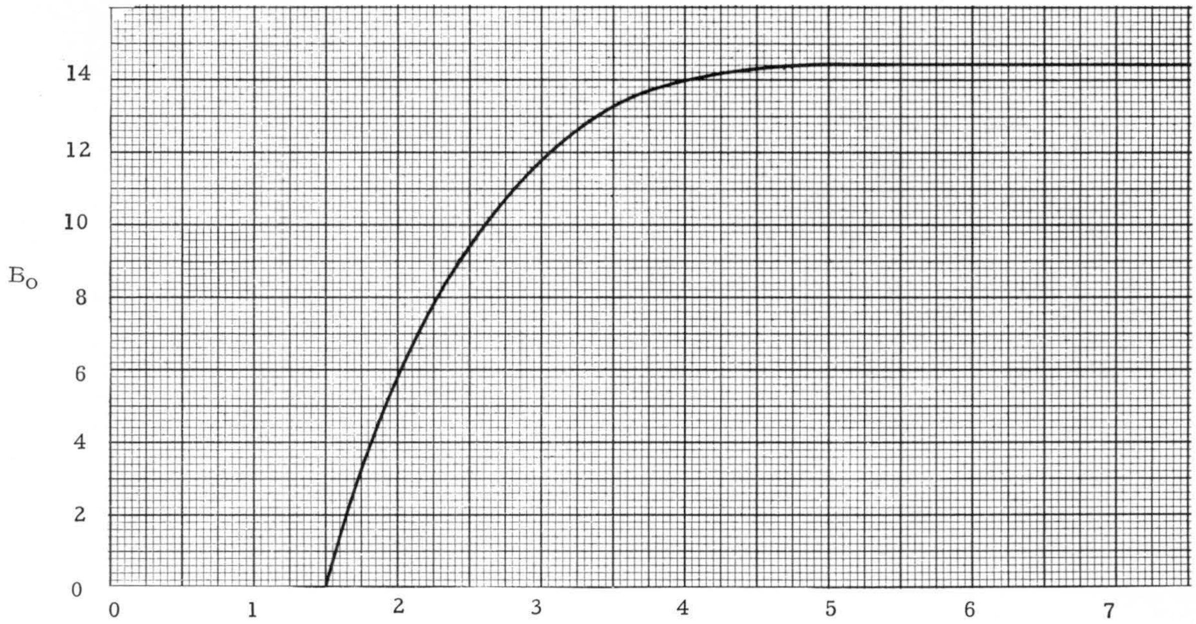
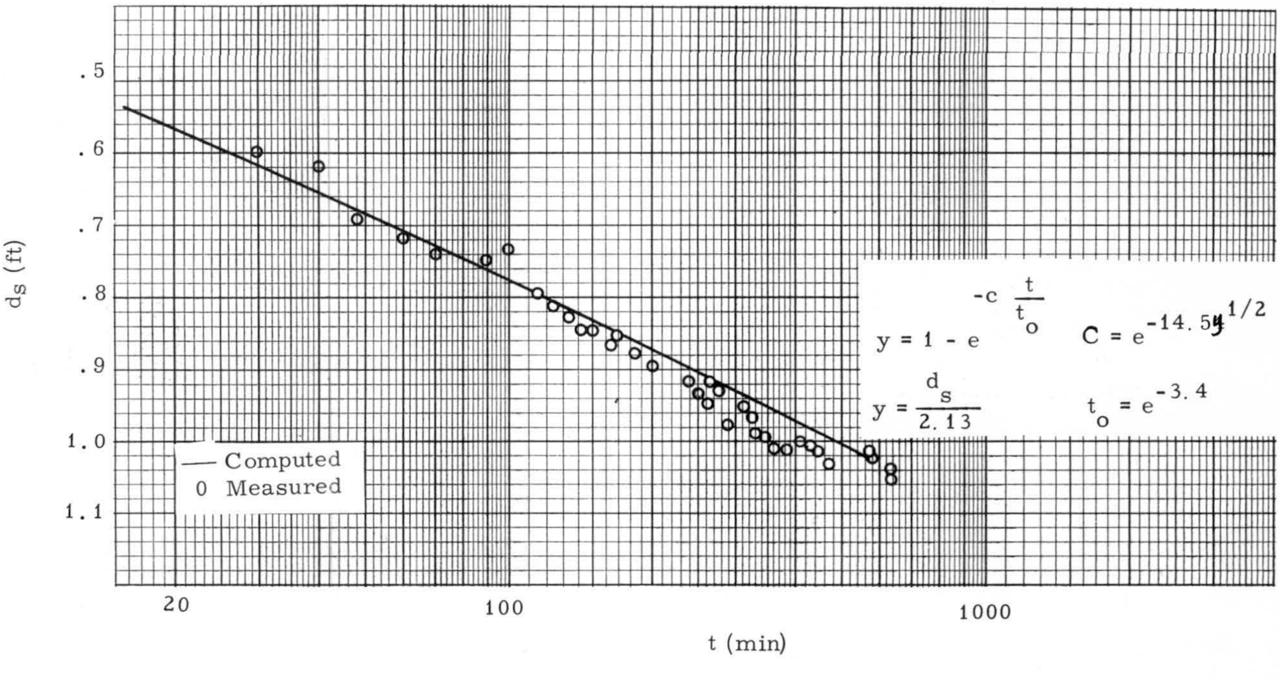


Figure 4. Determination of Coefficient A_o



$$\psi_{B_o} = F^{1.8} \left(\frac{a}{B}\right)^{0.8} \left(\frac{h_n}{B}\right)^{0.2} \left(\frac{h_n}{d_{50}}\right)^{1.4}$$

Figure 5. Determination of Coefficient B_o



$$y = 1 - e^{-c \frac{t}{t_o}} \qquad C = e^{-14.5y^{1/2}}$$

$$y = \frac{d_s}{2.13} \qquad t_o = e^{-3.4}$$

Figure 6a. Comparison of computed and measured scour rates for Run 38 (Ref. 11)

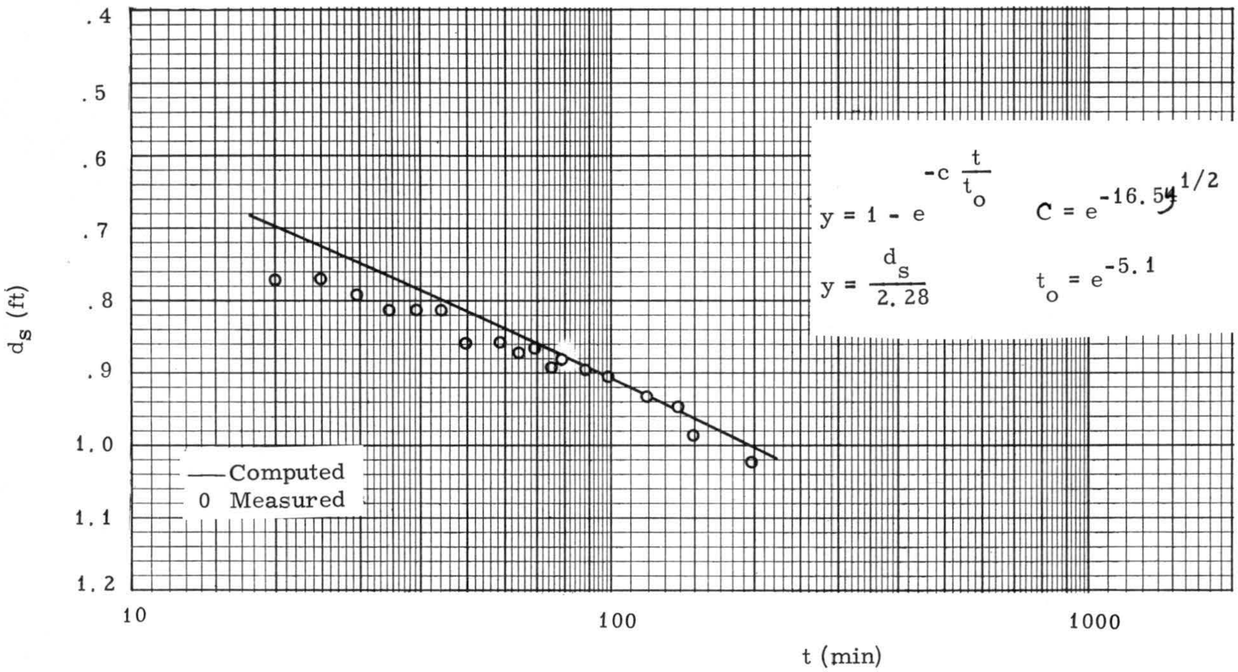


Figure 6b. Comparison of computed and measured scour rates for Run 39 (Ref. 11)

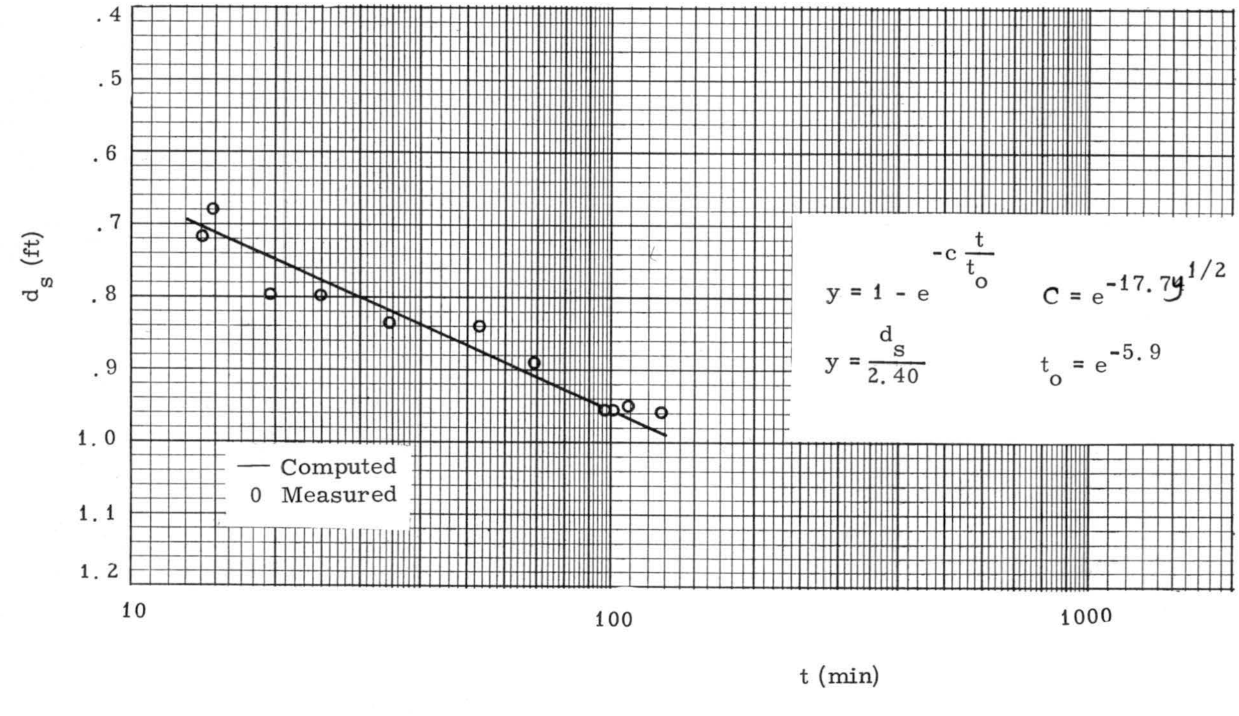


Figure 6c. Comparison of computed and measured scour rates for Run 40 (Ref. 11)

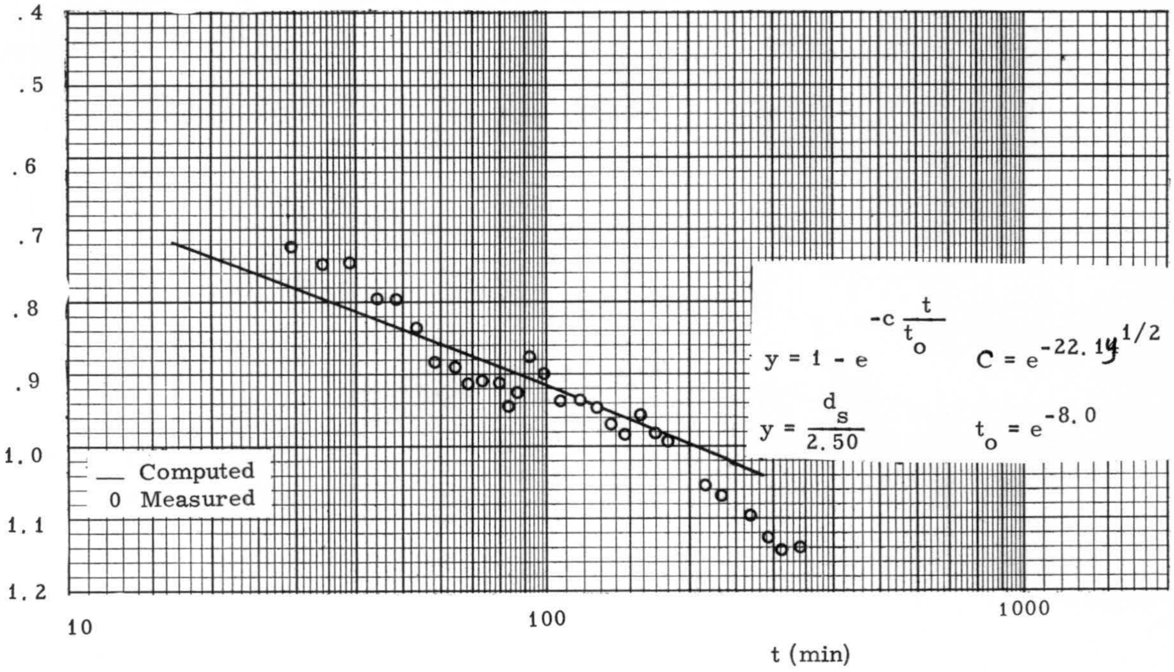


Figure 6d. Comparison of computed and measured scour rates for Run 41 (Ref. 11)

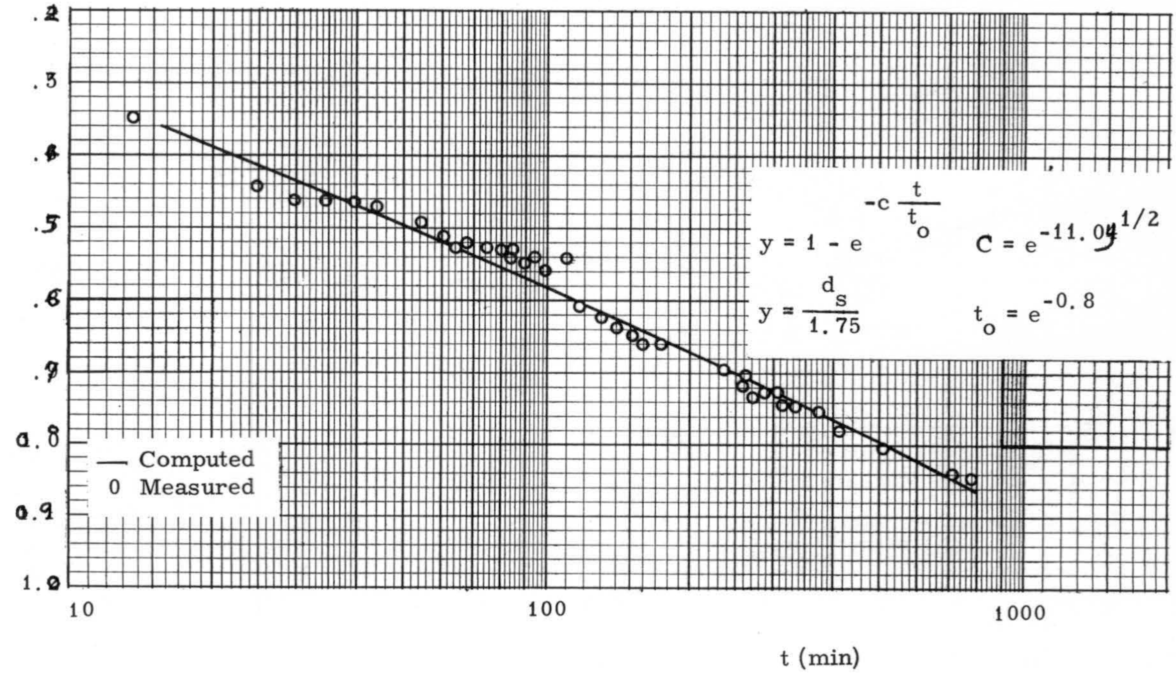


Figure 6e. Comparison of computed and measured scour rates for Run 73 (Ref. 11)

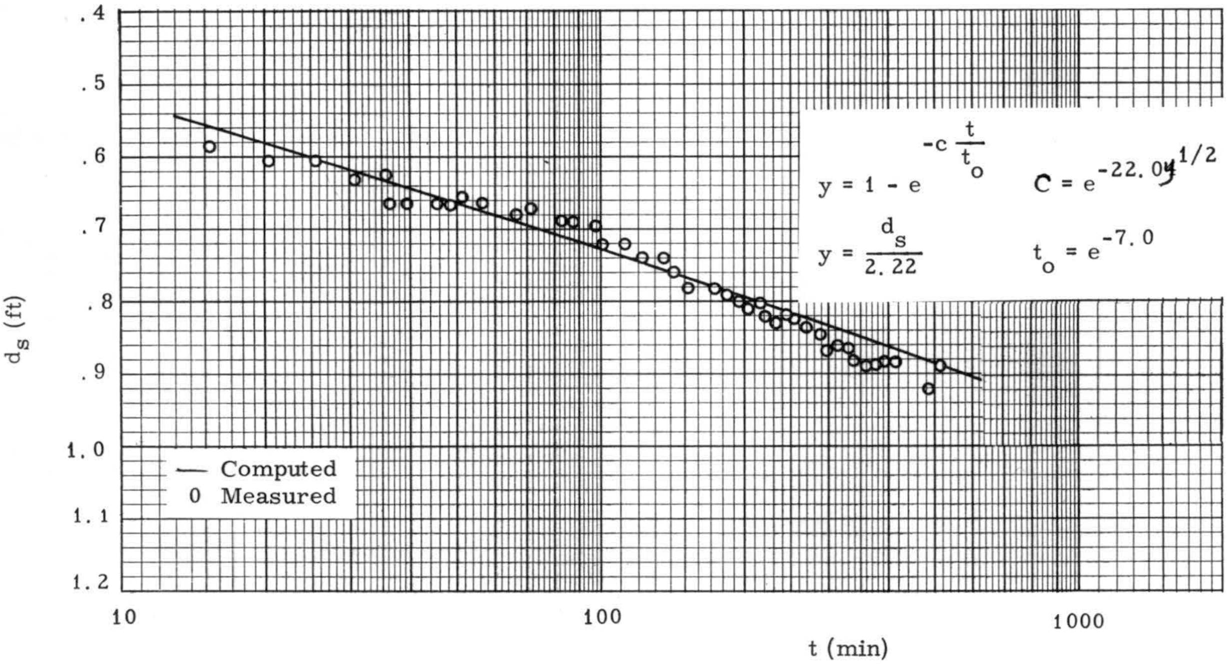


Figure 6f. Comparison of computed and measured scour rates for Run 75 (Ref. 11)

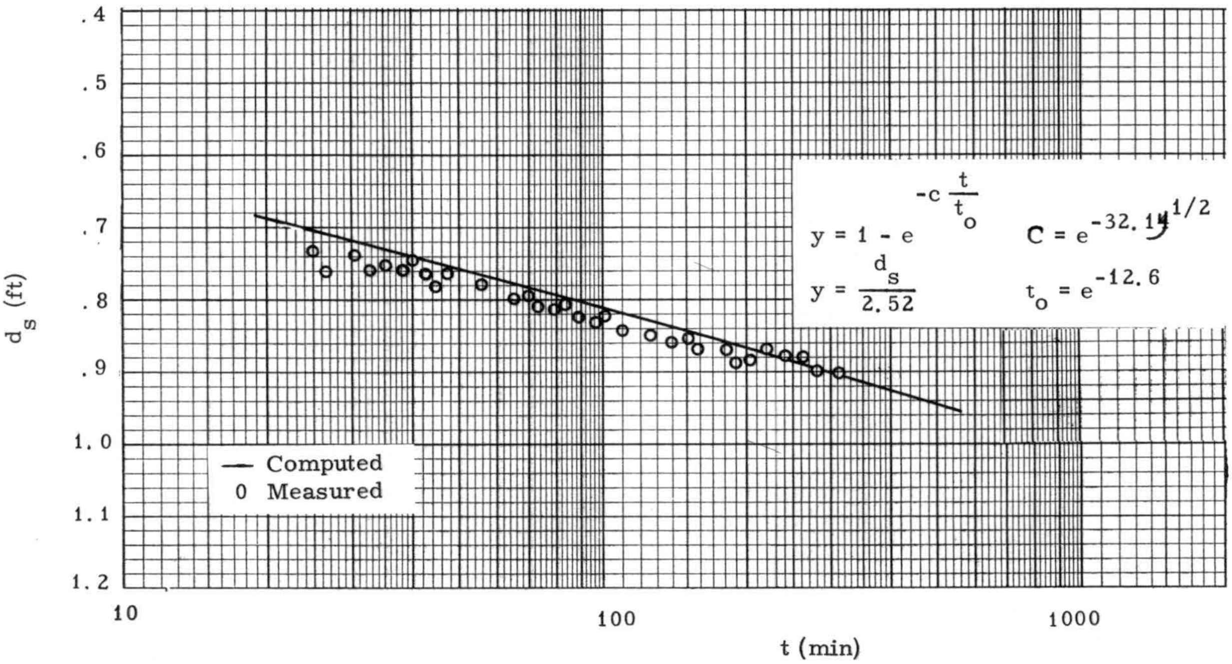


Figure 6g. Comparison of computed and measured scour rates for Run 76 (Ref. 11)

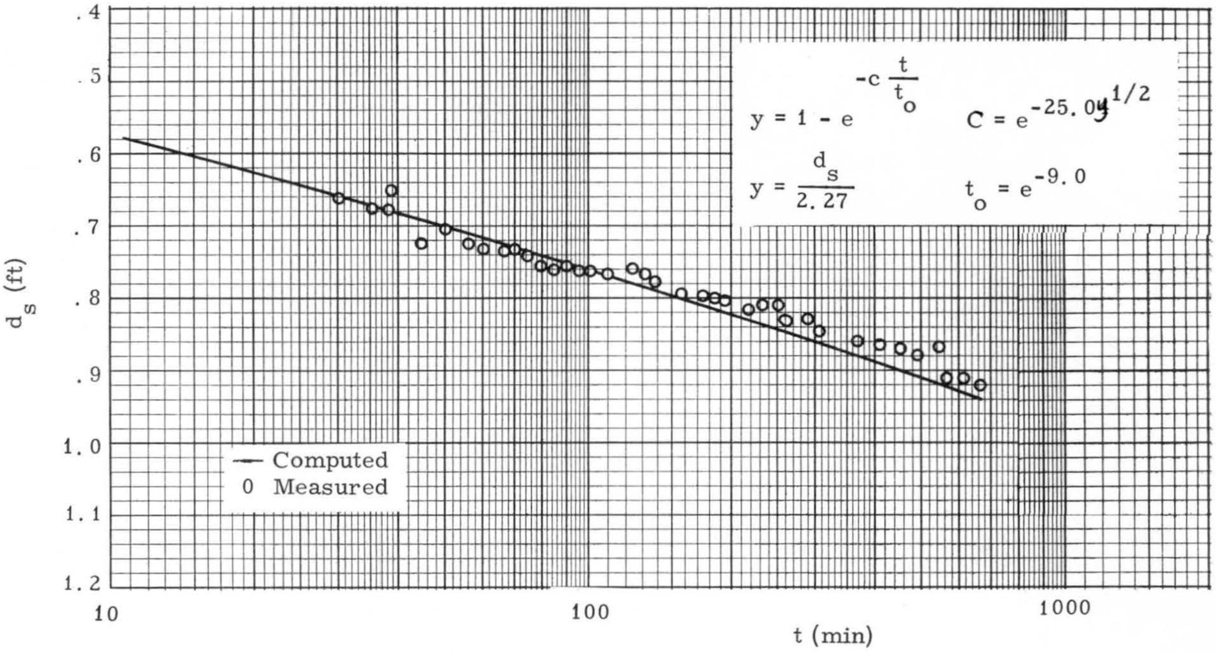


Figure 6h. Comparison of computed and measured scour rates for Run 77 (Ref. 11)

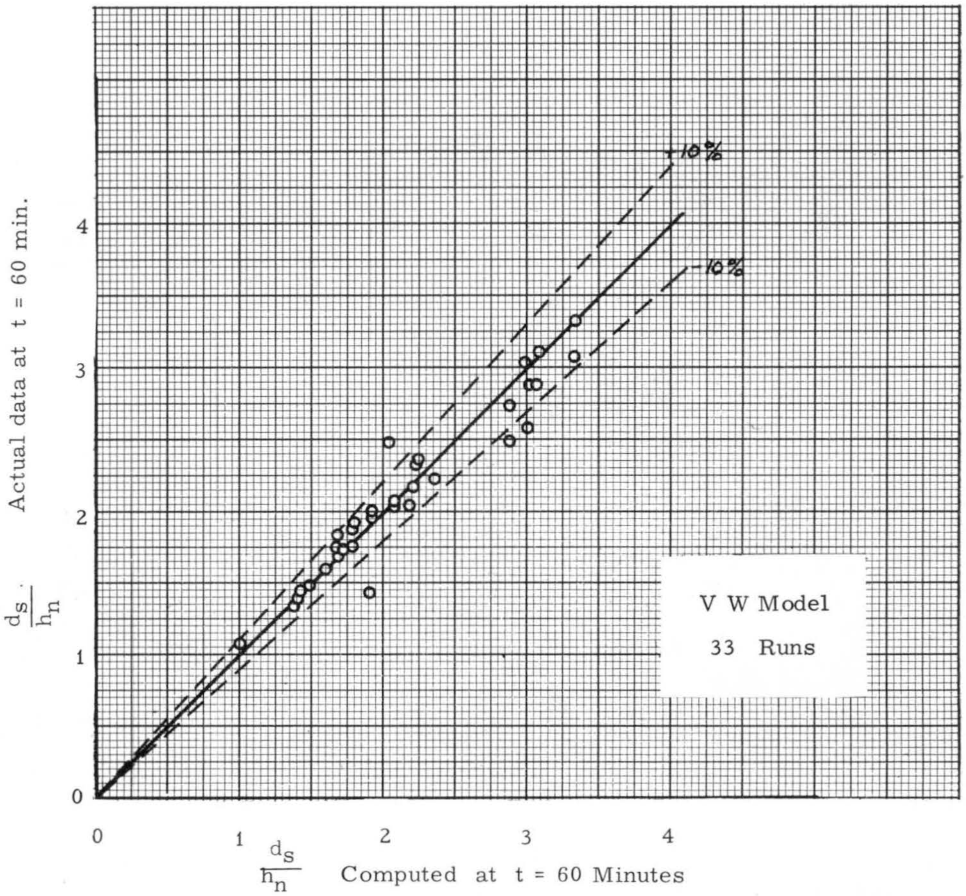


Figure 7. Comparison of computed and measured scour depth at time, t = 60 minutes.

TABLE IV. COMPARISON OF COMPUTED AND MEASURED SCOUR DEPTH AT TIME t = 60 MINUTES

Run	d_{SL}	A_o	B_o	Computed d_s	Measured d_s	Computed d_s/h_n	Measured d_s/h_n
2	3.04	18.0	5.1	.95	.93	2.06	2.02
3	3.49	25.2	9.0	1.08	1.03	2.35	2.24
4	3.95	30.0	11.6	1.22	- -	- -	- -
5	4.37	33.0	12.9	1.32	1.26	2.87	2.74
5A	4.37	33.0	12.9	1.32	1.14	2.87	2.48
6	4.83	35.4	13.8	1.38	1.18	3.00	2.57
6A	4.83	35.4	13.8	1.38	1.32	3.00	2.87
7	5.05	37.1	14.2	1.40	1.32	3.05	2.87
8	5.30	38.4	14.3	1.37	1.39	2.98	3.02
9	5.67	39.4	14.4	1.42	- -	- -	- -
10	3.70	29.4	10.4	1.05	1.02	1.36	1.33
11	4.62	35.5	13.7	1.32	1.33	1.71	1.72
12	5.39	39.1	14.3	1.36	1.35	1.77	1.75
13	6.62	42.0	14.4	1.48	1.53	1.92	1.98
14	7.62	43.0	14.4	1.71	1.78	2.22	2.31
15	6.62	43.0	14.4	1.48	1.52	1.92	1.97
16	4.62	42.0	14.4	1.04	- -	- -	- -
17	4.59	36.0	13.8	1.28	1.28	2.06	2.06
18	5.71	40.1	14.4	1.38	1.45	2.23	2.34
33	3.10	34.9	13.5	.89	.96	1.78	1.92
33R	3.05	34.5	13.4	.88	.94	1.76	1.88
34	4.35	41.4	14.4	1.02	~~12.4~~ 1.24	2.04	2.48
36	2.50	22.2	8.0	.86	- -	- -	- -
38	2.13	14.5	3.4	.71	.72	1.42	1.44
39	2.28	16.5	5.1	.84	.86	1.68	1.72
40	2.40	17.7	5.9	.86	.86	1.59	1.59
41	2.50	22.1	8.0	.87	.88	1.67	1.69
43	3.07	30.5	12.3	.99	.75	1.90	1.44
54	2.50	22.1	8.0	.86	.95	1.66	1.83
55	3.01	30.1	12.0	.98	.95	1.40	1.36
56	2.17	14.3	3.0	.70	.75	1.00	1.07
73	1.75	11.0	0.8	.52	.51	2.08	2.04
74	1.75	11.0	0.8	.52	.54	2.08	2.16
75	2.22	22.0	7.0	.68	.68	1.48	1.48
76	2.52	32.1	12.6	.77	.78	3.27	3.32
76R	2.52	32.1	12.6	.77	.72	3.27	3.06
77	2.27	25.0	9.0	.72	.73	3.06	3.10

IV. GENERAL ASPECTS OF MECHANICS OF LOCAL SCOUR

A. Definitions of Local Scour

Local scour may be divided in two interrelated phenomena:

1. Local scour in a river section takes place whenever there is a constriction or any substantial flow disturbance in a river reach, such as bridge piers and abutments, spur dikes, river training structures, sunken large objects, etc. The scour is characterized by a deepened river bed in a limited river reach. This is a concept of local scour in a broad sense.

2. Local scour is restricted to a narrow area produced by the effect of structures and is confined very close to the structures. Stream jets, secondary currents or any other type of change of velocity distribution occurring in a limited area, and their impact on the erodible bed are responsible for this type of local scour. Local scour can be found in the immediate vicinity of bridge piers, bridge abutments, at the heads of spur dikes, culvert outlets and at the ends of spillways. The scour hole is usually deep. This is the concept of specific local scour.

B. Hydrodynamic Characteristics of Local Scour

The main characteristics of local scour are:

1. Three-dimensional phenomenon. If an obstruction is introduced in a two-dimensional flow (i.e., a bridge pier in the middle of a straight and large channel), the flow becomes three dimensional in the region close to the obstruction. It is, therefore, difficult to justify an approximation of the stream flow in the vicinity of these obstructions by two-dimensional flow patterns. The three-dimensional aspect must be considered as the basic characteristic of any localized scour under natural conditions.

2. Transient unsteady flow regime. If the channel bed is erodible, and if the stream flow is steady, the channel bed is in equilibrium. (Either the stream does not move the particles on the bed, or the bed-load transport is constant, so that no change occurs in bed level.) An obstruction introduced in the stream will locally change the shear velocities at the bed, and local scour takes place. Scour is a function of time, and very often a long period of time is necessary before a pseudo-equilibrium state in the scour hole is attained. A pseudo-equilibrium status occurs in a scour hole or at any river section when the inflow and outflow seidment discharges are approximately equal. The transient period from beginning of scour to a pseudo-equilibrium state is characterized by unsteady flow in the scour region because the boundary of the scour hole changes. The changes in boundary form also effect changes in velocity and pressure distributions and sediment transport rate. An unsteady flow state in the scour region may exist even though a general steady or uniform flow occurs in the stream. Because the sediment supply increases downstream from the region of local scour, an adjustment in the stream bed configuration must take place.

3. Unsteady flow regime. During the unsteady flow regime in a stream, scour caused by the obstructions changes in relation to water and sediment discharges. During passage of a flood under a bridge or through a culvert, local scour holes generally increase in size because of increases in discharge and stage, beside the time effect, and the scour hole is partially refilled by the inflow bed load transported during the flow recession period. The unsteady state of local scour is, therefore, accentuated when the river flow and sediment transport regimes are unsteady.

4. Three groups of parameters. Three main groups of parameters are associated with local scour: (a) parameters which describe the flow regime, such as discharge, flow depth, variables related to velocity and pressure distributions, sediment transport; etc.; (b) parameters which describe the constriction factors; and (c) parameters related to the composition of bed material and bed-load material. The study of local scour is complex because most of the above three groups of parameters vary and are related to four-dimensional flow variations, the fourth dimension being time.

5. Water motion. The water motion around obstructions and in scour holes is often associated with flow separations, opposite currents, large and small eddies. The intermittent and pulsating phenomena--a creation of eddies and vortices, their temporary decay, re-creation and decay, and so on--appear in a given range of flow conditions. All these phenomena change as scour progresses and with changes in flow conditions (unsteady flow). The constrictions usually cause secondary currents to develop because of centrifugal forces and stream jet flows, especially diving flow jets close to and along the obstructions. The general results are that shear velocities at the bed around the obstructions increase, and the impact erosion forces on the bed become augmented. Prediction of local scour depth under given flow conditions is dependent on prediction or knowledge of shear velocity distributions at each phase of scour progress, as well as the transport potential for sediment removal. The shear velocity changes constantly with time as the scour hole deepens or as the scour hole and scour section are being refilled.

6. Sediment motion. Three basic phenomena of sediment motion occur: (a) Inflow of bed load into local scour holes or sections transported by the stream flow; which is complicated by the

different regimes of sediment transport; (b) Sediment outflow from the scour holes or sections; a sediment inflow-outflow equation helps to determine either a positive difference (scour progress), or a negative difference (the scour hole or section is being refilled progressively); and (c) Effect of sediment erosion or deposition in scour holes and sections on the immediate downstream channel reach.

7. Erosion phenomenon. The mechanics of local scour in a channel reach, caused by a constriction, can be treated in the same manner as mechanics of sediment transport in a normal channel. Increased velocities through the constriction are principally responsible for increased shear stresses on the bottom, and erosion takes place as long as the shear velocities are not decreased by a deepened scour section, or the resistance of the bed material is sufficient to withstand erosion.

The process of local scour around obstructions is often an intermittent phenomenon. It has been noted in many experiments, that the side slope of a scour hole are equal or very close to the natural repose slope of the sediment under water. It has been observed also, that the impact of diving jets or secondary currents intensifies the scour in a limited region, usually undercutting the base of the slopes. When the undercut is sufficiently large and deep, a sheet of sediment slides down the slope filling the undercut, and provides progressively greater area for jet impact. The next phase is the erosion and transport of this material out of the scour hole, and a new undercutting process begins. The relatively small area of intensified erosion is, therefore, the cause of this intermittent phenomenon. Neglecting the width of erosion area, this scour process may be designated as line-scour with intermittent sliding (affected also by approaching dunes, or other bed forms) to differentiate it from the sheet erosion process which takes place on a larger area of local scour.

8. Removal of sediment out of scour holes. The removal of sediment out of a scour hole or section, usually upward from the bottom and sides of the local scour hole or section, is effected to a large degree by turbulence and eddies created by the obstruction or stream jet inside the hole or section. The mechanics of this removal is a very complex phenomenon.

V. RESEARCH METHODS IN THE STUDY OF LOCAL SCOUR

A. Current methods for research of local scour. Four methods current in the research of local scour are: (1) Analytical studies; (2) Basic experimental studies; (3) Applied experimental studies; and (4) Field observations and studies.

The complex scour phenomenon described in the preceding section explains why the problem has been studied predominately by either an applied experimental approach, or by observations in nature. Analytical approaches have been carried out under very simplified conditions and with relatively little success.

1. Analytical studies. Some theoretical approaches to analytical treatment of local scour have been developed from the viewpoint of jet impact, secondary currents, application of the Bernoulli equation, and the like. The limitation of these approaches is that they use simplifying assumptions of a very complex problem. The theories have not been able to adequately describe the mechanics of scour, and have not as yet been found feasible for practical applications.

The potential possibility for analytical treatment of local scour is encouraging, but the complexity of the phenomenon will require a period of study before suitable and applicable theories can be developed. This is probably one of the fields of fluid mechanics which will require very close interchange of results between analytical studies, basic and applied experimental research, and field observations.

2. Basic experimental studies. The complex nature of local scour has in the past limited research to simplified cases, such as symmetrical jet erosion and erosion around a cylinder in a stream.

The outlook is good for a more complex treatment of the local scour problem to be solved successfully, if the basic experimental research would be systematically carried out jointly with the analytical studies.

3. Applied experimental studies. This has been the principal approach to the study of local scour. The applied research, very often supported by dimensional analysis has produced some results, and has emphasized the importance of one or more hydrodynamic variables in a general manner.

The hydraulic model studies have been carried out usually in a limited range of Froude numbers which has been characterized as the main dimensionless parameter. The boundary conditions were generally such that model conditions cannot be readily applied to the prototype. It would seem that applied experimental research by itself, without basic experimental and analytical research as directive and corroboration with observations in nature could not contribute substantially to the understanding of mechanics of local scour, or to solution of practical scour problems under natural conditions.

4. Field observations. Although there are some recorded field observations of local scour, they are difficult to interpret. This is principally because most of the observations were made after the flood wave had passed. This is a static situation and the scour hole is viewed only as an erosion problem. It is a known fact that some failures of structures by local scour occurred just a short time after flood peaks. The maximum scour depths are associated with maximum water levels or discharge with a time lag depending on two phenomena, rate-of-change of flood discharge and the corresponding rate-of-change of local scour depth. A flash flood of the same peak discharge would create, under the same conditions, a smaller scour depth and scour hole than a long-duration peak of the same discharge.

Continuous observations of local scour development are generally limited to measurement of scour depths at one or two points in the scour hole with periodic survey of the scoured area, usually after a flood wave has passed through the channel.

Systematic observations of local scour development in nature, for which the necessary instrumentation is available, would probably disclose many phenomena in the mechanics of scour and in the secondary effects of scour, as well as to produce data which could be compared with applied or basic research experiments. These observations would also provide good insight to model-prototype relationships.

5. Research approach. In general, it appears from the review of literature that of the four research methods applicable to the study of local scour, applied experimental research has been predominantly stressed. The apparent reasons for this have already been enumerated. In order to obtain maximum benefits from previous studies and to proceed in a logical manner, greater emphasis should be placed on analytical and experimental studies. The analytical and experimental studies are intimately related and should be conducted concurrently, so that one can augment the other during each step of the research. The two studies jointly are termed basic research. A program to continue detailed observations and surveys of field conditions should be planned to augment present knowledge. This is not to imply that applied experimental research should be discontinued; neither is it intended to imply increased efforts in applied research.

B. Suggested Procedure for Basic Research

1. Analytical study. Assuming a priori that local scour is an unsteady three-dimensional flow phenomenon, the basic partial differential equations of local scour should be derived, regardless of their complex form. These derivations should be based on physical phenomena observed in basic experimental studies for specific cases: obstructions in the middle of a stream, obstruction from one or both sides of the stream, their combinations, jet impacts at the outlets of different structures, etc.

It can be expected, that the fundamental forms of basic partial differential equations would be the same for the above cases, but with different relationships between streams and obstructions, of jets and impact area, there would be different boundary conditions to be imposed on these basic differential equations.

2. Basic experimental studies. There has been a trend to reduce the problems of local scour to an unsteady two-dimensional problem. Three-dimensional and unsteady nature of the local scour problem should be assumed from the beginning of basic experimental studies, and the models and experiments should be conducted from these basic viewpoints.

The principle of stabilizing the scour hole configuration, (that is, fixing the bed configuration relative to any instant of time) for selected times during the process of scour is a necessary experimental procedure. In this technique, the configuration of the scour hole and stream bed at any time, t_n, would be replaced by a stabilized boundary of the same configuration. Velocity and pressure distributions would be recorded, especially in the region of the scour hole or section, with an emphasis of measuring the shear-velocity distributions, as well as the turbulence conditions in the hole or section. It is the turbulence which enables the stream to carry out the eroded sediment. By de-stabilizing the bed, the process of scour would continue until at another time, t_{n+1}, the procedure would be repeated.

An approach of this kind could be used to study, for example, scour around a bridge abutment. The water and sediment are moved along the abutment in a spiral motion in the scour hole. By employing the stabilizing and de-stabilizing technique, it should be possible to investigate the hydrodynamic conditions and phenomena at any time, t_n , in the development of the scour hole, and at any point in the flow, at the upstream face, around the head, and at the downstream face of abutment. After the phenomena for the case of a plane vertical sheet, simulating the abutment, have been thoroughly investigated, different shapes of abutment may be considered.

The selection of specific times for the stabilizing procedure must be based on phenomena significant to the progress of local scour. When specific changes in flow patterns, or scour hole development are not determinable because of transient conditions, a representative coverage of the scour process must be made by selection of specific intervals in time. These intervals cannot be selected from preliminary runs of specific test conditions.

Knowledge of velocity distributions as well as observed changes in water surface configurations would help to express mathematical expressions to describe the unsteady three-dimensional case of local scour.

3. Field measurements and studies. An organized field observation program designed to add information to present knowledge of local scour around the obstructions, or at outlets of culverts would add materially to understanding the mechanics of local scour. These observations and surveyed information would be the basic source of describing different phenomena occurring in nature which are related to the local scour problem.

The research program which has been outlined briefly, would enable a synthetic approach, pulling together information from all four research methods: analytical, basic experimental, applied experimental, and survey of field conditions, to develop further knowledge about the local scour phenomenon.

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