Abstract of Thesis

by

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ABSTRACT OF THESIS

COMPARISON OF SCOUR CAUSED BY HOLLOW AND SOLID JETS OF WATER

Submitted by
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ABSTRACT

The importance of Sediment Engineering in relation to the design and maintenance of irrigation structures is being realized increasingly by both hydraulic and irrigation engineers. Though great strides have been taken during the last 25 years toward the solution of many of its complicated problems, there are still many more awaiting solution. One of the problems which has hitherto received very little attention is that of scour by jets.

A jet may be square, rectangular, circular, or even tubular in cross section. When the flow through the outlet conduit of a dam, for instance, is regulated by a needle valve at the downstream end, the resulting discharge is in the form of a solid circular jet. In recent years, however, there has been an increasing use of the hollow-jet valve on many irrigation projects. This valve has a smaller cost-discharge ratio and is so arranged that all the mechanical parts are easily removed. Water discharges from this valve in the form of a tubular or hollow jet.

The problem

The problem for which this thesis seeks to

furnish an answer may be stated as follows: What is the scouring capacity of a hollow jet of water and how does it compare with that of a solid jet?

Analysis of the problem.--A general appraisal of the problem presents the following questions:

1. What are the factors affecting the phenomenon of scour by jets?

2. How do these factors govern scour?

3. How does the hollow jet compare with the solid jet in respect to scouring capacity?

Factors affecting scour by jets

There are several factors that exert influence to a varying degree on the phenomenon of scour. Some of them have a direct bearing on the problem and the others are related only indirectly. All of the important factors may be grouped under four headings.

Characteristics of the jets.--Important factors included in this group are:

1. Shape of jet
2. Area and velocity of jet
3. Height and travel of jet
4. Inclination of jet.

Characteristics of the pool.--The factors that are related to the pool are:

5. Size of pool
6. Initial disturbances in the pool.

Characteristics of the inflow.--The two main factors that characterize the inflow are:

7. Sediment load of inflow

8. Duration of inflow.

Characteristics of the sediment.--Important factors included in this group are the following:

9. Mean fall-velocity and standard deviation of the sediment

10. Shear resistance of the bed material.

Theoretical analysis

Problems dealing with clear water having no sediment load are often so complicated that it is difficult to solve them rationally. Taken with its sediment load, however, the flow depends upon so many variables it is generally impossible to solve the problem from the rational point of view.

In the first place, if the jet is discharged into the air it entrains the air and disintegrates before it strikes the surface of the pool. After it plunges into the pool it diffuses until it reaches the bed and scours a hole in it. The material thus loosened is carried into suspension or along the bed by the turbulent eddies of various sizes. Much more information on the diffusion of jets in air and water and the turbulence mechanism, all of which are involved in the phenomenon of scour, is needed before analytical solutions to the problems of the type of scour by jets can be attempted. A theoretical approach in such cases, therefore, is no closer to the prediction of the needed solution than the recognition of the parameters which are involved in the phenomenon and their generalized functional relationship. It is believed that dimensional analysis offers the most direct means of exploring the general forms of functional relationships between the variables.

Dimensional analysis.--For purposes of dimensional analysis, all the variables that govern the phenomenon of scour by jets may be arranged under four groups.

a. Geometric characteristics -- Let the extent of pool be L units long, B units wide and b units deep. Further let d be the depth of sediment, H be the height of the exit of the jet above the bed, θ be the angle which the center line of the jet makes with the surface of the pool, and f be the shape factor for the jet.

b. Flow characteristics -- Let A and V be the area and velocity of the jet respectively, t be the duration of inflow, D_1 be a term characterizing the initial disturbance in the pool, D be the coefficient of turbulent diffusion in the pool, and C_s be the concentration of sediment in the jet.

c. Fluid characteristics -- Let ρ be the mass density and μ the viscosity of the water at temperature t_1.

d. Sediment characteristics -- Let w_m be the mean fall-velocity of sediment, $\sigma_{\overline{w}}$ the standard deviation of the fall-velocity, and ρ_s the mass density. Further, let p be a factor representing the 'shear capacity of the sediment and h be the depth of scour.

At the outset, it is clear that too many variables enter the problem for an experiment to be carried out successfully and that some of them must therefore be eliminated. If it is decided to experiment with a square pool which is also free from initial disturbances, then B equals L and D_1 need not be taken into consideration. Further, if the experiment is so planned that the depth of sediment is never exceeded by the depth of scour, d can be omitted. Because the incoming flow will carry no sediment, C_s may be considered zero.

Except for its effect on the value of w_m, the flow is not influenced by vicosity and consequently μ can be neglected. The material to be used will be gravel and will not be compacted initially in any way. Under such circumstances, the water has negligible difficulty penetrating the bed between the grains. Therefore, it may be assumed that the factor p has no significant effect on the results. Both D and h are dependent variables and since there should be only one such variable the former is omitted. The most general relationship between the remaining variables may be expressed as follows:

$$\phi_1 (L, H, \theta, b, f, V, A, t, \rho, \rho_s, w_m, \sigma_{\bar{w}}, h) = 0 \quad (1)$$

Choosing A, ρ, and w_m, as the repeating variables, dimensional analysis yields

$$\phi_2 \left[\frac{L}{\sqrt{A}}, \frac{H}{\sqrt{A}}, \theta \; \frac{b}{\sqrt{A}}, f, \frac{V}{w_m}, \frac{w_m t}{\sqrt{A}}, \frac{\rho_s}{\rho}, \frac{\sigma_{\bar{w}}}{w_m}, \frac{h}{\sqrt{A}} \right] = 0 \quad (2)$$

Further simplification of the problem is necessary, however, before it could be handled practically. If the studies are confined to a jet with its exit at a constant level from the bed of sediment, then $\frac{H}{\sqrt{A}}$ is constant so long as the studies relate to a given jet. Furthermore, $\frac{\rho_s}{\rho}$ may be considered constant for all practical purposes if water and gravel are used throughout the studies within a small range of temperature. Further, if the sediment to be used has a narrow size range, $\frac{\sigma_{\bar{w}}}{w_m}$ may be treated as zero. The resulting relationship then becomes

$$\phi_3 \left[\frac{L}{\sqrt{A}}, \theta, f, \frac{h}{\sqrt{A}}, \frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{b} \right] = 0 \quad (3)$$

If $\frac{L}{\sqrt{A}}$, θ , and f are held constant for a series of runs then the relation reduces to

$$\phi_4 \left[\frac{h}{\sqrt{A}}, \frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{\sqrt{A}}\right] = 0 \qquad (4)$$

from which

$$\frac{h}{\sqrt{A}} = \phi_5 \left[\frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{\sqrt{A}}\right] \qquad (5)$$

If $\frac{h}{\sqrt{A}}$ and $\frac{w_m t}{\sqrt{A}}$ are each divided by $\frac{b}{\sqrt{A}}$ the relationship becomes

$$\frac{h}{b} = \phi_6 \left[\frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{b}\right] \qquad (6)$$

It is now possible to study, for instance, the variation of $\frac{h}{b}$ with respect $\frac{w_m t}{b}$ for different values of $\frac{V}{w_m}$ while the value of $\frac{b}{\sqrt{A}}$ is held constant.

Delimitation.--Because of the obvious complexity of the problem, this study is limited to an investigation of scour, in a bed of material of relatively uniform size, by a jet from a hollow-jet valve as compared with a solid jet. The jet is to be discharged vertically downward from a constant height above the original level of the bed.

Experimental equipment and procedure

The laboratory equipment needed for this study mainly consisted of devices for obtaining hollow and solid jets, gravels of suitable size-ranges, a water-supply system with means to regulate the discharge, and a flume to accommodate the gravel and the flow.

General layout of the equipment.--A 4-in. deep-well turbine pump was used to pump clear water from the sump, located beneath the floor of the laboratory, through a 2-in. galvanized iron water-supply line. The discharge through the line was regulated by means of a valve just above the floor level. At the end of the water-supply line was a 2-in. diameter copper pipe 40 1/4 in. in length with a steel flange at the end to enable the hollow-jet valve and the solid-jet nozzles to be fixed. The fabrication of the water-supply line was such that with proper levelling the vertical copper pipe was exactly centered over the head-box of the flume containing a bed of gravel 47 in. by 47 in. and 25 in. in depth. A tail-water gate was used to control and vary the depth of water over the bed. Since it was necessary to have a known depth of water over the gravel before the jet was allowed to strike the pool, a wooden trough was used to divert the stream beyond the gravel bed. At the end of the flume was a calibrated weir to measure the discharge.

A 2-in. brass model of the hollow-jet valve, borrowed from the hydraulic laboratory of the Bureau of Reclamation, Denver, Colorado, was used to obtain the hollow jet. For the solid jet, two nozzles with exit diameters of 1.68 in. and 1.145 in. were turned on the lathe from solid steel. Two grades of gravel, obtained from the Cache La Poudre River at Bellvue, Colorado, were used. One of them consisted of particles passing through a sieve with 2 meshes to the inch but retained by a sieve with 4 meshes to the inch. The particle size-range of the second gravel was 1/4 to 1/8 in.

Procedure.--To begin an experiment, the gravel bed was levelled and the wooden trough was placed below the jet to divert it downstream. The pump was then started and, when the level of the water over the bed was brought to the required depth, the trough was withdrawn allowing the jet to strike the pool. Care was taken to note the time the jet struck the pool. After it had run for the proper length of time, 15 minutes for instance, the pump was stopped. The drain-valve was opened to lower the water-level in the box to expose fully the scoured region. Because the scour was almost symmetrical and conical in shape about the center of the jet, only one central line of measurements was taken transverse to the box with every experiment. The experiment was repeated with the same depth of water in the pool with the jet running for an additional 15 min so that the total time for the second experiment was 30 min. A 30-min run for the third time, and 1-hr run for the fourth, made the duration of the third and fourth experiments 1 hr and 2 hrs respectively. After the completion of one set of experiments with a particular depth of water b, the gravel bed was levelled before beginning the next set with another depth.

A total of 87 experiments were conducted with the hollow jet and 97 with the solid jet. The data were represented graphically in accordance with Eqs. (5) and (6) and the following were the important findings:

a. If the material is relatively uniform, the depth of scour depends upon the area and velocity of the jet, the mean fall-velocity of the material, the depth of water over the bed, and the duration of the scouring action.

b. The magnitude of scour increases with an increase in velocity whether this increase occurs due to a change in the area of the jet with the discharge remaining constant or due to a change in the discharge while the area remains constant.

c. The incremental increase of scour, with time as a geometric progression, is a constant. No equilibrium is to be expected with any depth after any period of time.

d. The magnitude and rate of scour decrease with a decrease in the ratio of jet velocity to fall-velocity--approaching zero as the ratio approaches unity. This result leads to the inference that if the material were to consist of several sizes of particles the heavier ones would gradually line the scour hole therefore decreasing the value of $\frac{V}{w_m}$ and increasing the tendency for the hole to become stabilized.

e. The most interesting result which at first appeared to be contrary to the commonly held opinion is that, other factors remaining constant, scour increases with increase in the depth of pool until the depth reaches a critical value. Any further increase in the depth of pool diminishes the resulting scour.

Emperical expressions for scour.--Attempts to work out, with the aid of experimental results, an expression involving the dimensionless parameters of Eq. (6) resulted in the equation

$$\frac{h}{b} = \frac{0.023\sqrt{A}}{b} \log\left[\frac{w_m t}{b}\right]^{\left[\frac{V}{w_m} - 1\right]} - 0.032\frac{b}{\sqrt{A}} + 0.5 \qquad (7)$$

for the hollow jet when it is fully open and

$$\frac{h}{b} = \frac{0.023\sqrt{A}}{b} \log\left[\frac{w_m t}{b}\right]^{\left[\frac{V}{w_m} - 1\right]} - 0.022\frac{b}{\sqrt{A}} + 0.4 \qquad (8)$$

for the solid jet with a corresponding area. Though the equations have been based on studies made under idealized conditions, they do establish the fundamental principles which govern the phenomenon of scour.

Comparison of the results obtained with the hollow and solid jets under similar conditions lead to the following generalized statements.

a. For a given area of jet the comparison of the scour resulting from the two types of jets appears to indicate one trend. With a change in area the results of comparison show quite a different trend. This inconsistency may be due to the fact that a variation in the area alters the diffusion of the jets and the turbulence mechanism in the pool. Further it will also introduce two additional variables $\frac{L}{\sqrt{A}}$ and $\frac{H}{\sqrt{A}}$ into the study.

b. The scouring capacity alone, divorced from other hydraulic, structural, and economic factors, is not important enough to make one of the two types of jets superior to the other unless it is decided to operate the one jet only in the specific range in which experimental studies have established its superiority over the other.

Suggestions for further study.--This study is just one aspect of a multiphased problem. Attention was directed to the investigation of the effect of only six factors out of a total of 18. An extension of the present study without the inclusion of additional variables might be carried out as indicated below:

a. Experiments may be conducted to obtain further information to define more clearly the two regimes of the phenomenon of scour on either side of the critical depth and to relate this depth with $\frac{V}{w_m}$.

b. Studies may be extended to include additional sizes of valves in order to relate the scouring capacity with the variation of the area A.

In order to augment the usefulness of the results to the solution of practical problems the studies may be further extended to include the following additional variables.

c. Studies may be made to evaluate the effect of the inclination of the jet θ on scour.

d. Experiments may be conducted with sediment having appreciable size range of particles thereby making $\frac{\sigma_w}{w_m}$ an important variable.

e. It may be interesting to study the effect of the relative dimensions of the pool and to find the size at which the scour ceases to be affected by it.

A complete comprehension of the problem, of course, is possible only when the effects of all the factors that influence scour are evaluated.

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DODDIAH DODDIAH

ENTITLED COMPARISON OF SCOUR CAUSED BY HOLLOW AND AND SOLID JETS OF WATER

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

CREDITS 9

Committee on Graduate Work

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Chapter I

INTRODUCTION

The past quarter of a century has been witnessing the rapid development of a branch of engineering which may be called "Sediment Engineering." (8:68) This field of science is of utmost importance to the irrigation engineer, especially in view of the fact that many irrigation projects have become either partially or completely useless because of man's inability to cope with the forces involved. It deals with problems arising from the fact that flowing water has ability to carry sediment with it. This ability to transport sediment, however, is not unlimited. When the flow receives more sediment than it can convey, or its power to carry is curtailed, deposition of sediment takes place. On the other hand, if it is deprived of its load without having its carrying capacity reduced, it picks up sediment causing scour. Problems of sediment, therefore, may be classified broadly into:

a. those dealing with deposition of sediment which results in silting-up of reservoirs, obstruction of floodways and navigation channels, and blocking of outlets of sewers, water intakes, and drainage and navigation canals,

b. those dealing with deposition and scour which affect channel alignment and hydraulic conditions around newly built structures,

c. those dealing with scour, that causes damage to irrigation lands, scour of canals, and undermining of structures.

Large areas of land are denuded by the process of scour. Although seemingly insignificant in depth, this process is fraught with disastrous consequences in the long run. Scour which is confined to a small area may be termed localized scour. It may occur in streams at certain places across the section, as at bridge piers for instance, where the local conditions are such as to cause the scouring capacity of the flow to be more pronounced and concentrated. Another source of scour is a jet, either 2-dimensional or 3-dimensional, which impinges on the river bed.

With particular reference to localized scour, two classes of jets may be distinguished. One is exemplified by the nappe over a spillway. This 2-dimensional jet extends over the full width of the energy dissipating structure, is guided by a fixed boundry, and is subject to a varying pressure around the periphery. Unless its energy is destroyed before it leaves the nonerodible bed it may cause scour of the erodible material downstream.

Water issuing from outlet conduits in dams, either controlled by gates or regulated by valves, forms the second class of jets. Such jets may be submerged or may discharge into the air. In both the cases, the resulting turbulence is a maximum within the jet at the point of greatest shear, decreasing with distance from the center of the jet.

The needle valve and its various modifications, with which the discharge through the outlet conduits of several dams have been controlled, give solid cylindrical jets. In fact this shape is the most common one associated with jets. Recent years, however, have seen the installation in many irrigation projects of a regulating device called a hollow-jet valve. This valve has a lesser cost-discharge ratio and is so arranged that all the mechanical parts that require maintenance are easily removed. Water discharges through this valve in the form of a tubular or hollow jet. The hollow form has been developed with a view to distribute the energy over a comparatively large area, facilitating its dissipation and lessening the destructive action in the stilling pool.

The problem

The problem for which this thesis seeks to furnish an answer may be stated as follows: What is the scouring capacity of a hollow jet of water and how does it compare with that of a solid jet?

An attempt to further analyze this problem in a search for its solution, will be much facilitated by a review of the work that other investigators have already done in this field.

Chapter II

REVIEW OF LITERATURE

The phenomenon of localized scour has hitherto had very little systematic investigation. Generally experimental studies are made to prevent scour below dams in relation to particular structures and attention is directed to see that, by the time the flow reaches an erodible bed after passing through an energy dissipating structure, its flow pattern is such that no dangerous scour will occur.

For scour to occur, the flow must be able to dislodge material from the bed and convey it either along the bed or in suspension. Thus, localized scour is just a phase of sediment transportation. Therefore, the search for information pertaining to the problem set forth for investigation includes literature which deals with (a) factors that influence scour in general, (b) analytical or functional relationships between these factors, and (c) quantitative studies of localized scour in particular.

The English system of units (foot-pound-second) is used throughout this study unless otherwise stated.

Factors affecting scour

Gilbert (5) 1914, who pioneered in making sediment transportation experiments in flumes, carried out comprehensive studies to investigate the effect of slope, discharge, size of sediment, ratio of depth to width, and velocity on the ability of a stream to transport bed-load. His important conclusions which have a bearing on this thesis are noted below:

a. With the width, the slope, and the size of debris remaining constant, the ability of the stream to transport material, that is its capacity, increases with the increase in stream discharge.

b. For constant values of width, slope, and discharge, the capacity of the flow increases when the size of the material decreases.

c. The capacity of the stream also increases with velocity. It varies on the average with the velocity to the 3.2 power provided the increase in the velocity is due to an increase in discharge.

Rubey (13), in 1938, in a theoretical analysis of the various hypotheses regarding the force required to move particles on a stream bed made the following observations:

a. A particle on a stream bed moves due to impact of water against it or to frictional drag on its surface or to differences in pressure on its top and bottom caused by the velocity gradient.

b. The "sixth-power law", stating that the weight of the largest particles moved by a stream varied as the sixth power of velocity, is based on impact theory and this law refers to the size of the particles moved and has nothing to do with the total amount of sediment transported by the stream. Re-examination of Gilbert's (5) results showed that the movement of coarse sand and gravel followed the "sixth-power law" but the smaller particles required higher velocities than were indicated by this function.

c. The velocity on the stream bed is more significant than the mean velocity of the entire section.

Kalinske (6), in 1940, conducted experiments at the University of Iowa to study the fluctuation of the velocity and turbulence mechanism in turbulent flow by injecting, with a fine hypodermic-type of needle tube, drops of carbon tetrachloride and benzine having the same specific gravity as the water and photographing their movement. By an analysis of the velocity fluctuations, both parallel and normal to the direction of flow, he pointed out that the fluctuating velocities in the turbulent flow are statistically distributed according to the normal error law. Further, an expression for the turbulent diffusion, similar to that for molecular diffusion, was shown to be of the form

$$\overline{Y^2} = \frac{2\ Dx}{\overline{V}} \qquad (1)$$

where $\overline{Y^2}$ is the mean square spread of the particles, D is a measure of the diffusing power of turbulence, $\overline{V}$ is the mean velocity of flow, and x, in inches, is the distance downstream from the point of injection. His study of the diffusion characteristics of the turbulence throughout the section of an open channel by injecting droplets of carbon tetrachloride and benzine corroborated the theoretical approach.

Krumbein (7) made flume studies in 1942 to determine the effect of the shape of the particles on bed-load transportation and to relate this behavior to its settling-velocity. The data were confined to the bed-movement of single particles of cement mortar having a constant volume but varying systematically in shape. The shapes studied were classified as cubes, disks, rollers, bricks, and fragments. He defined the sphericity Ψ of the particle, one of the characteristics of shape, by the relationship

$$\Psi = \sqrt[3]{\left[\frac{b_1}{a}\right]^2 \left[\frac{c}{b_1}\right]} \qquad (2)$$

where a, b_1, and c are respectively the longest, intermediate, and shortest mutually perpendicular axes through the particle. His conclusions may be summarized by the following statements.

a. For all shapes, the ratios of particle velocity w to the velocity of flow V, increase rapidly at low Froude numbers F_r and level off toward asymtotes between $\frac{w}{V}$ equal to 0.8 and 0.9. Compared with disks, the sperical particles have a higher ratio of $\frac{w}{V}$.

b. The particles of greater sphericity in general have higher settling velocities.

c. In view of the close correspondence between the relative behavior of rollers and discs during settling and in the flume, the settling-velocities of the particles furnish an adequate index for studies of particle transportation either in suspension or along the bed.

In 1948, Albertson and others (1) published a study of the diffusion and deceleration of the submerged jet resulting from the turbulence generated by it. Analytical expressions were derived to evaluate the characteristics of the resulting mean flow both within the zone of flow establishment and that of established flow. The analysis was substantiated by experimental results.

According to them, the equation for the distribution of the longitudinal velocity component in the zone of establishment for the three-dimensional jet is

$$\log_{10} \frac{v_x}{v_o} = -33 \left[0.081 + \frac{r - D_o/2}{x}\right]^2 \qquad (3)$$

and for the zone of established flow,

$$\log_{10} \frac{v_x}{v_o} \frac{x}{D_o} = 0.79 - 33 \frac{r^2}{x^2} \qquad (4)$$

where v_o is the exit velocity of the jet, v_x is the velocity at a distance x from the efflux section, D_o is the diameter of the orifice, and r is the radial distance.

Specific forms of equations for the volume-flux and the energy-flux are respectively

$$\frac{Q}{Q_o} = 1 + 0.083 \frac{x}{D_o} + 0.0128 \frac{x^2}{(D_o)^2} \qquad (5)$$

$$\frac{E}{E_o} = 1 - 0.090 \frac{x}{D_o} - 0.029 \frac{x^2}{(D_o)^2} \qquad (6)$$

Corresponding equations for the zone of established flow are

$$\frac{Q}{Q_o} = 0.32 \frac{x}{D_o} \qquad (7)$$

$$\frac{E}{E_o} = 4.1 \frac{D_o}{x} \qquad (8)$$

Approximate turbulence characteristics were also studied, but only qualitatively. A similar analysis was made for a two-dimensional jet.

Corey (4), 1949, studied the influence of the shape of the rock particles on the fall-velocity. The study was limited to sands of sieve diameters corresponding to 4 to 14 meshes to the inch. The shape factor was expressed by the ratio

$$sf = c/\sqrt{ab_1} \qquad (9)$$

A photographic method was adopted for measuring the fall-velocity w. He obtained satisfactory correlation between the shape factor and the fall-velocity by plotting the coefficient of drag C_D as a function of Reynolds number R in which C_D was defined as $\frac{F/d^2n}{\rho w^2/2}$ and R as $\frac{wd_n}{\nu}$, d_n being the nominal diameter. He also pointed out there was scarcely any correlation between the same two factors when C_D and R were defined respectively as $\frac{F/ab}{\frac{\rho w^2}{2}}$ and $\frac{wb_1}{\nu}$.

Analytical or functional relationships

MacDougall (9), in 1933, conducted a series of experiments in the River Hydraulic Laboratory of the Massachusetts Institute of Technology to find the variation in the transportation of bed-load when velocity, discharge, and depth are increased. The results showed that the amount of bed-load transported increased with an increase of any one of the three factors, other conditions remaining unaltered. The form of the equation which was found to fit his data accurately was

$$G = K_1 S_o^{K_2} \; (S_o q - K_3)(S_o q - K_3) \qquad (10)$$

where G is the discharge of bed load in pounds per foot of width per second, S_o is the slope, q is the discharge in cfs per foot of width, and K_1 and K_2 are constants dependent only on the specific gravity and mechanical composition of sediment. When q equals q_o, K_3 equals $S_o q_o$, q_o being the initial discharge at which sand begins moving. The unsolved problem, however, was the determination of the relationship between the constants K_1, K_2, and K_3 and the characteristics of the sediment.

Rouse (11) 1939, analyzing the problem of transportation of suspended load in the light of the turbulence of the flow, pointed out that the average sediment parameters to be considered are, primarily, the magnitude of the geometric mean value of fall-velocity versus frequency curve, and secondarily upon the extent to which the fall-velocity deviates from the mean. He further developed the general functional relationships that existed between all the pertinent parameters for several phases of suspended sediment transportation.

He showed that for the concentration of sediment C at any elevation over the vertical section of the flow the function is of the form

$$C = \phi_1 \left[C_a, \frac{a}{D}, \frac{w_m}{\sqrt{\tau_o/\rho}}, \frac{\sigma_w}{w_m} \right] \qquad (11)$$

where C_a is the concentration of sediment by weight at the elevation a, D is the total depth of flow, w_m is the geometric mean fall-velocity of sediment, τ_o is the boundary shear, ρ is the mass density of water, and

σ_w is the standard geometric deviation of w - frequency.

If Q_1 is the quantity in suspension then by substituting the absolute value of roughness k for a,

$$Q_1 = \phi_2 \left[C_k, \ \frac{k}{D}, \frac{w_m}{\sqrt{\tau_o/\rho}}, \ \frac{\sigma_w}{w_m} \right] \tag{12}$$

where the magnitude of C_k in turn varies with k, w_m, σ_w, bed concentration C_o, and the effective mixing at the bed ε_k, that is,

$$C_k = \phi_3 \left[C_o, \ \frac{\varepsilon_k}{k w_m}, \ \frac{\sigma_w}{w_m} \right] \tag{13}$$

The function relating G, the rate of sediment discharge by weight, is of the form

$$\frac{G}{Q} = \phi_4 \left[C_o, \ \frac{k}{D}, \ \frac{V}{w_m}, \ \frac{\sigma_w}{w_m} \right] \tag{14}$$

Rouse (12) 1940, also indicated that, for scour by jets in which the fluid characteristics such as weight and viscosity have no effect on the flow and in which these variables effect the sediment only in so far as they vary the magnitude of w_m, the functional relationship is of the form

$$\frac{S}{b} = \phi_5 \left[\frac{w_m t}{b}, \ \frac{V}{w_m}, \ \frac{\sigma_w}{w_m} \right] \tag{15}$$

the variable b being some length characteristic of the boundary geometry.

Quantitative studies of localized scour

In 1935, Schoklitsch (14), Germany, published his comprehensive studies of scour and energy dissipation. Part of his work has been translated by Edward F. Wilsey of the United States Bureau of Reclamation. According to Schoklitsch, the depth of scour T of an unprotected river bed due to free overfall over a weir is given by the formula

$$T = \frac{0.30}{d_m^{0.32}} d_1^{\,0.2} q^{0.57} \qquad (16)$$

where T is the maximum depth of water above the scoured region in feet, q is the discharge in cfs per unit width of dam, d_1 is the head in feet measured from the head-water elevation to the tailwater elevation and, d_m is the effective diameter of the bed material in millimeters and is defined in such a way that ten per cent by weight of the sample is coarser.

The depth of scour calculated from the formula is the maximum occurring over the entire width of stream after a prolonged impact of the discharge. This study covers in detail the relationship between the depth of scour, length of apron, size of material, and the elevation of apron.

Rouse (12) reported in 1940 the results of a systematic study of scour with a two dimensional vertical jet impinging on an originally level bed of prepared sand in a small glass-walled flume 6 in. wide. The following is a summary of the conclusions from the study:

a. Two distinct regimes of flow are possible, the jet either being deflected through nearly 180 degrees or following the boundary of the scour as far as the crest of the dune that forms out of the scoured material.

b. In either regime, the depth of scour in uniform material depends upon the size and velocity of the jet, the mean fall-velocity of the material, and the duration of the scouring action.

c. The relative rate of scour produced by a given jet at a given stage depends only upon the ratio of the jet velocity to the mean fall-velocity of sediment. The scour approaches zero as the ratio approaches one.

d. With a relatively uniform material, no equilibrium of scour can be expected at any depth, the removal of material continuing as an exponential function of the time, with only the fixed boundaries governing the ultimate limit of excavation. If the material were to have a wide range of sizes, selective sorting would take place with the result that the magnitude of w_m of the material lining the hole would steadily rise. Under these circumstances, there would be a tendency to approach a state of equilibrium.

e. The equation which would express, with good approximation, the relationship between the magnitude of scour and the other independent variables is of the form

$$\frac{h}{b} = \phi_6 \left[\left[\log \left(\frac{w_m t}{b} \right) \left(\frac{w_m}{V} \right)^3 \right]^{\left(\frac{V}{w_m} - 1 \right)} \right] \qquad (17)$$

where V with the dimensions of velocity has a value of 5.2 for all of the three sands used in the experiments.

Its significance, however, is not entirely clear.

In 1942, Blaisdell (3) carried out model studies in an effort to use the erosion in the stream bed to compare the efficiencies of different types of stilling basins at the end of culvert-outlets. Of the two grades of sand used one did not contain grains coarser than 8 mesh and the other coarser than 12 mesh to the inch. His observations lead to the following conclusions.

a. The variations in scour patterns for the same structure under the same test conditions were not appreciable.

b. The increase in depth and volume of erosion with time was very rapid at first and then the increase slowly approached a maximum asymptotically. For the experiments which were made, 65 per cent of the total erosion occurred in 12 1/2 per cent of the total time and the remaining 35 per cent took 87 1/2 per cent of the total time.

c. The depth of erosion was nearly the same for both of the sands used in the experiments.

Summary

The salient points in the review of studies made by several investigators may be summarized by the following statements.

a. In order to study the individual influences of several factors affecting the mechanics of bed movement, flume studies are still as important and necessary as they were when Gilbert (5) pioneered them.

b. More studies of the type made by Kalinske (6), and Albertson (1), which help in understanding the inner mechanism of physical occurrences are needed for obtaining rational solutions of many problems in sediment engineering.

c. The geometric mean fall-velocity of sediment w_m and its standard deviation σ_w are the necessary and sufficient sediment characteristics to be taken into consideration in sediment problems. This has been amply proved in studies made by Rouse and Krumbein (7, 11, 12).

d. Hitherto very little systematic investigation of scour by jets has been carried out.

e. The study by Rouse (12) with a 2-dimensional jet is one of basic research. It establishes the law of scour in a relatively uniform material under idealized conditions. It is important to note that this is the only study that has attempted to find the variation of scour with respect to time. It also took into consideration, although only indirectly, the effect of change in the size of pool as a result of scour by the jet.

f. A very comprehensive study of scour in relation to engineering structures has been made by Schoklitsch (14). However, the fact that he has considered only the effective diameter of sediment and has not considered time as a variable in his experiment minimizes the scope of its general applicability.

g. Blaisdell's (3) approach of making scour a criterion for the extent of energy dissipation appears to be logical. His studies would have been more informative if he had taken into consideration the parameters w_m and σ_w and related them with the depth of water over the erodible bed and the duration of scour.

Chapter III

ANALYSIS OF THE PROBLEM

The numerous factors that govern the phenomenon of scour by jets have been discussed in the preceding chapter. Before attempting to solve a problem experimentally, however, it first should be analyzed as thoroughly as possible; therefore, an explanation of the complexities that beset a purely theoretical analysis is given as a prelude to dimensional analysis with which the general forms of functional relationships between important dimensionless parameters have been obtained. The analysis has been followed by the delimitation of the problem and a study of the range of the variables necessary to furnish adequate information for solving the problem.

General study of the problem

A general appraisal of the problem set forth at the end of the first chapter presents the following questions:

1. What are the factors affecting the phenomenon of scour by jets?

2. How do these factors govern scour?

3. How does the hollow jet compare with a solid jet with respect to scouring capacity?

Factors affecting scour by jets

The review of the studies made by several investigators in the field of sediment transportation has indicated the many factors that exert an influence to a varying degree on the phenomenon of scour. Some of the factors discussed had a direct bearing on the problem while others were related only indirectly. An analysis of these various factors, with particular reference to the jet scour, is made in the following pages beginning with the group of factors that affect as well as those which define the characteristics of jets.

Characteristics of the jet.--The following factors describe the main features of the jet.

1. Shape of jet -- For close regulation in the release of stored waters upstream from large-size dams, scores of outlets are provided. Because of the greater facility of construction, these outlets are generally square, rectangular, or circular in section. The shapes of the jets issuing from the conduits, irrespective of the methods of control at the upstream end, are fixed accordingly. When the discharge through an outlet is regulated by means of a hollow-jet valve

at the downstream end of the conduit, the jet is tubular. The shape of the jet may also be elliptic or parabolic but the construction of conduits of such shapes is definitely more difficult. The shape of the jet at its exit must have an influence on the extent of deformation it undergoes beyond the efflux section.

2. Area and velocity of jet -- The area and velocity together are a measure of the rate of inflow of both mass and energy. Since it is the excess kinetic energy of the jet that is responsible for the dislocation of sediment particles, the jet discharge must be one of the primary factors affecting scour. Whether or not scour is independent of changes in the area and the velocity of the jet must be determined by investigation. If it is not independent, an additional problem, from the point of view of scour, of the relative merits of a small jet with a high velocity or a large jet with a small velocity for a given discharge needs to be solved.

3. Height and travel of jet -- The height of the exit of the jet above the bed governs the travel of the jet. It may travel partly in air and partly in water depending on the position of the efflux section. Submerged jets pass only through water before reaching the bed of material. The extent of travel and the mediums through which it has to travel determine the degree of disintegration which the jet will undergo.

Some of the early engineers seem to have paid attention to the height of the jet only when they tried to dissipate its destructive energy by providing water-cushions. From observations of several natural water-falls they discovered that the depth of water-cushion generally varied from 1/5 to 1/7 the height of fall. Experimental studies on the Bari Doab canal in India showed that when the depth of water-cushion equalled 1/3 to 1/4 the height of fall the jet had no injurious effect on the floor of the water-cushion (16:187).

4. Inclination of jet -- The angle at which the jet hits the bed may affect the upward and the forward movement of particles of sediment. The turbulence and resulting scour pattern may become more and more unsymmetrical with a decrease in the inclination of the jet from the horizontal.

<u>Characteristics of the stilling pool</u>.-- The factors pertaining to the stilling pool are explained below.

5. Size of pool -- The boundaries of the pool are likely to influence the scour in two ways: first, the formation of subsidiary currents and eddies may be modified; second, the scour pattern may be affected, particularly if the scoured region were to extend to the experimental boundaries. The depth of the stilling pool, therefore, is a very important factor

with respect to the diffusion of a jet.

6. Initial disturbances in pool -- If a jet discharges into a pool where other jets are also emptying or where the flow is already in a disturbed state, as for example, due to a spillway nappe plunging into it, the scour pattern must certainly be affected.

Characteristics of the inflow.--The two main factors that characterize the inflow are:

7. Sediment load of inflow -- The extent of additional entraiment in any flow depends, among other factors, on the amount of sediment that it is already carrying. It is natural to expect that, with an increase of sediment load in the inflow, the extent of scour will decrease and if the sediment load is equal to that which the jet can scour, the scour pattern should become stabilized, as implied by the studies of Rouse (12).

8. Duration of inflow -- The scour should depend not only upon the rate of inflow but also upon the time during which the jet is running unless conditions are such as to stabilize the scour pattern with respect to time. This fact has been demonstrated by the results of Blaisdell (3) and Schoklitsch (14) and is implied in the results obtained by Rouse (12).

Characteristics of the sediment.--Important factors included in this group are the following:

9. Mean fall-velocity and standard deviation

of sediment -- From the point of view of its entrainment in water, the important properties of sediment are particle size, particle shape, and specific gravity. All three have a primary effect upon the rate at which suspended particles settle in water and this combined factor largely controls the movement of suspended sediment. As a result, in any sediment problem the fall-velocity of the individual particle has come to be regarded as a characteristic of considerable practical as well as analytical value. This has been well established by the studies of Krumbein (7) and Rouse (11). Since sediment consists of innumerable particles differing in size, shape, and, to a smaller degree, in specific gravity, the fall-velocity generally varies over a considerable range for a given sediment and it is necessary in any problem to consider both the geometric mean fall-velocity and its standard deviation.

10. Shear resistance of bed material -- It is conceivable that, depending on the nature of sediment, there is more or less resistance offered by the particles to be torn away from the rest of the mass. The angle of repose of the material, the bearing power of the soil or a combination of these and other factors may govern this resistance as indicated by Rouse (12).

Theoretical analysis

The movement of sediment, whether by flowing water or by the action of a jet, is a very complicated problem. It depends upon so many variables that it is generally impossible to solve the problem by using purely rational methods.

If the jet is discharged into air, for example, it entrains air and breaks up before it strikes the surface of the pool. If the distance of its travel in air is considerable "the jet may show very little solid water but instead resemble a dense spray" (15:142). Due to the shear at the boundary of the jet its kinetic energy is fast consumed. The center of the jet which is conical in shape gradually disintegrates due to shear. If the jet travels for sufficient distance in air it will be completely disintegrated and will result in a cloud of spray which then drops vertically downward. After it plunges into the pool with whatever energy it has at the end of its travel in air, it begins to diffuse, both inwards and outwards, until it reaches the bed and finally erodes it. The extent of its penetration into the bed depends upon the energy that it possesses when it reaches the bed. The material thus loosened is carried into suspension by the turbulent eddies of various sizes. The quantity of material which is picked up and the height to which it is thrown depend upon the degree of the turbulence and the grain size. This action is opposed by the settling of the particles due to gravity. If steady conditions prevail, as when the depth of scour approaches a state of equilibrium, there will be a state of balance between the rate at which sediment is raised from the bed by the turbulence and the rate at which it settles or is carried down again onto the bed. If the nominal limit of upward throw of particles is X units then, that height may be taken as limiting the edge of the zone beyond which the activity of the upward currents and eddies cease to have perceptible effect on the diffusion of the incoming jet. Thus, in general, three distinct stages of disintegration of the jet is discernible, one in air, another in water, and the third in a mixture of water and sediment. Under some circumstances, the first or perhaps both the first and second phases of diffusion may be absent. To heighten the complexity every one of the three stages of disintegration is influenced by many of the factors described in the preceeding paragraphs.

Very little information is available on the problem of entrainment of air by a jet and its disintegration. The analysis of the diffusion of a 3-dimensional jet, provided its efflux section is submerged, is possible by use of Eqs. (3) to (8). The turbulence mechanism in the zone of height X is another complicated phenomenon which depends much on what happens to the jet in the first two phases. Future investigations in the field of turbulence mechanism involving transfer of sediment may lead, for instance, to a relationship associating the characteristics of the jet, the stilling pool, and the sediment with the factor D of Eq. (1) which is a measure of the molar mixing in which finite masses of fluid in eddy diffusion play a role similar to that of the molecules in molecular diffusion.

The preceding remarks serve to indicate the complexity of the problem of jet scour. A theoretical approach to such problems, therefore, can be no closer to the prediction of the needed solution than the recognition of the parameters which are involved in the phenomenon and their generalized functional relationship. It is believed that dimensional analysis offers the most direct means of exploring the general forms of functional relationship between the variables.

Dimensional analysis.--For purposes of dimensional analysis, all the variables that govern the phenomenon of scour by jets may be arranged under four groups.

a. Geometric characteristics -- Let the extent of pool be L units long, B units wide, and b units deep. Further, let d be the depth of sediment, H be the height of the exit of the jet above the bed, θ be the angle which the center line of the jet makes with the surface of the pool, and f be the shape factor for the jet.

b. Flow characteristics -- Let A and V be the area and velocity of the jet respectively, t be the duration of inflow, D_1 be a term characterizing the initial disturbance in the pool, D be the coefficient of turbulent diffusion in the pool, and C_s be the concentration of sediment in the jet.

c. Fluid characteristics -- Let ρ be the mass density and μ the viscosity of water.

d. Sediment characteristics -- Let w_m be the geometric mean fall-velocity of sediment, σ_w the standard deviation of the fall-velocity, and ρ_s the mass density. Further, let p be a factor representing the shear capacity of the sediment and h be the depth of scour.

At the outset it is clear that too many variables enter the problem for an experiment to be carried out successfully and that some of them must therefore be eliminated. If it is decided to experiment with a square pool which is also free from initial disturbances, then B equals L and D_1 need not be taken into consideration. Further, if the experiment is so planned that the depth of sediment is never exceeded by the depth of scour, d can be omitted. Because the incoming flow will carry no sediment, C_s may be considered zero. Except for its effect on the value of w_m the flow is not influenced by viscosity and consequently μ can be neglected. The material to be used, will be gravel and will not be compacted initially in any way. Under such circumstances the water has negligible difficulty penetrating the bed between the grains. Therefore it may be assumed that the factor p has no significant effect on the results. Both D and h are dependent variables and since there should be only one such variable the former is omitted. The most general relationship between the remaining variables may be expressed as follows:

$$\phi_7(L, H, \theta, b, f, V, A, t, \rho, \rho_s, w_m, \sigma_w, h) = 0 \quad (18)$$

Since there are 13 physical quantities involved and since three fundamental physical dimensions are required to express them, there will be 10 non-dimensional parameters according to Buckingham's Pi-theorom (10:14). Choosing A, ρ, and w_m as the repeating variables, dimensional analysis yields

$$\phi_8\left[\frac{L}{\sqrt{A}}, \frac{H}{\sqrt{A}}, \theta, \frac{b}{\sqrt{A}}, f, \frac{V}{w_m}, \frac{w_m t}{\sqrt{A}}, \frac{\rho_s}{\rho}, \frac{\sigma_w}{w_m}, \frac{h}{\sqrt{A}}\right] = 0 \quad (19)$$

Further simplification of the problem is necessary, however, before it could be handled practically. If the studies are confined to a jet with its exit at a constant level from the bed of sediment then $\frac{H}{\sqrt{A}}$ is constant so long as the studies relate to a given jet of particular area. Furthermore, $\frac{\rho_s}{\rho}$ may be considered constant for all practical purposes if water and gravel are used throughout the studies within a small range of temperature. Finally, if the sediment to be used has a narrow size range $\frac{\sigma_w}{w_m}$ may be treated as zero. The resulting relationship then becomes

$$\phi_9 \left[\frac{L}{\sqrt{A}}, \theta, f, \frac{h}{\sqrt{A}}, \frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{\sqrt{A}} \right] = 0 \qquad (20)$$

If $\frac{L}{\sqrt{A}}$, θ, and f are held constant for a series of runs then the relation reduces to

$$\phi_{10} \left[\frac{h}{\sqrt{A}}, \frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{\sqrt{A}} \right] = 0 \qquad (21)$$

from which

$$\frac{h}{\sqrt{A}} = \phi_{11} \left[\frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{\sqrt{A}} \right] \qquad (22)$$

If $\frac{h}{\sqrt{A}}$ and $\frac{w_m t}{\sqrt{A}}$ are each divided by $\frac{b}{\sqrt{A}}$ the relationship becomes

$$\frac{h}{b} = \phi_{12} \left[\frac{b}{\sqrt{A}}, \frac{V}{w_m}, \frac{w_m t}{b} \right] \qquad (23)$$

It is now possible to study, for instance, the variation of $\frac{h}{b}$ with respect to $\frac{w_m t}{b}$ for different values of $\frac{V}{w_m}$ while the value of $\frac{b}{\sqrt{A}}$ is held constant.

Delimitation.--Because of the obvious complexity of the problem, this study is limited to an investigation of scour, in a bed of material of relatively uniform size by a jet from a hollow-jet valve as compared with a solid jet. The jet is to be discharged vertically downward from a constant height above the original level of the bed.

Range of variables.--Referring to the Eq. (23) it is seen that the three parameters $\frac{b}{\sqrt{A}}$, $\frac{V}{w_m}$, and $\frac{w_m t}{b}$ form the independent variables and control the variation of $\frac{h}{b}$. It is evident that different values for these parameters may be obtained by changing any one of the quantities constituting the parameter. In order to utilize the existing equipment and complete the study in the limited time available, the dimensionless parameters are varied as shown in Table 1, Appendix B.

Chapter IV

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The analysis of the problem in the foregoing chapter reveals the complexities and indicates the limitations which must be imposed on its scope to make a laboratory investigation practicable. The range of variables is fixed with a view to obtaining adequate information to answer the problem within the limitations. This chapter describes the equipment that was necessary and the procedure that was followed for orderly collection of sufficient data.

Equipment

The laboratory equipment needed for this study consisted mainly of devices for obtaining hollow and solid jets, gravel of suitable size-range, a water-supply system with means of regulating the discharge, and the flume to accommodate the gravel and the flow.

General layout of the equipment.--Fig. 1 shows the assembly of the equipment. A ten-stage, four-inch, deep-well turbine pump, with a maximum capacity of 1/3 cfs against a head of 150 feet, was used to pump clear water through the pipe line P_1, P_2, P_3, and P_4 from the sump located beneath the floor of the laboratory. The discharge through the supply line was regulated by the valve V_1 located just above the floor. The pipe line above the floor level consisted of galvanized iron pipes 2 in. in diameter. The vertical pipe P_1 was connected to the longitudinal member P_2 through a bend. The transverse pipe P_3 was supported by two wooden beams, W_1 and W_2 6 in. by 4 in. in section, with clamps and terminated with a vertical copper pipe P_4 which was 2 in. in diameter and 40 1/4 in. in length. The copper pipe had a steel flange welded onto it at the end to enable the hollow-jet valve and the solid-jet nozzles to be attached by means of studs or bolts and nuts. The fabrication of the water supply line was such that with proper levelling the vertical copper pipe was exactly centered over the head-box of the flume. The exit of all jets was at a fixed height of 28 1/3 in. above the gravel bed.

The head-box was 36 in. by 47 in. by 48 in. and was filled to a depth of 25 in. with gravel which was supported on one side by a plank strengthened by 2-in. by 4-in. wooden rails. The area of gravel bed was 47 in. by 47 in. In continuation of the top surface of the gravel bed and supported on wooden sills nailed to the sides of the box was a horizontal platform extending 24 in. downstream from the end of the gravel bed. There was a gap between this platform and the regular floor of the flume in order to trap the gravel that was expected to be washed out by the action of the jet.

To vary the depth of water over the gravel bed, a tail-water gate was formed out of boards 4 in. wide laid across the flow. Closer adjustments in the depth of water was secured by placing narrow slats vertically on the upstream side of the partition formed by transverse boards. On one side of the box were marked horizontal lines at intervals of 2 in. from the top of gravel bed to gage the depth of water. Since it was necessary to have a known depth of water over the gravel before the jet was allowed to strike the pool, a wooden trough 6 in. wide and 8 in. deep was used to divert the jet downstream beyond the gravel bed onto the extension platform. A scale was prepared on one face of a steel angle and graduated in tenths of an inch on each side of center to measure the horizontal dimensions of the scour hole. A steel scale with a plumb-bob fastened to it was used to measure the depths of the scour pattern.

At the end of the flume was a calibrated sharp-crested weir with a hook-gauge and well attached to one side. Passing over the weir, the water spilled into a return channel below the floor level which carried it back into the sump. The formula for the discharge Q over the weir with depth H_1 was

$$Q = 5.35\, H_1^{\frac{3}{2}}$$

A mercurial thermometer, graduated to 0.5 degree C. was used to measure the temperature of water in the pool.

Hollow-jet valve.--The 2-in. brass model of the hollow-jet valve used in this experiment was borrowed from the Hydraulic Laboratory, Branch of Design and Construction, Bureau of Reclamation, Denver, Colorado. The hollow-jet valve (2) is a regulating control used exclusively at the end of an outlet conduit. It consists of a bell-shaped outer shell or body, a stationary tube toward the downstream end supported on ribs, and a closure element or needle on the upstream side telescoping inside the stationary tube, Fig. 2. In the model the needle is operated by a screw geared to a handle and is closed completely by 14 turns. Water discharges from the valve in a tubular or hollow jet the outer diameter of which remains constant at any opening of the valve.

Since the area of the water-section of the hollow jet changes with the position of the needle, and as this area is not possible to be calculated from the drawing, it was decided to find the area by measuring the velocity with known discharge. To this end a pitot tube was made by welding an hypodermic needle to a 1/8 in. brass tube. This was placed below the jet with the needle pointing upstream and was connected by means of rubber tubing to a mercury manometer. The algebraic difference in the depth of mercury in the two legs of the manometer was noted and the velocity calculated. From the corresponding discharge the area of the jet was found. The area of the hollow jet when the valve was fully open was 2.06 sq. in. and when it was closed by nine turns it was 0.90 sq. in.

Solid-jet nozzles.--To properly compare the scour caused by the hollow jet with that caused by a solid jet, the discharge and velocity must have the same values for each jet. In other words, for proper comparison the area of the water-section of the hollow jet should be the same as that of the solid jet if the discharge is the same in both cases. The two nozzles used in this experiment had diameters 1.62 in. and 1.145 in. respectively to give cross-sectional areas of 2.06 sq. in. and 1.02 sq. in. Both nozzles were turned on the lathe to conform with details shown in Fig. 3. The diameter of the bigger nozzle was such that the area of the resulting jet equalled the water-section area of the hollow jet when the valve was fully open and the diameter of the other was $1/\sqrt{2}$ times the first giving an area slightly larger than the corresponding area of the hollow jet. This was necessary in order to make use of the nozzles conveniently for future research.

Gravel.--Gravel that had been used for another experimental research project was used for this investigation. It came from the Cache La Poudre River at Bellvue, Colorado, and was prepared for use by screening into grades by a system of sieves. Each gravel was composed of grains which passed through a certain mesh and was arrested by a smaller one. Thus the 1/2- to 1/4-in. grade consisted of grains passing through a sieve with two meshes to the inch but being retained by a sieve with four meshes to the inch. Two gravels having 1/2- to 1/4-in. and 1/4- to 1/8-in. size ranges, were used in this experiment and were designated for the sake of brevity as No. 1 and No. 2.

The average shape factors, as defined by the Eq. (9) were found for both the grades by measuring the axes of the grains contained in a representative sample from each. The details are shown in Tables 2 and 3. To find the mean fall-velocity of the two grades, larger samples were used. The sample of gravel No. 1 contained 668 grains and that of No. 2 1353 grains. The average weight of a single grain was calculated by measuring the weight and volume of the samples. The average fall-velocity of gravel No. 1 was then calculated with the aid of the curve corresponding to the shape factor of 0.65 to 0.75 in. Fig. 4 as worked out by Corey. Since Fig. 4 does not have a curve corresponding to the shape factor 0.609 of gravel No. 2, a curve to represent shape factor 0.609 was interpolated between those pertaining to shape factors averaging 0.70 and 0.35 and used for calculating the fall-velocity of gravel No. 2.

Procedure

To begin an experiment, the gravel bed was levelled. The wooden trough was placed below the valve to divert the water downstream and the transverse tail-water boards were set to approximately the height required to give the required depth of water over the gravel bed. Next, the pump was started and the depth of water over the bed was adjusted by introducing vertical tail-water slats when necessary. The hook-gage reading was noted for all experiments.

When the level of water over the bed had remained steady for a few minutes, the trough was withdrawn allowing the jet to strike the pool, taking care to note the time of its striking. After it ran for 15 min, for instance, the pump was stopped and the drain-valve was opened to lower the water level in the box to expose the scoured region fully. As the scour was almost symmetrical and conical in shape about the center of the jet, only one central line of measurements transverse to the box was taken with each experiment. For this purpose, the steel angle scale was placed with its zero to coincide approximately with the center of the scour.

The depths were measured always to the left and to the right of center to complete one experiment.

The next experiment was made with the same depth of water in the pool and the jet running for an additional 15 min thereby making the total time for the second experiment 30 min. A 30-min run for the third time and 1-hr run for the fourth made the duration of the third and fourth experiments 1 hr and 2 hrs respectively. After the completion of a set of experiments with a particular value of b, the gravel bed was levelled before beginning the next set with another value for b.

For convenience in discussion, all the experiments pertaining to one value of b with one type of jet and a constant value of $\frac{V}{w_m}$ have been called a set. Four sets with a particular jet and with a constant value of $\frac{V}{w_m}$ have been termed a series. Thus series No. 1, includes all the experiments made with the hollow jet and gravel No. 1 when $\frac{V}{w_m}$ was equal to 10.40 and the area of jet 2.06 sq. in. One series of experiments consisted normally of 12 to 16 runs, there being three to four experiments for each value of b. The depth b was changed from 2 in. to 16 in. in four stages in every series. With gravel No. 1 and the hollow-jet valve, two series of experiments were made with the valve fully open and one series when the valve was closed by nine turns out of 14 possible turns. With the same gravel, two series of experiments were conducted with 1.62-in. nozzle

After completing the foregoing tests, the gravel No. 1 was replaced by gravel No. 2. Using a similar procedure, three series with the hollow-jet valve, three with the 1.62-in. nozzle and two with the 1.145-in. nozzle were carried out. In all, 13 series totalling 184 experiments were made.

Suggestions for the improvement of technique

The arrangement of diverting the jet by means of a wooden trough in order to bring the level of water up to the required depth before turning the jet into the pool, was not satisfactory at higher velocities of the jet. The disturbance in the pool made close regulation of the depth of water difficult. A better arrangement for this purpose would be to have a by-pass from the water-supply line discharging at a considerable distance downstream from the gravel bed.

It also would be better to have the water-supply system such as to provide a greater range of discharge through the valves in order to experiment with a wider range of values of $\frac{V}{w_m}$ for any particular gravel.

Further, if the equipment is such as to enable the measurement of the depth of scour that exists when the jet is running it would not only decrease the amount of work and time needed for every experiment but also would eliminate the dependence on the cross sections of scour patterns for obtaining the depths of scour.

Chapter V

PRESENTATION OF DATA AND DISCUSSION OF RESULTS

In the first part of this chapter the data collected by conducting 184 experiments as explained in the preceding chapter are presented with the intention of making them throw all possible light on the results. Empirical relationships between the parameters of Eq. (23) for both the hollow jet and solid jet have been developed. Finally, the results of the investigation have been set forth and discussed in the latter part of the chapter.

Presentation of data

The Eqs. (22) and (23), obtained by dimensional analysis and a systematic simplification of the problem, evidently afford the best means for graphical representation of the data. These equations include the quantity h, which is a characteristic depth of scour and has to be obtained from the cross sections of the scour patterns. Typical cross sections have been included in Appendix E. Appendix C consists of the experimental data of center line depths of scour pattern. A uniform scale of one-fourth actual size has been adopted for all the sections.

An examination of the cross sections makes it apparent that the characteristic depth of scour may be distinguished by at least two methods. It may either refer to the amount of material that is permanently removed from the region of scour below the original bed level, as evidenced by the volume of the scour hole after the jet is turned off, or it may refer to the total material that is excavated during the period that the jet runs, including both the material that is transferred beyond the scoured region and that which happens to be in suspension. A characteristic depth of the latter type is more significant for the design engineer and is therefore adopted here. Such a depth, however, is not directly measurable from the cross sections. Therefore, to determine the depth of scour it was decided to estimate the elevation of the point of intersection of the side slopes of the cross-section relative to the undisturbed bed level. Furthermore, it was thought that the side slopes of the cross-sections should remain the same so long as they all pertained to one material. No two plotted slopes, however, were found to be the same even though all those pertaining to one type of gravel showed a particular trend of orientation. The reason for this was soon evident in that when the jet is running the distribution of the material held in suspension is by no means uniform around the periphery of the jet.

Therefore, when the flow stops and the material falls directly to the bottom, the side slopes become irregular. During the operation of the jet, however, the sides may be expected to assume a more or less regular slope characteristic of the material only. With a greater depth of water b the zone of suspension and general size of the flow pattern is much greater and consequently the settlement of material covers a wider area and is distributed more uniformily. This uniform distribution is also conspicious with the higher velocities. For shallower depths and lower velocities, on the other hand, most of the material deposits itself at the center. It may therefore be assumed that irregularity of any cross section is an indication of the haphazard deposition of the material in suspension. Conversely, if the side slopes of any cross section are quite straight, the implication is that there was either uniform deposition or no deposition at all over the surface of the scour hole.

In view of the foregoing analysis of the scour mechanism the sloping lines were drawn with the greatest emphasis being placed on those plotted points which most nearly gave a straight line. Another factor that was kept in mind while fixing the depth of scour was that the provision made for the material in suspension should be the same as nearly as possible for all the cross sections of any one set of experiments. By using this technique, it was found that the average slope of the line, which is as close as possible to the side slopes of the majority of the cross sections, was $28^{\circ}- 30'$ for gravel No. 1 and 27° for gravel No. 2. The final location of the side slopes drawn to obtain the depth of scour h, is shown in the cross sections and the values of h have been given in Tables 4 to 16. It should be noted that a number of trials were necessary before a consistent value of h was obtained.

Preliminary graphical representation of the data in accordance with Eqs. (22) and (23) showed that Eq. (23) gave plots which were more clearly indicative of some of the results. Figs. 5, 6, 7, and 8 show the value of $\frac{h}{b}$ plotted against $\frac{w_m t}{b}$ for different values of $\frac{V}{w_m}$ while the value of $\frac{b}{\sqrt{A}}$ is held constant. In Fig. 5, for instance, the family of curves shown at the bottom is for values of $\frac{h}{b}$ against $\frac{w_m t}{b}$ when $\frac{V}{w_m}$ varies from 10.40 to 26.01 with $\frac{b}{\sqrt{A}}$ remaining constant at 1.39. The number of lines in any group equals the number of series of experiments conducted with the particular jet and area. Each figure has four groups or families of curves corresponding to four values of b, 2 in., 4 in., 6 in., and 16 in.

The equation for any one of the lines in Figs. 5 to 8 is of the form

$$\frac{h}{b} = m \log \frac{w_m t}{b} + c_1 \qquad (24)$$

The values of m and c_1 for all the four families of lines in Figs. 5 and 6 are shown in Tables 17 and 18 respectively. When values of m are plotted against $\frac{V}{w_m} - 1$ on rectangular cross-section paper, Fig. 9, it is found that all of the four lines pass through the origin and the equation of any one of the lines has the form

$$m = m_1 \left[\frac{V}{w_m} - 1 \right]$$

Values of m_1 corresponding to the four values of $\frac{b}{\sqrt{A}}$ have been calculated for the 2.06-sq. in. hollow jet and are given in Table 17. The plot of m_1 as the ordinate with $\frac{b}{\sqrt{A}}$ as abscissa produced a straight line, Fig. 11, with the equation

$$\log m_1 = - \log \frac{b}{\sqrt{A}} + 0.023$$

the slope of the line being -1.

Therefore

$$m_1 = 0.023 \sqrt{\frac{A}{b}}$$

whence

$$m = 0.023 \frac{\sqrt{A}}{b} \left[\frac{V}{w_m} - 1 \right]$$

The values of c_1 of Eq. (24), when plotted with $\frac{b}{\sqrt{A}}$ as the abscissa, resulted in the irregular curves shown in Fig. 9. It is seen that the lines are closer with larger values of $\frac{b}{\sqrt{A}}$. With a view to simplifying the analytical expression, the curves were approximated by the straight line shown in Fig. 9 and its equation is

$$c_1 = - 0.032 \frac{b}{\sqrt{A}} + 0.5$$

Substitution of the values of m and c_1 in Eq. (24), then, gives the relation between $\frac{h}{b}$ and $\frac{V}{w_m}$, $\frac{b}{\sqrt{A}}$, and $\frac{w_m t}{b}$ in the following form

$$\frac{h}{b} = \frac{0.023\sqrt{A}}{b} \log \left[\frac{w_m t}{b}\right]^{\left(\frac{V}{w_m} - 1\right)} - 0.032 \frac{b}{\sqrt{A}} + 0.5 \qquad (25)$$

A similar equation for the solid jet is

$$\frac{h}{b} = \frac{0.023\sqrt{A}}{b} \log \left[\frac{w_m t}{b}\right]^{\left(\frac{V}{w_m} - 1\right)} - 0.022 \frac{b}{\sqrt{A}} + 0.4 \qquad (26)$$

It may be noted that the value of m is the same for the two equations.

Figs. 14 and 15 are additional plots of $\frac{h}{\sqrt{A}}$ against $\frac{b}{\sqrt{A}}$ for different values of $\frac{w_m t}{\sqrt{A}}$ with constant value of $\frac{V}{w_m}$.

Discussion of results

Factors and their effect on scour.--While analyzing the problem by the theory of dimensional homogeneity it was shown that there are at least 18 relatively important independent factors to influence the phenomenon of scour. Of these, only six, f, b, A, V, w_m, and t, were chosen for this study and the results indicate that for a relatively uniform material the depth of scour depends upon b, A, V, w_m, and t. A comparison of depths of scour obtained by using the hollow jet with those obtained by using the solid jet under similar conditions reveals that scour is influenced also by the shape of the jet.

From Series 1 and 2 or from 7 and 8 the discharge has been increased by about 50 per cent while the area remains constant. The resulting increase in the depth of scour is very marked. Likewise, from Series 2 and 5 or from 8 and 13 the discharge is held almost constant although the area is decreased by nearly half. The increase in scour is again conspicuous.

It may therefore be stated that, other factors remaining constant, the scour increases with velocity whether this velocity increase is brought about either by decreasing the area and keeping the discharge constant, or by increasing the discharge while the area remains constant.

An examination of the graphical representation of the results shows the following trends which are common to all the families of lines in Figs. 5 to 8:

a. With given values of $\frac{b}{\sqrt{A}}$ and $\frac{V}{w_m}$, the increment of scour remains constant with time increasing in geometric progression. In other words, a state of equilibrium in the process of scour cannot be expected either at any depth or after any period of time. Therefore, the ultimate limit of the magnitude of scour is the fixed boundaries.

b. The magnitude and rate of scour decrease with $\frac{V}{w_m}$ decreasing at any given value of $\frac{b}{\sqrt{A}}$. As shown in Figs. 9 and 10, the slope of the lines is proportional to $\frac{V}{w_m} - 1$ indicating zero scour when the velocity of the jet equals the mean fall-velocity of the material. This result leads to the inference that if the material were to consist of several sizes of particles the heavier ones would gradually line the scoured hole thereby decreasing the value of $\frac{V}{w_m}$ and increasing the tendency for the hole to become stabilized.

It may be noted that the above two findings indicate the behavior of a 3-dimensional jet may be identical in these respects with that of the 2-dimensional one which was investigated by Rouse (12).

c. A comparison of the values of h in any Series and the families of curves in Figs. 14 and 15 reveal that, with $\frac{V}{w_m}$ remaining constant, the magnitude of scour increases with increase in the depth of water. This phenomenon of greater scour in a deeper pool runs counter to commonly held opinion and needs further discussion.

The increase in the magnitude of scour, which is comparable to the progress of the work of excavation equipment depends upon the amount of material that is picked up and the extent of dispersion laterally from the zone of jet erosion. The greater the lateral dispersion the lesser will be the percentage of displaced material that falls back to the place of excavation. Therefore, if an increase in the value of a certain factor were to accelerate the process of scour its contribution would be in one or both of the following ways.

1. It may be responsible for an increase in the amount of material that is thrown into suspension.

2. It may increase the lateral dispersion of the material.

Whether an increase in the depth of water in the pool is conducive to increasing scour may now be examined in the light of the foregoing remarks.

With the energy of inflow assumed constant, the extent of the turbulence may be expected to increase when the depth of water in the pool increases because with a greater depth there is greater scope for the full development of the flow pattern. The photos in Figs. 16-19 included in Appendix D appear to support this assumption. With an increase in the size of the zone of turbulence the area from which the grains are picked increases; this should therefore result in an increase in the total quantity of material that goes into suspension.

Further with shallower depth the local "boils" are concentrated round the immediate periphery of the jet. Observations during the experiments showed that when the jet is discharging into a shallow pool the height of the "boils" above the surface of the pool often exceeds the depth of the pool and consist of a mixture of gravel and water most of which falls or is carried back again and again into the place of its removal. In other words, the vertical component of the velocity seems to be more predominant which, while increasing the lift, will not help the lateral dispersion of the material. With an increase in the depth of the pool, the "boils" cover a wider area giving rise to a pronounced ring-vortex form of flow pattern. Even though the total energy may almost remain the same, the formation of the ring vortex may be expected to increase the horizontal component of the velocity. As a result, the material is thrown farther and farther from the center of the jet.

This development of flow pattern, however, will result in a maximum scouring capacity at a certain depth depending upon the characteristics of the jet, pool, flow, and sediment. It is therefore clear that, with a given exit velocity of the jet and with all the other factors remaining constant, the rate of removal of the material and the rate of its dispersion continue to increase as the depth of the pool increases. The rates attain a maximum when the depth of water over the erodible bed reaches a certain critical value b_c. At this stage the flow pattern accompanied by the ring-vortex form of motion has reached its maximum scouring capacity.

When the depth exceeds the value b_c, the scouring capacity decreases due to a greater diffusion of the jet in the deeper pool, even though the exit velocity may remain a constant, with the result that the magnitude of scour also decreases.

d. Study of the values of h in any series brings out the general trend that, while an increase in the magnitude of h occurs with increase in b, the incremental increase in h with respect to the time in geometric progression is the same with all the depths with only a few exceptions. The last set of experiments in Series 5, 8, and 13 are among the exceptions. It will be interesting to see whether future studies made with equipment having facilities to measure the depth of scour while the jet is running will substantiate or modify this statement.

Emperical expressions for scour.--Attempts to establish a relationship between the dimensionless parameters of equation (23) with the necessary numerical constants obtained from the experimental data resulted in Eqs. (25) and (26). Although the equations have been developed from results obtained under idealized conditions, they do establish the fundamental principles governing the phenomenon of scour.

To indicate the extent of agreement between the computed values of $\frac{h}{b}$ and those from experimental data, Figs. 12 and 13 have been prepared. The dots in Fig. 12, for instance, represent the values of $\frac{h}{b}$ in Series 1, plotted against the corresponding values of $\frac{h}{b}$ as computed from Eq. (25), represented by the 45° line shown in the same Fig. 12.

Comparison of the hollow and solid jets in respect to scouring capacity.--The values of h in

Series 1 to 4 obtained with the hollow jet correspond to those of Series 7 to 10 with the solid. Similarly, Series 5 and 6 are comparable to Series 12 and 13. By comparing the values of h in Series 1 to 4 with those of Series 7 to 10, it seems that the scouring capacity of the hollow jet is greater than that of the solid jet for values of $\frac{V}{w_m}$ upto about 20. For values of $\frac{V}{w_m}$ greater than 20, however, the scour capacity of the hollow jet is exceeded by that of the solid jet. Furthermore, in the Series 1 to 4 the critical value $\frac{b_c}{\sqrt{A}}$ lies between 5.58 and 11.16 whereas such a value exceeds 11.16 in the case of the solid jet. The results of Series 5 and 6 when compared with those of 12 and 13 do not portray the same trends as were evident in the previous comparison. For instance, with $\frac{b}{\sqrt{A}}$ remaining constant at 2.11 and $\frac{w_m t}{b}$ changing from 5.16×10^3 to 3.88×10^3 h increases from 4.20 to 5.80 when $\frac{V}{w_m}$ changes from 41.40 to 57.60 for the hollow jet, whereas with the solid jet the change in h is from 3.90 to 5.25 while $\frac{V}{w_m}$ increases from 28.10 to 50.70. These figures point to the possibility that the scour by the solid jet when $\frac{V}{w_m}$ is 57.70 may be less than that caused by the hollow jet, namely 5.80, thus reversing the trend noticed when the area of the jet was larger.

Further, in Series 6, it is seen that the magnitude of scour is increasing when $\frac{b}{\sqrt{A}}$ has reached 16.88, whereas with the solid jet the maximum scour lies between 7.92 and 15.84.

Two factors seem to contribute to the discontinuity in the trend of results when the areas of the two types of jets are changed. Firstly, the external diameter of the hollow jet remains constant irrespective of the change in the area of the water section whereas with the solid jet it changes with the area. Since the volume of the zone of turbulence mechanism is likely to change with the diameter of the jet, the effect of a decrease in area may have quite dissimilar effects on the resulting intensity of turbulence with the two types of jets. Secondly, the phenomenon of diffusion of a solid jet (1:1589, Fig. 15) is such that the average velocity decreases due to diffusion more rapidly as the diameter of the jet diminishes.

The preceding discussion about the relative scouring capacity of the two types of jets under similar conditions leads to the following generalized statements.

a. There does not seem to be any uniformity in the trend of results with respect to the scour caused by the two types of jets when the area of the jets is varied. The scour caused by one may be less than the other only in some specified range of given conditions but not under all possible variations.

b. The scouring capacity, by itself, divorced from other hydraulic, structural, and economic factors, is not important enough to make one of the two types of jets superior to the other; it may become significant, however, when the operating conditions are so restricted as to require the jet to operate with a constant area.

Suggestions for further studies.--This study is just one aspect of a multiphased problem. Of the 18 relatively important factors attention was directed to the investigation of the effect of only six of them. An extension of the present study without the inclusion of additional variables might be carried out as indicated below.

a. Experiments may be conducted to obtain further information to clearly define the two regimes of the phenomenon of scour on either side of the critical depth and to relate this depth with $\frac{V}{w_m}$.

b. Studies may be extended to include additional values of A with a view to relating the scouring capacity with the variation of A. This will increase the scope of the applicability of the results for design purposes where the suitability of outlets of different diameters have to be considered before final selection.

In order to augment the usefulness of the results in the solution of practical problems, it is suggested that the studies may be further extended to include additional variables as indicated below.

a. Studies might be made to evaluate the effect of the inclination of the jet, θ, on scour.

b. Experiments might be conducted with sediments having appreciable size range of particles. The standard deviation σ_w would then be an important variable.

c. It may be interesting to study the effect of the dimensions of the pool and to find the size at which the scour ceases to be affected by it. With such a study the length L and breadth B of pool require consideration.

A complete comprehension of the problem is, of course, possible only when the effects of all the factors that influence scour are evaluated. It may be remarked that if it is possible to take into account the average velocity at the bed instead of the exit velocity of the jet or the energy of turbulance for correlation with scour then there is a likelihood of the number of independent variables being reduced.

Chapter VI

SUMMARY

The importance of Sediment Engineering in relation to the design and maintenance of irrigation structures is being increasingly felt by hydraulic and irrigation engineers alike. During the last 25 years great strides have been taken toward the solution of many of the problems of this complicated science. There are many more problems, however, which are still awaiting solution. One of the problems which has hitherto received very little attention is that of scour by jets. In cross section, a jet may be square, rectangular, circular, or even tubular. When the flow through the outlet conduit of a dam, for instance, is regulated by a needle valve at the downstream end the result is a solid circular jet. Outlets of some of the dams built recently have hollow-jet valves to regulate the discharge. The jet from such a valve is hollow or tubular in cross section. This study was concerned with scour caused by hollow and solid jets.

The phenomenon of scour by jets is influenced by all the factors that characterize the jet -- the pool into which it discharges, the flow, and the sediment which constitutes the erodible bed of the pool. A close examination of all the factors showed there are at least 18 independent quantities to affect the magnitude of scour. To make the problem susceptible to laboratory investigation, it was decided, after a detailed dimensional analysis, to restrict the investigation to the study of scour in a bed of relatively uniform material by a jet from a hollow-jet valve discharging vertically downward from a constant height above the sediment and comparing the results with those obtained from a solid jet under similar conditions. Using dimensional analysis the following general functional relationships were obtained for a jet of given inclination, shape, and area.

$$\frac{h}{b} = \phi_1 \left[\frac{b}{\sqrt{A}}, \ \frac{w_m t}{b}, \ \frac{V}{w_m} \right]$$

and

$$\frac{h}{\sqrt{A}} = \phi_2 \left[\frac{b}{\sqrt{A}}, \ \frac{w_m t}{\sqrt{A}}, \ \frac{V}{w_m} \right]$$

where h is the depth of scour,

b is the depth of water over the bed,

A is the area of the jet, and

t is the duration of the scouring action.

A 2-in. brass model of the hollow-jet valve installed in many of the dams recently built by the Bureau of Reclamation was used to obtain the hollow jet. For a solid jet, two nozzles with exit diameters of

1.62 in. and 1.145 in. were turned on the lathe from solid steel. The arrangement of the water supply line was such as to make the jet central to a bed of gravel which was 47 in. by 47 in. and 25 in. deep in the head-box of a flume. At the end of the flume was a calibrated weir to measure the discharge.

A total of 87 experiments were conducted with the hollow jet and 97 with the solid jet. The scour pattern was conical in shape and almost symmetrical about the center of the bed.

The data have been represented graphically in accordance with the equations mentioned earlier. The following are the important findings:

a. If the material is relatively uniform the depth of scour depends upon the area and the velocity of the jet, the mean fall-velocity of the material, the depth of water over the material, and the duration of the scouring action.

b. The rate of increment in scour with respect to time increasing in geometric progression is constant. In other words a state of equilibrium in the process of scour cannot be expected either at any depth or after any period of time.

c. The magnitude of scour decreases with a decrease in the ratio of jet velocity to fall-velocity --approaching zero as this ratio approaches unity.

d. The most interesting result which appears to be strange and contrary to the commonly held opinion is that scour increases with increase in the depth of water over the erodible bed until the depth reaches a critical value. Any further increase in depth will diminish the resulting scour.

e. For a given area of jet, the comparison of the scour resulting from the two types of jets appears to indicate one trend. With a change in area the results of comparison show quite a different trend. This inconsistency may be due to the fact that a variation in the area alters the diffusion of the jets and the turbulence mechanism in the pool. Further, it introduces two additional variables $\frac{L}{\sqrt{A}}$ and $\frac{H}{\sqrt{A}}$ into the study.

f. Except when the operating conditions are so restricted as to require the jet to operate with a constant area, the scouring capacity by itself divorced from other hydraulic, structural, and economic factors, is not important enough to make either one of the two types superior to the other.

A P P E N D I X

APPENDIX TABLE OF CONTENTS

Appendix A.--Figures 1-15

LIST OF FIGURES

LIST OF FIGURES--Continued

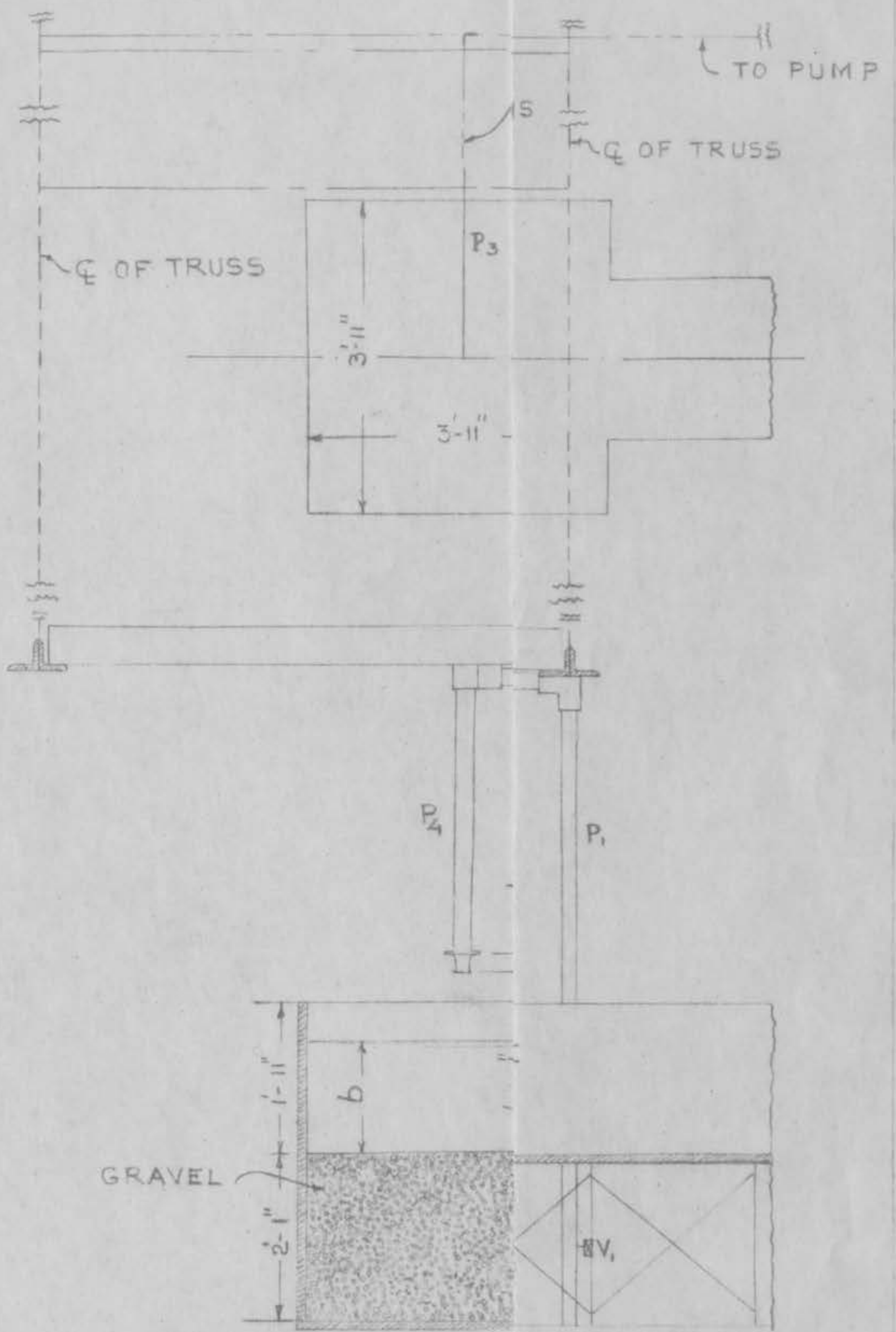

FIG. I LAY-OUT

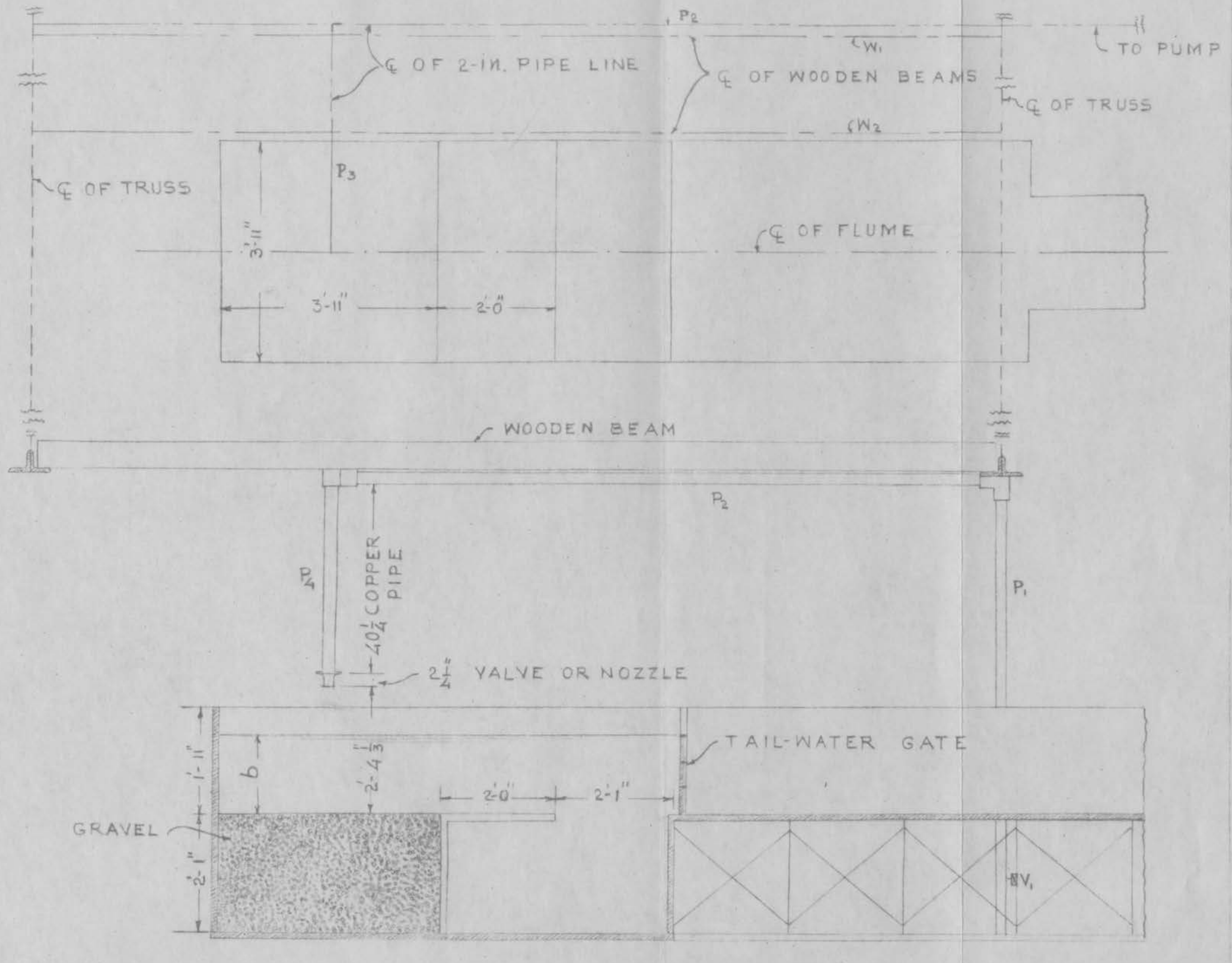

FIG. I LAY-OUT SKETCH OF EXPERIMENTAL EQUIPMENT

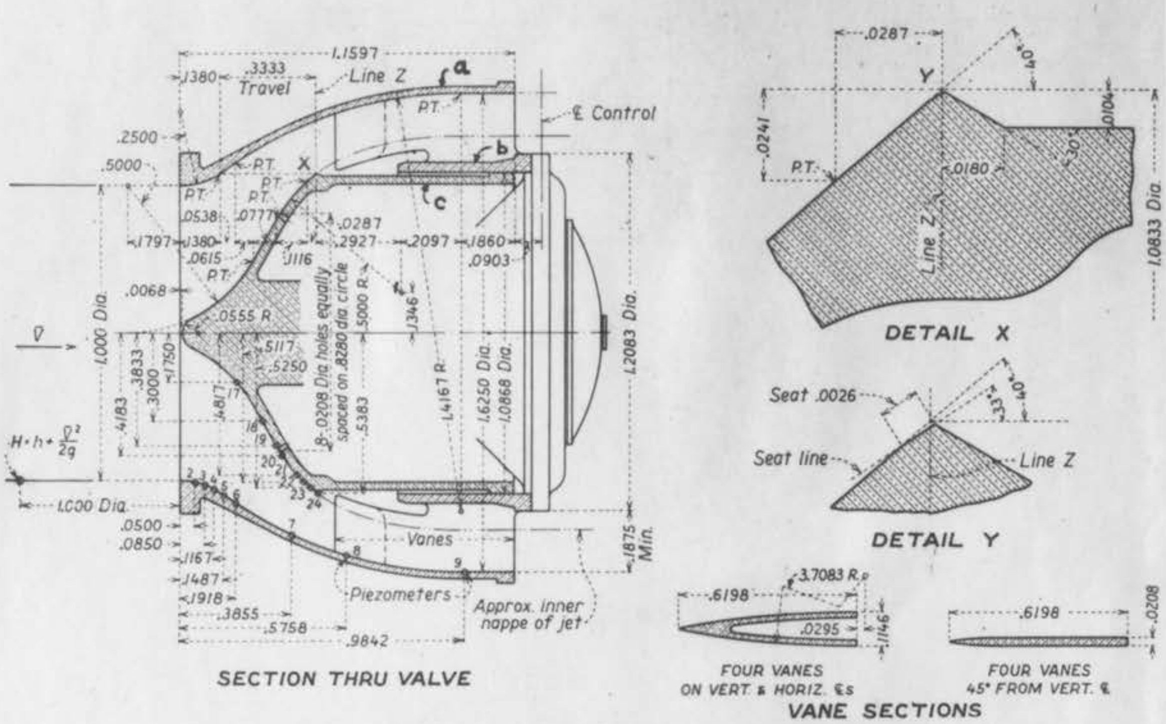

FIG. 2 HOLLOW-JET VALVE

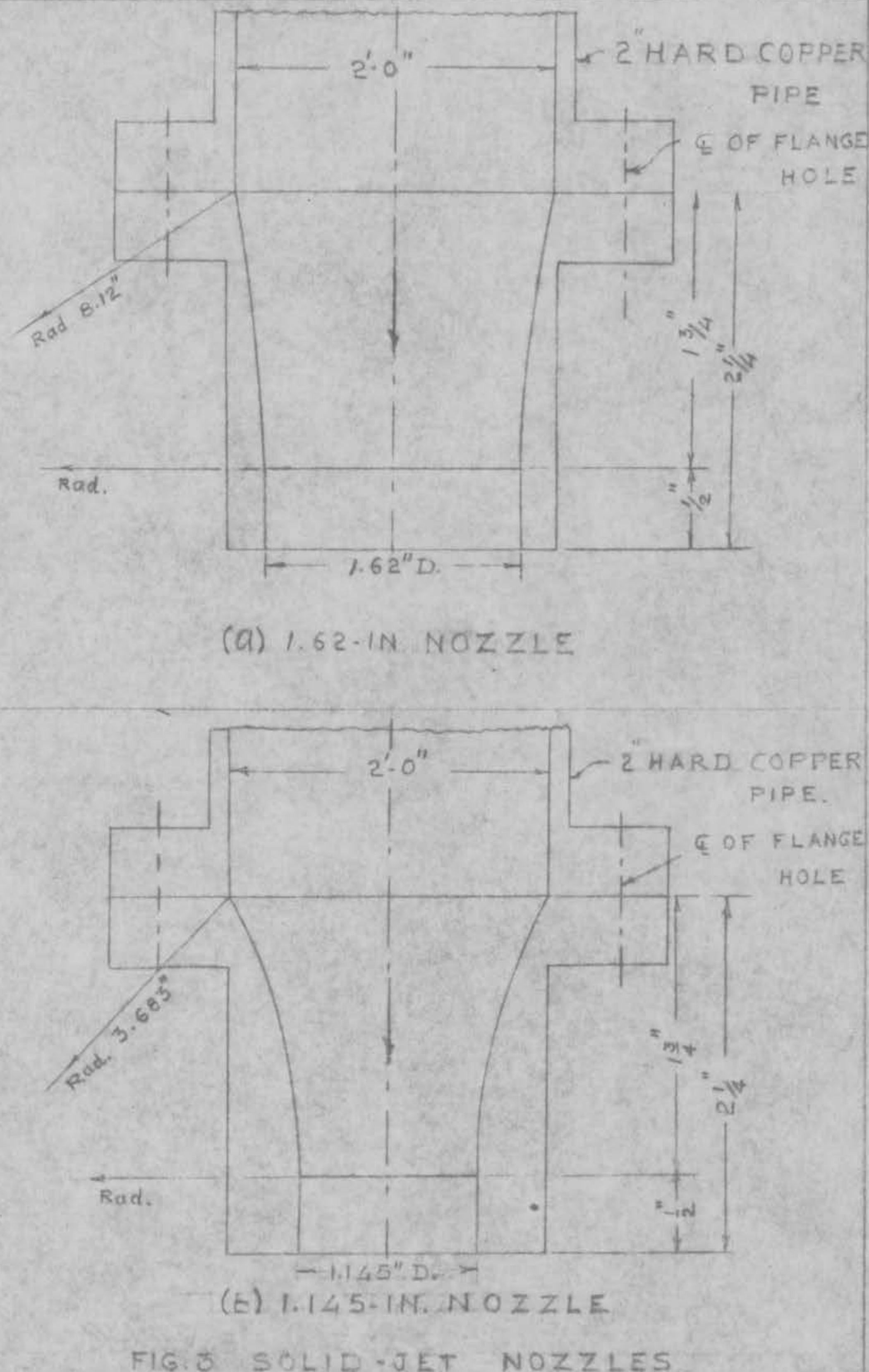

FIG. 3 SOLID-JET NOZZLES

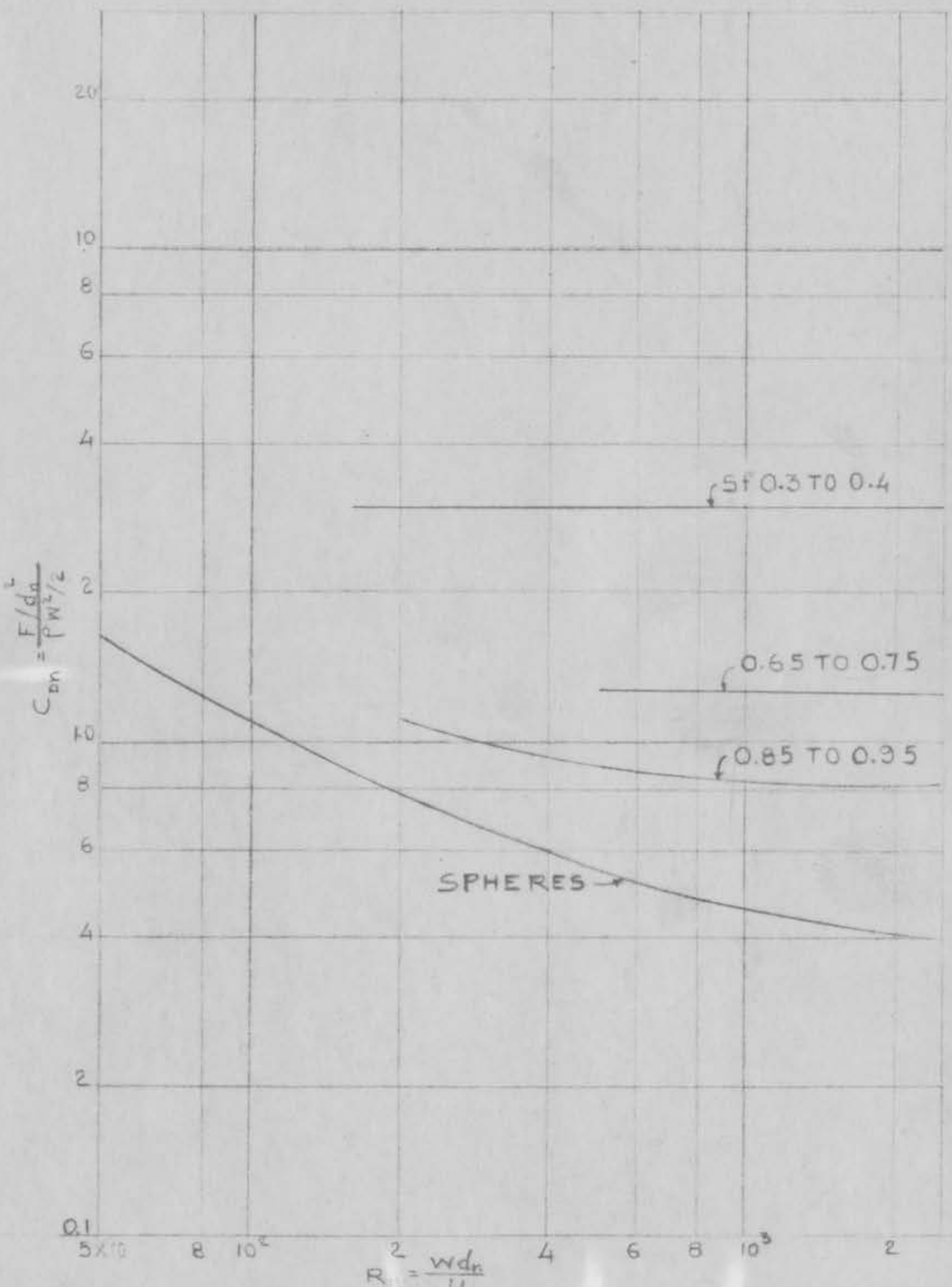

FIG. 4 VARIATION OF C_{D}, WITH R, [AFTER COREY(4)]

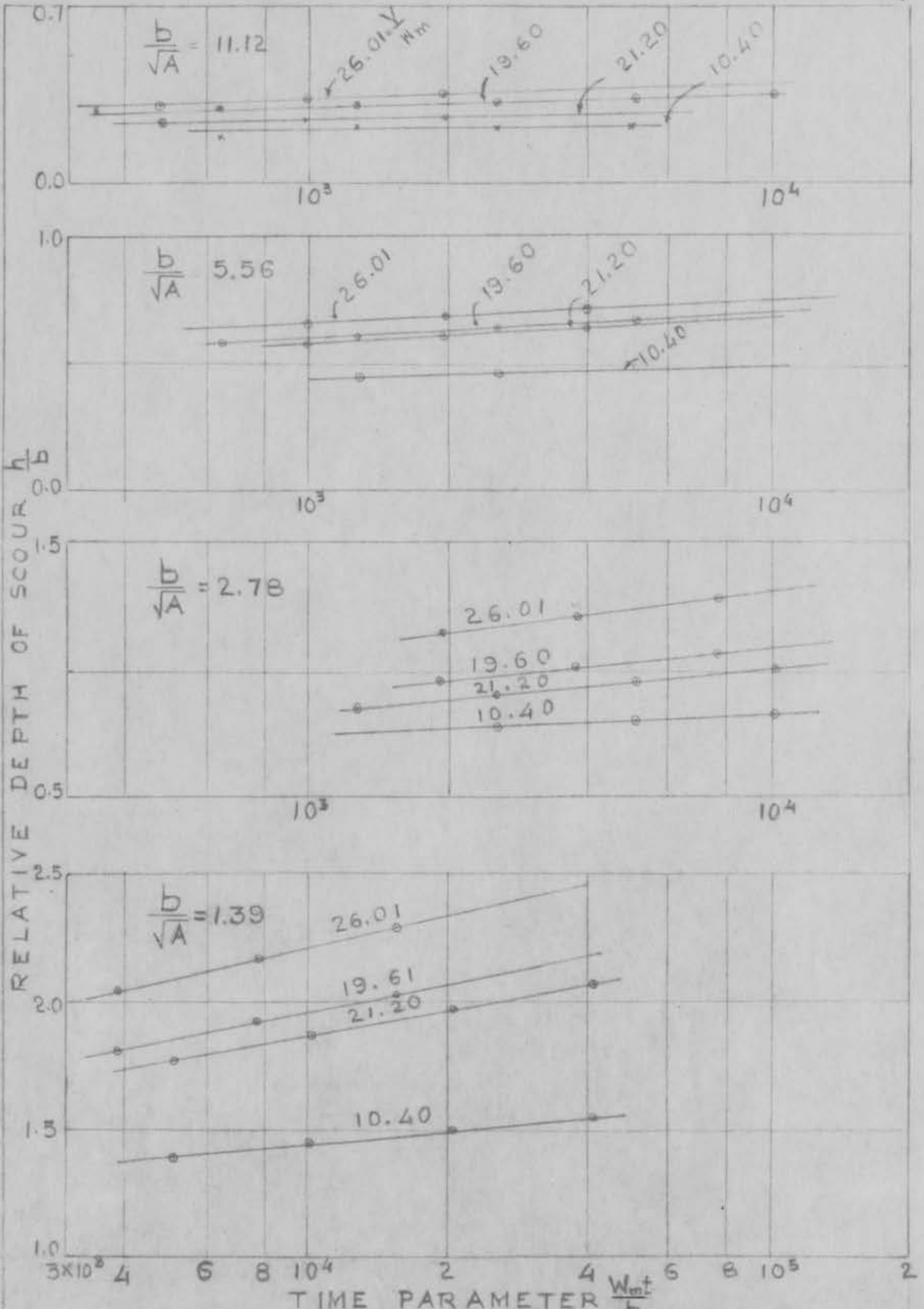

FIG. 5 VARIATION OF $\frac{h}{b}$ WITH $\frac{W_m t}{b}$ FOR 2.06-SQ.IN HOLLOW JET

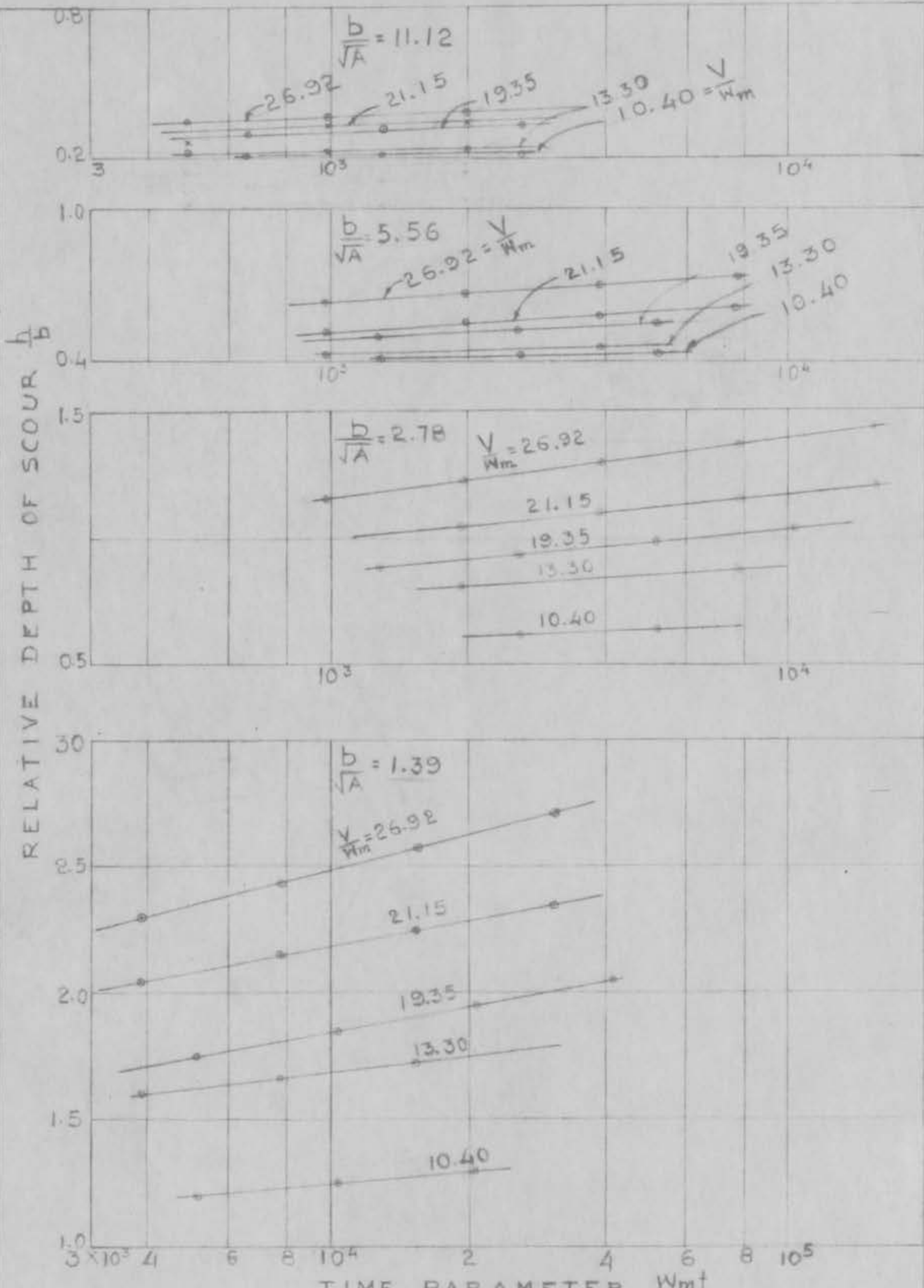

FIG. 6 VARIATION OF $\frac{h}{b}$ WITH $\frac{W_m t}{b}$
FOR 2.06-SQ.IN. SOLID JET

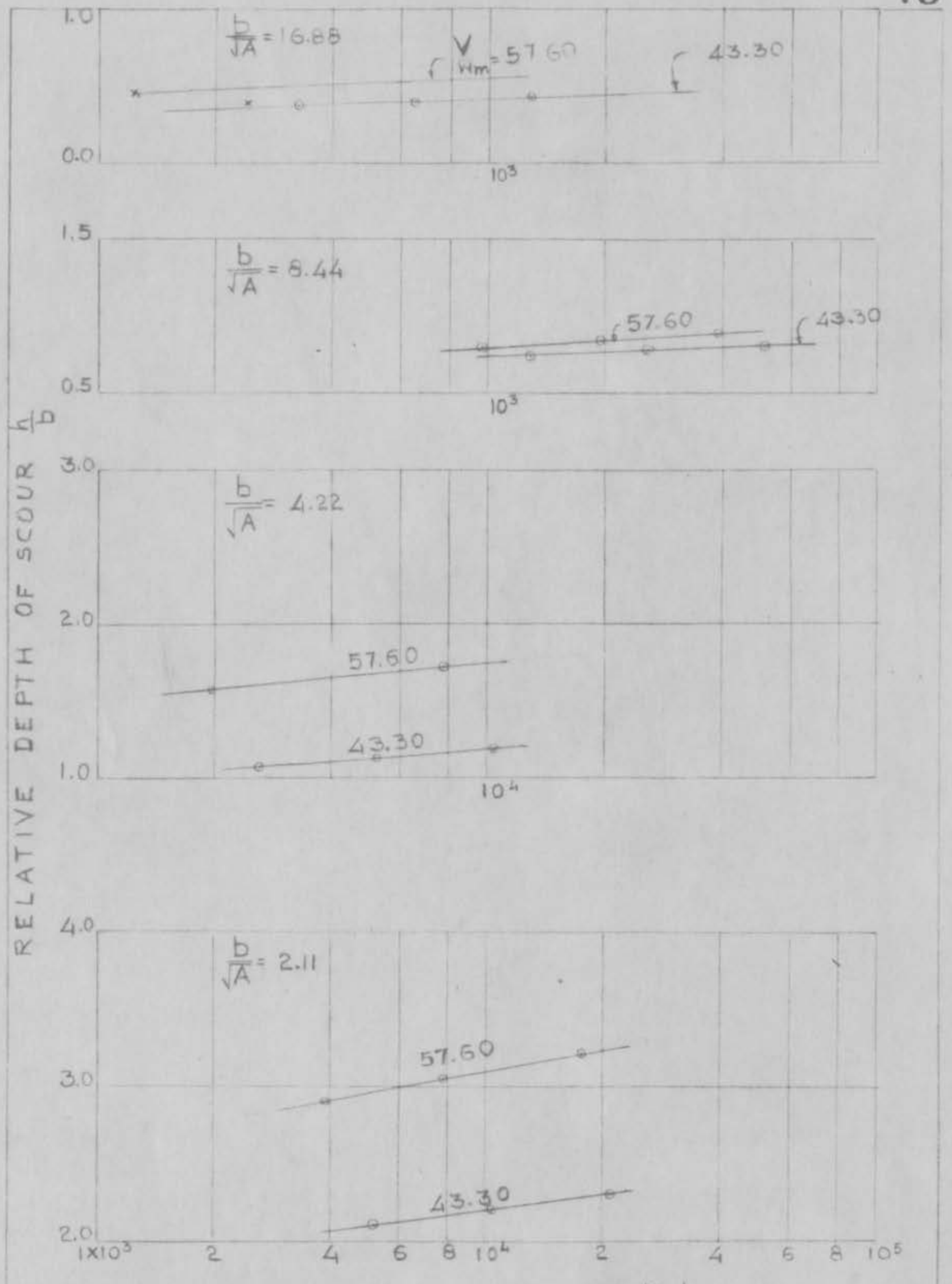

FIG 7 VARIATION OF $\frac{h}{b}$ WITH $\frac{W_m t}{b}$ FOR 0.90-SQ.IN. HOLLOW JET

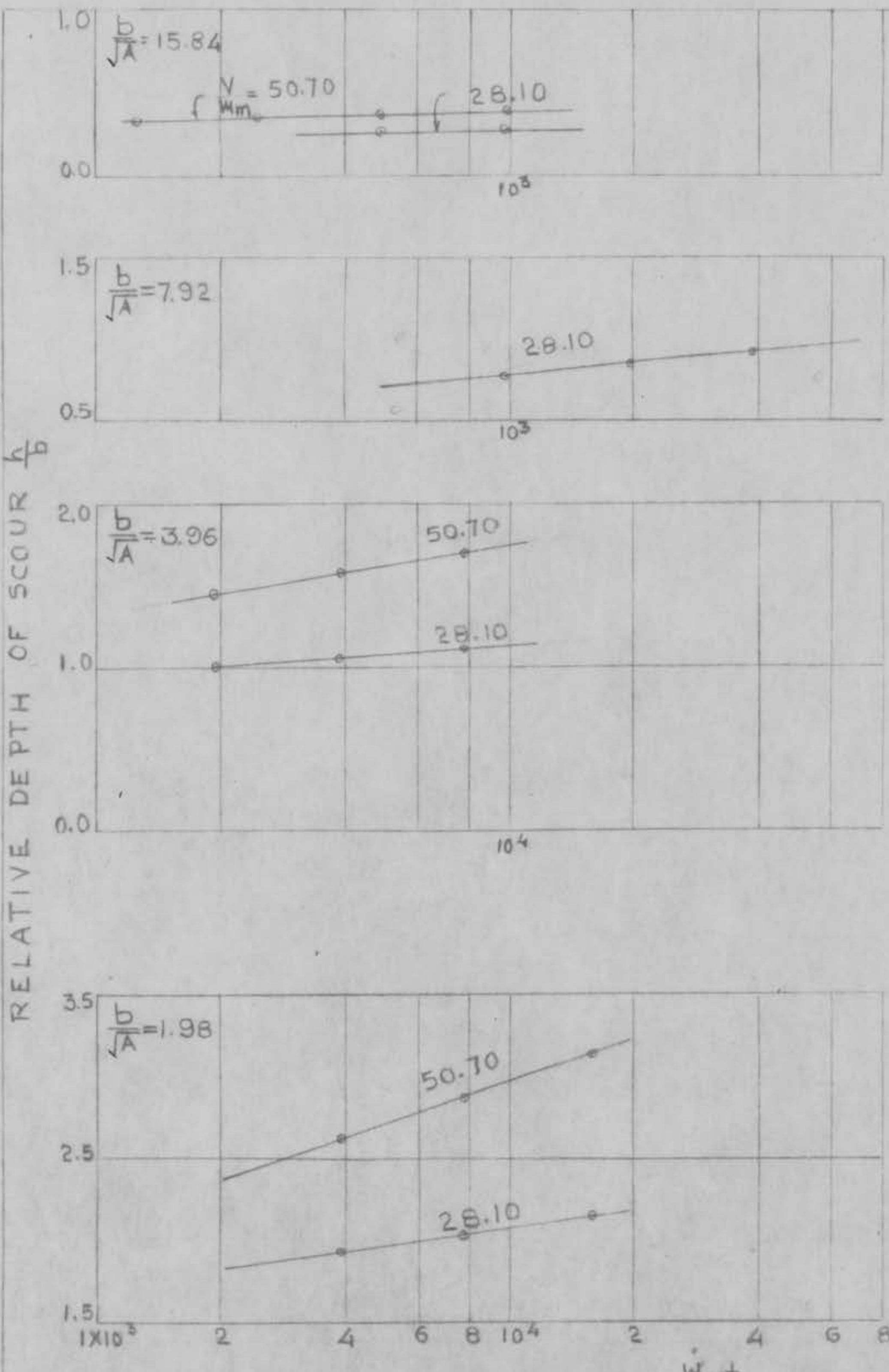

FIG. 8 VARIATION OF $\frac{h}{b}$ WITH $\frac{W_m t}{b}$ FOR 1.02-SQ.IN. SOLID JET

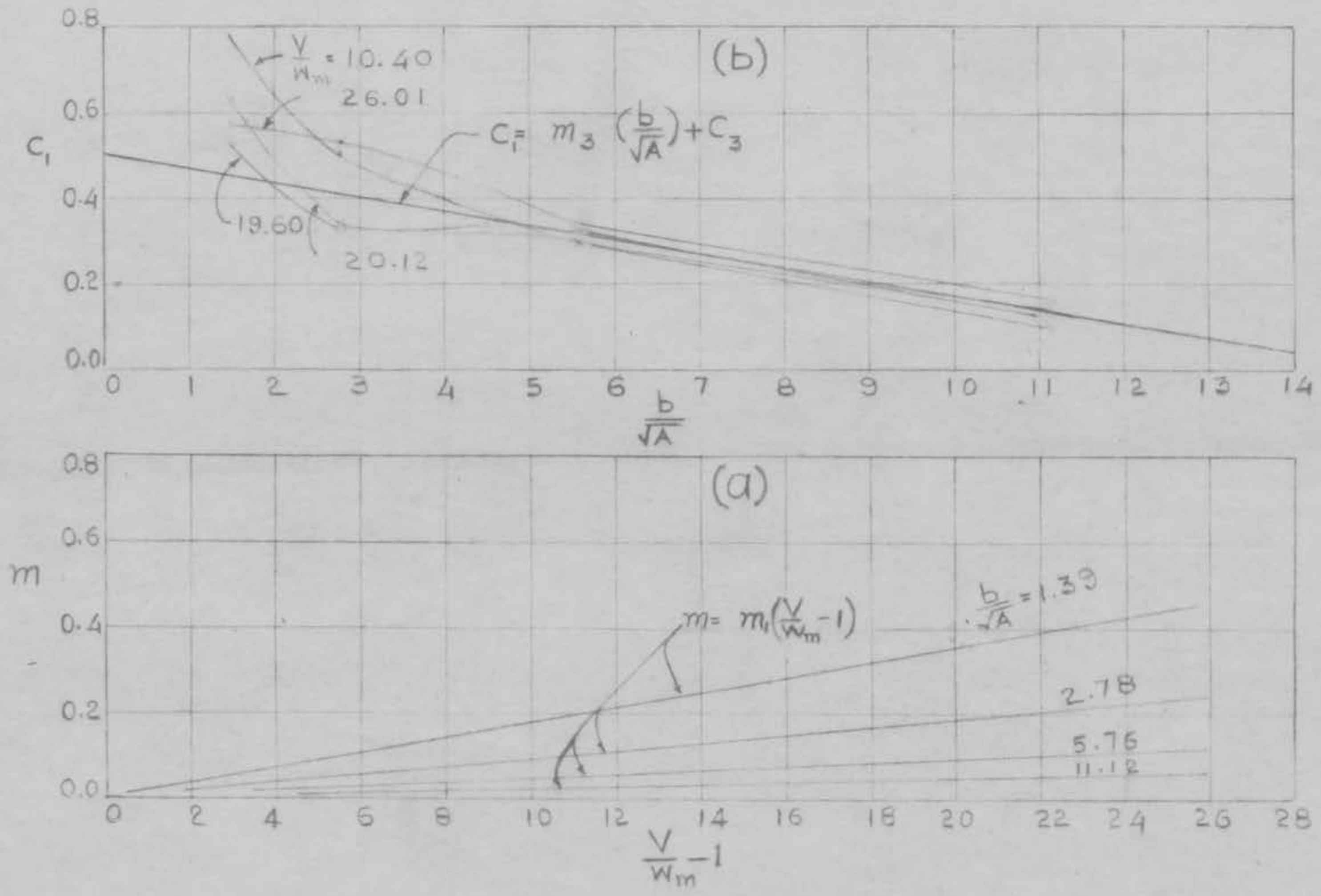

FIG. 9 (a) VARIATION OF m WITH $\frac{V}{W_m} - 1$ FOR HOLLOW JET
(b) VARIATION OF C_1 WITH $\frac{b}{\sqrt{A}}$ FOR HOLLOW JET

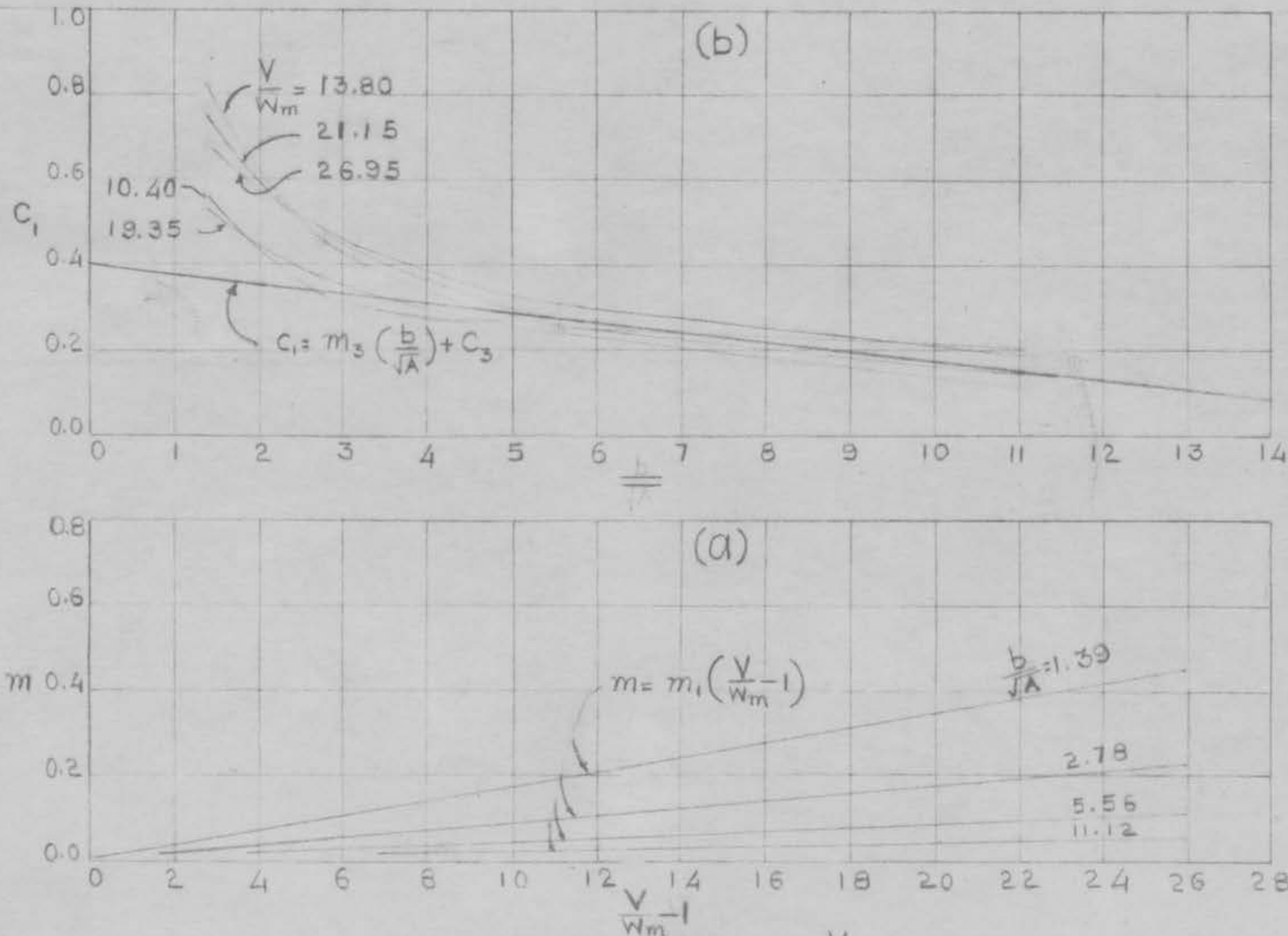

FIG. 10 (a) VARIATION OF m WITH $\frac{V}{W_m}-1$ FOR SOLID JET
(b) VARIATION OF C_1 WITH $\frac{b}{\sqrt{A}}$ FOR SOLID JET

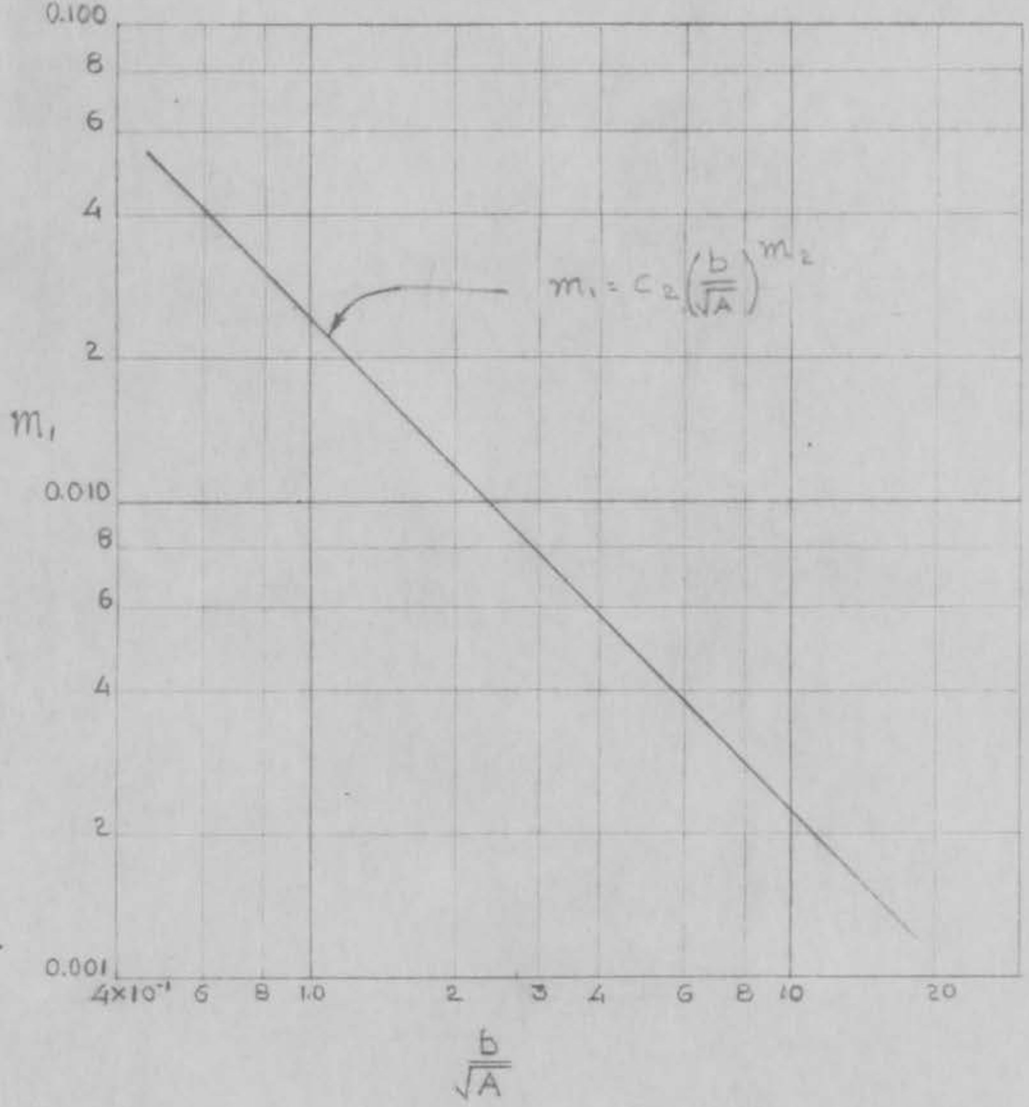

FIG. 11 VARIATION OF m_1 WITH $\frac{b}{\sqrt{A}}$ FOR HOLLOW AND SOLID JETS

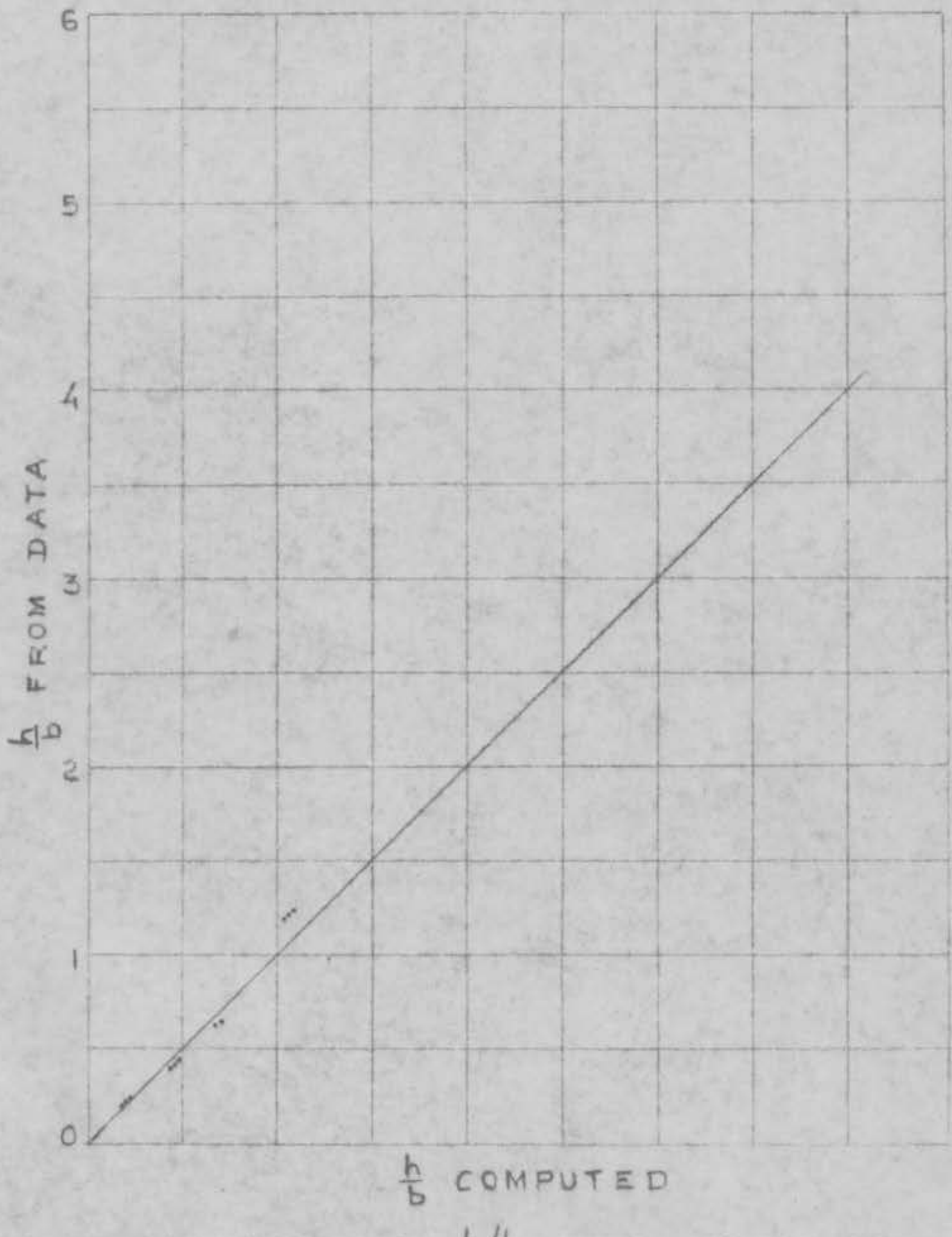

FIG. 12 VARIATION OF h/b FROM DATA WITH COMPUTED h/b FOR 2.06 SQ. IN. HOLLOW JET

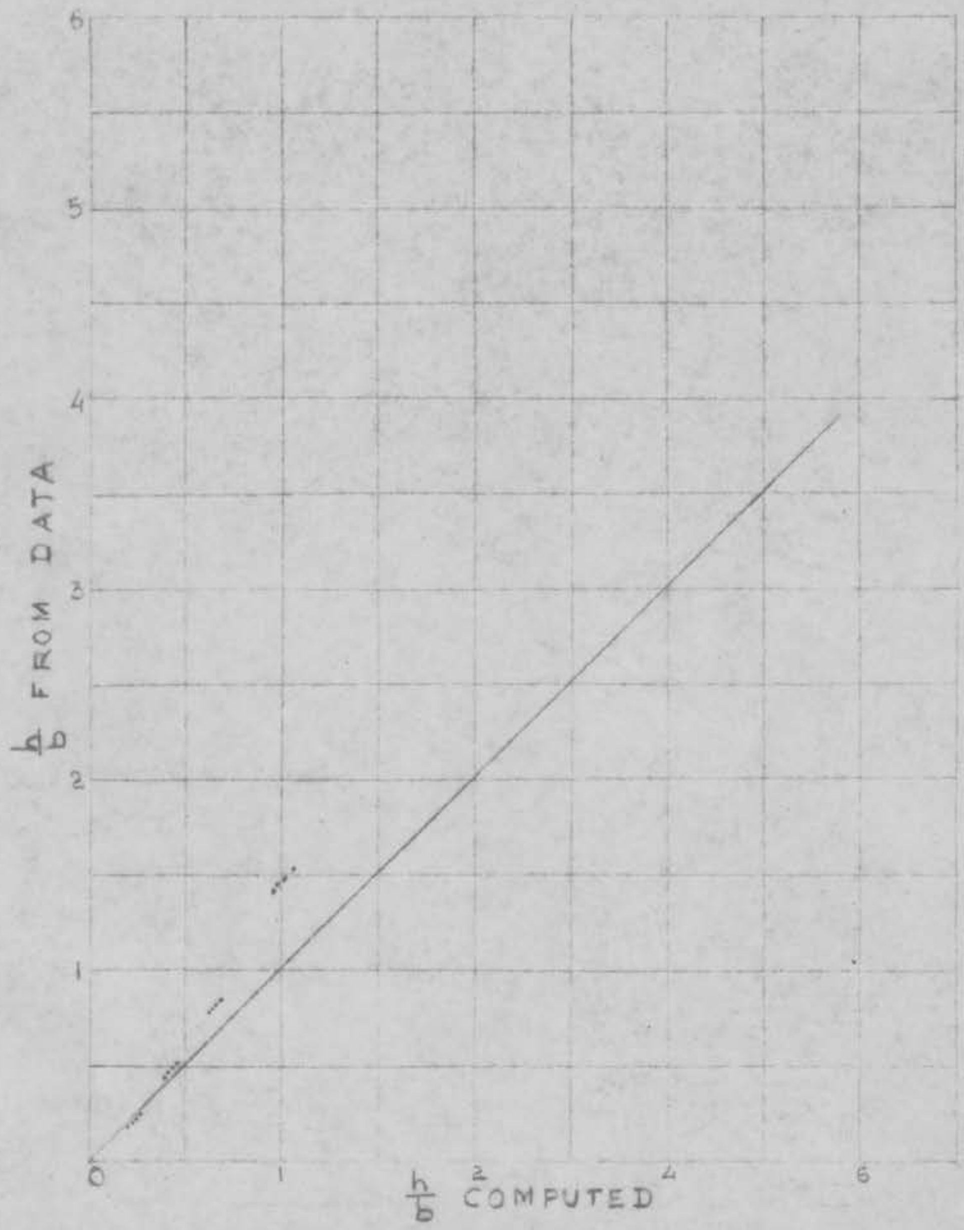

FIG. 13 VARIATION OF h/b FROM DATA WITH COMPUTED h/b FOR 2.06 SQ.IN. SOLID JET

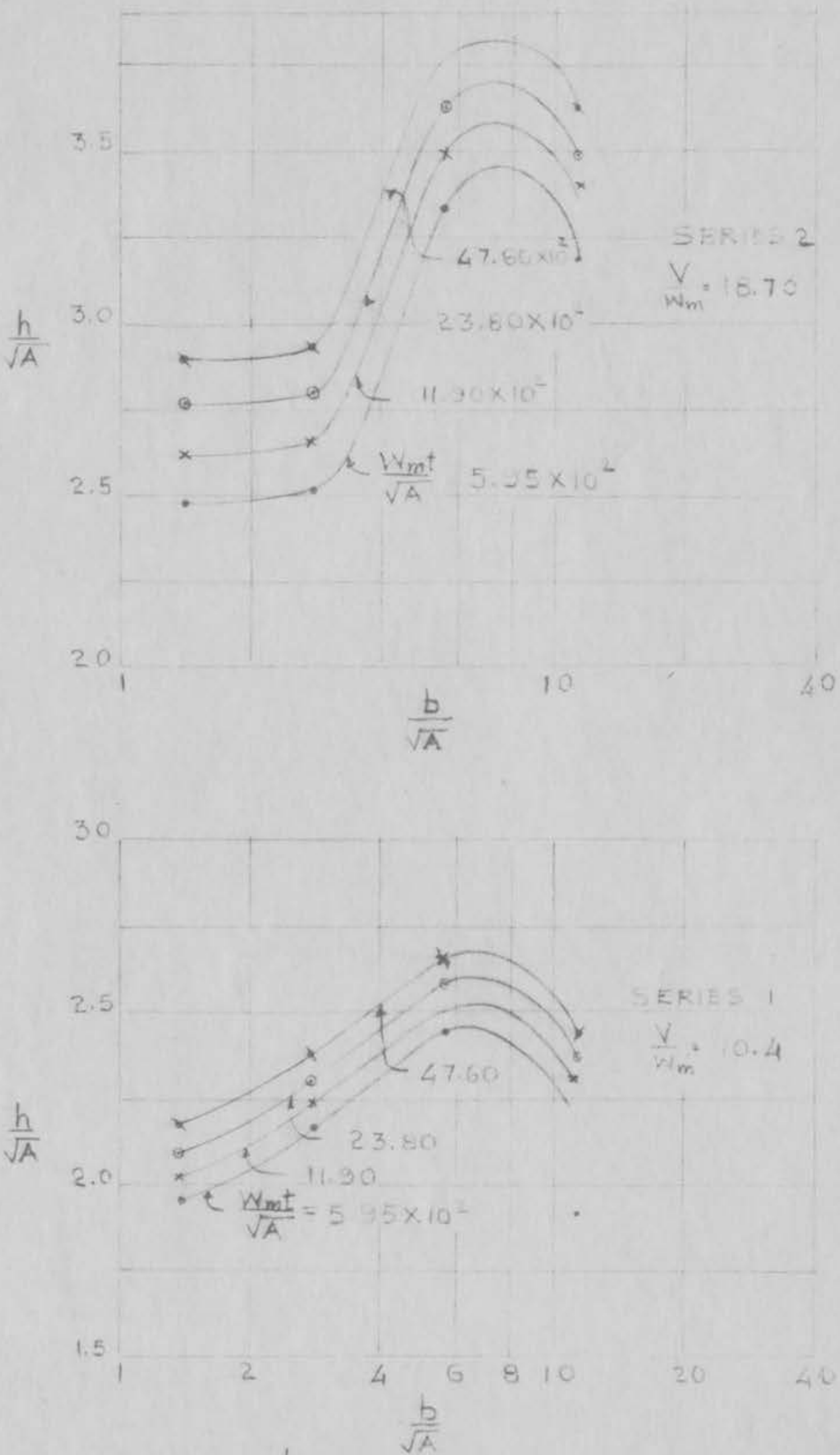

FIG. 14 VARIATION OF $\frac{h}{\sqrt{A}}$ WITH $\frac{b}{\sqrt{A}}$ FOR 2.06-SQ.IN. HOLLOW JET

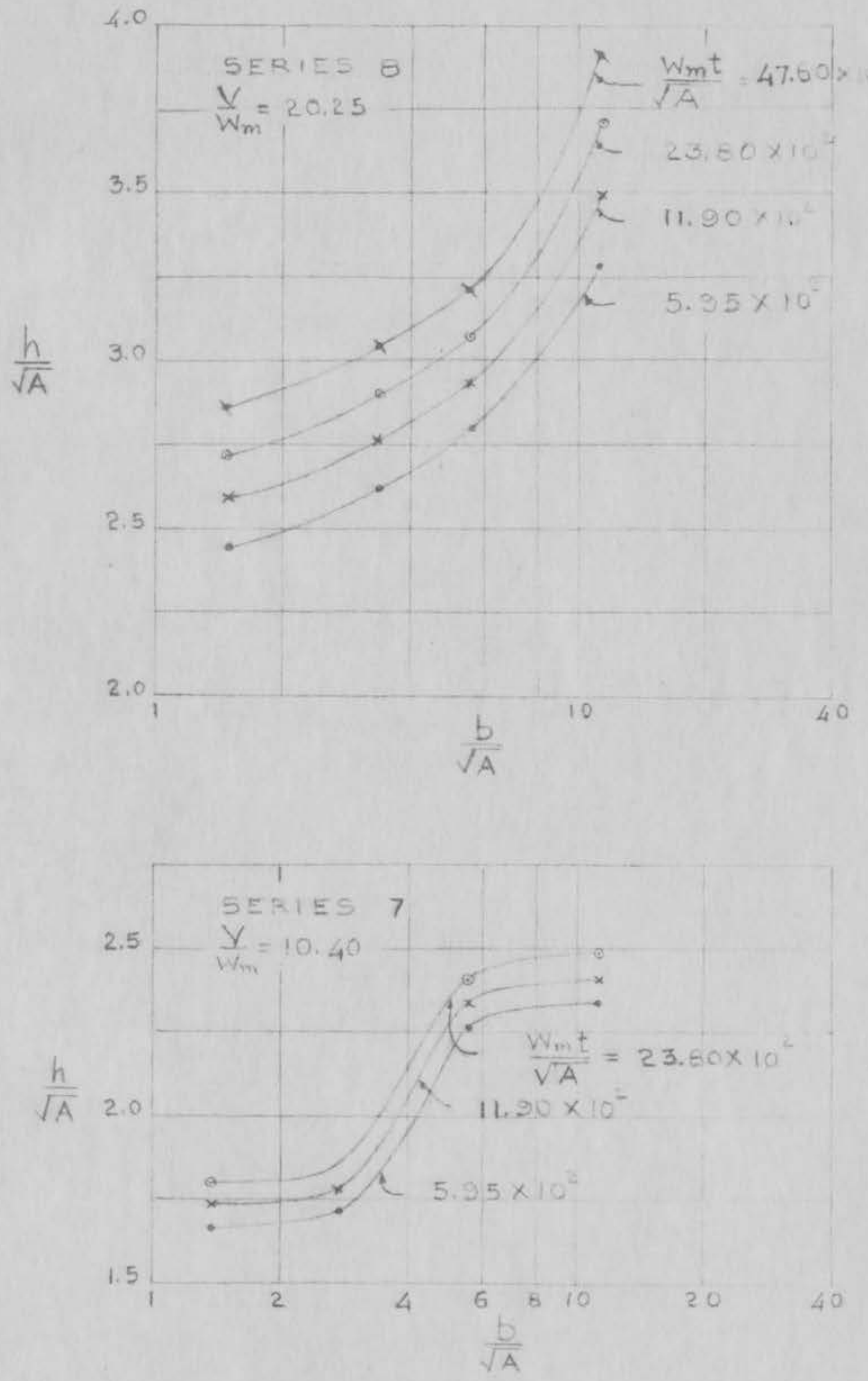

FIG. 15 VARIATION OF $\frac{h}{\sqrt{A}}$ WITH $\frac{b}{\sqrt{A}}$ FOR 2.06-SQ.IN. SOLID JET

Appendix B.--Tables 1-18

LIST OF TABLES

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Table 1.--RANGE OF VARIABLES

Type of jet	A in.^{2}	b in.	$\frac{b}{\sqrt{A}}$	V	w_m	$\frac{V}{w_m}$	t	$T = \frac{w_m t}{b}$
Hollow jet	2.06	2	1.39	9.93	0.955	10.40	15	4.85×10^2
		4	2.78	18.70	0.955	19.60	30	to
		8	5.56	15.20	0.719	21.12	60	4.12×10^4
		16	11.12	18.70	0.719	26.01	120	
	0.90	2	2.11	41.40	0.955	43.30	15	4.85×10^2
		4	4.22	41.40	0.719	57.60	30	to
		8	8.44				60	4.12×10^4
		16	16.88				120	
Solid jet	2.06	2	1.39	9.93	0.955	10.40	15	4.85×10^2
		4	2.78	19.35	0.955	20.25	30	to
		8	5.56	9.93	0.719	13.80	60	4.12×10^4
		16	11.12	15.20	0.719	21.15	120	
				19.35	0.719	26.92		
	1.02	2	1.98	20.20	0.719	28.10	15	4.85×10^2
		4	3.96	36.42	0.719	50.70	30	to
		8	7.92				60	1.55×10^4
		16	15.84					

Table 2.--SHAPE FACTOR AND OTHER CHARACTERISTICS OF GRAVEL NO. 1

Grain No.	Axis a in.	Axis b in.	Axis c in.	Shape factor $\frac{c}{\sqrt{ab}_1}$	Remarks
1	0.334	0.262	0.185	0.615	Specific gravity 2.650
2	0.328	0.275	0.261	0.856	
3	0.354	0.240	0.164	0.562	Average submerged weight of grain 0.000466
4	0.486	0.395	0.295	0.674	
5	0.384	0.293	0.206	0.615	
6	0.279	0.233	0.177	0.694	Average sedimentation diameter 0.0205
7	0.255	0.180	0.150	0.702	
8	0.308	0.281	0.186	0.633	
9	0.325	0.283	0.186	0.612	Mean fall-velocity 0.955
10	0.414	0.258	0.218	0.665	
11	0.359	0.241	0.187	0.636	
12	0.441	0.182	0.169	0.596	
13	0.350	0.302	0.122	0.356	
14	0.432	0.256	0.204	0.623	
15	0.342	0.209	0.210	0.784	
16	0.245	0.219	0.162	0.698	
17	0.243	0.210	0.150	0.664	
18	0.240	0.233	0.193	0.818	
Average shape factor				0.656	

Table 3.--SHAPE FACTOR AND OTHER CHARACTERISTICS OF GRAVEL NO. 2

Grain No.	Axis a in.	Axis b in.	Axis c in.	Shape factor $\frac{c}{\sqrt{ab}_1}$	Remarks
1	0.273	0.264	0.139	0.519	Specific gravity 2.505
2	0.264	0.090	0.066	0.429	
3	0.275	0.295	0.159	0.652	
4	0.257	0.182	0.122	0.565	Average submerged weight of grain 0.00019
5	0.270	0.205	0.193	0.817	
6	0.261	0.217	0.149	0.626	
7	0.278	0.208	0.155	0.646	Average sedimentation diameter 0.0135
8	0.255	0.194	0.142	0.637	
9	0.272	0.195	0.152	0.657	Mean fall-velocity 0.719
10	0.228	0.153	0.142	0.760	
11	0.222	0.184	0.125	0.619	
12	0.179	0.116	0.093	0.641	
13	0.227	0.152	0.138	0.742	
14	0.302	0.173	0.114	0.498	
15	0.290	0.188	0.173	0.740	
16	0.428	0.202	0.127	0.432	
17	0.211	0.191	0.138	0.687	
18	0.209	0.164	0.091	0.492	
19	0.273	0.136	0.116	0.601	
20	0.346	0.152	0.114	0.496	
21	0.201	0.163	0.131	0.724	
22	0.265	0.165	0.108	0.516	
Average shape factor				0.609	

Table 4.--SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 1

Series 1

$V = 9.93$; $w_m = 0.955$; $\frac{V}{w_m} = 10.40$; $A = 2.06$ in.^{2}; $\sqrt{A} = 1.435$ $Q = 0.1420$; $T = 62.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
	15	2.80	1.40	5.16×10^3	
	30	2.90	1.45	1.03×10^4	
2	60	3.00	1.50	2.06×10^4	1.39
	120	3.12	1.56	4.12×10^4	
	15	3.10	0.775	2.58×10^3	
	30	3.20	0.800	5.16×10^3	2.78
4	60	3.30	0.825	1.03×10^4	
	120	3.40	0.850	2.06×10^4	
	15	3.50	0.4375	1.29×10^3	
	30	3.80	0.4500	2.58×10^3	5.56
8	60	3.70	0.4625	5.16×10^3	
	120	3.80	0.4750	1.03×10^4	
	15	2.75	0.1719	6.44×10^2	
	30	3.30	0.2062	1.29×10^3	
16	60	3.40	0.2125	2.58×10^3	11.12
	120	3.50	0.2188	5.16×10^3	

Table 5.--SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 1

Series 2

$V = 18.70$; $w_m = 0.955$; $\frac{V}{w_m} = 19.60$; $A = 2.06$ in.^{2};
$\sqrt{A} = 1.435$; $Q = 0.2673$; $T = 66.2$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
	7.5	3.35	1.675	2.58×10^3	
	15	3.55	1.775	5.16×10^3	
	30	3.75	1.875	1.03×10^4	
2	60	3.95	1.975	2.06×10^4	1.39
	120	4.15	2.075	4.12×10^4	
	240	4.35	2.175	8.25×10^4	
	7.5	3.40	0.850	1.29×10^3	
	15	3.60	0.900	2.58×10^3	
	30	3.80	0.950	5.16×10^3	2.78
4	60	4.00	1.000	1.03×10^4	
	120	4.20	1.050	2.06×10^4	
	7.5	4.60	0.575	6.44×10^2	
	15	4.80	0.600	1.29×10^3	
8	30	5.00	0.625	2.58×10^3	5.56
	60	5.20	0.650	5.16×10^3	
	7.5	4.22	0.2638	3.22×10^2	
	15	4.55	0.2844	6.44×10^2	
	30	4.88	0.3050	1.29×10^3	11.12
16	60	5.00	0.3125	2.58×10^3	
	120	5.20	0.3250	5.16×10^3	
	240	5.40	0.3375	1.03×10^4	

Table 6.--SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 2

Series 3

$V = 15.20$; $w_m = 0.719$; $\frac{V}{w_m} = 21.12$; $A = 2.06$ in.^{2};
$\sqrt{A} = 1.435$; $Q = 0.2170$; $T = 55.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	3.62	1.81	3.88×10^3	1.39
	30	3.84	1.92	7.76×10^3	
	60	4.06	2.03	1.55×10^4	
4	15	3.82	0.955	1.94×10^3	2.78
	30	4.04	1.010	3.88×10^3	
	60	4.26	1.065	7.76×10^3	
8	15	4.62	0.5775	9.70×10^2	5.56
	30	4.84	0.6050	1.94×10^3	
	60	5.06	0.6325	3.88×10^3	
16	15	3.52	0.2200	4.85×10^2	11.12
	30	3.74	0.2338	9.70×10^2	
	60	3.96	0.2475	1.94×10^3	

Table 7.--SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 2

Series 4

$V = 18.70$; $w_m = 0.719$; $\frac{V}{w_m} = 26.01$; $A = 2.06$ in.^{2}; $\sqrt{A} = 1.435$; $Q = 0.2673$; $T = 55.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	4.10	2.050	3.88×10^3	1.39
	30	4.35	2.175	7.76×10^3	
	60	4.60	2.300	1.55×10^4	
4	15	4.60	1.150	1.94×10^3	2.78
	30	4.85	1.212	3.88×10^3	
	60	5.10	1.275	7.76×10^3	
8	15	5.20	0.6500	9.70×10^2	5.56
	30	5.45	0.6812	1.94×10^3	
	60	5.70	0.7125	3.88×10^3	
16	15	5.00	0.3125	4.85×10^2	11.12
	30	5.25	0.3281	9.70×10^2	
	60	5.50	0.3434	1.94×10^3	

Table 8.--SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 1

Series 5

$V = 41.40$; $w_m = 0.955$; $\frac{V}{w_m} = 43.30$; $A = 0.90$ in.^{2};
$\sqrt{A} = 0.95$; $Q = 0.2581$; $T = 66.2$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	4.20	2.10	5.16×10^3	2.11
	30	4.40	2.20	1.03×10^4	
	60	4.60	2.30	2.06×10^4	
	120	4.80	2.40	4.12×10^4	
4	15	4.30	1.075	2.58×10^3	4.22
	30	4.50	1.125	5.16×10^3	
	60	4.70	1.175	1.03×10^3	
	120	4.90	1.225	2.06×10^3	
8	15	5.95	0.7438	1.29×10^3	8.44
	30	6.15	0.7699	2.58×10^3	
	60	6.35	0.7938	5.16×10^3	
	120	6.55	0.8188	1.03×10^4	
	240	6.75	0.8438	2.06×10^4	
16	7.5	6.00	0.3750	3.22×10^2	16.38
	15	6.38	0.3988	6.44×10^2	
	30	6.76	0.4225	1.29×10^3	

Table 9.--SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 2

Series 6

$V = 41.40$; $w_m = 0.719$; $\frac{V}{w_m} = 57.60$; $A = 0.90$ in.^{2};
$\sqrt{A} = 0.95$; $Q = 0.2581$; $T = 55.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15 30 60	5.80 6.10 6.40	2.90 3.05 3.20	3.88×10^3 7.76×10^3 1.55×10^4	2.11
4	15 60	6.30 6.90	1.575 1.725	1.94×10^3 7.76×10^3	4.22
8	15 30 60	6.40 6.70 7.00	0.8000 0.8375 0.8750	9.70×10^2 1.94×10^3 3.88×10^3	8.44
16	3.75 7.50	7.20 6.20	0.4500 0.3875	1.22×10^2 2.44×10^2	16.88

Table 10.--SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 1

Series 7

$V = 9.93$; $w_m = 0.955$; $\frac{V}{w_m} = 10.40$; $A = 2.06$ in.^{2}; $\sqrt{A} = 1.435$; $Q = 0.1420$; $T = 62.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	2.4	1.20	5.16×10^3	1.39
	30	2.5	1.25	1.03×10^4	
	60	2.6	1.30	2.06×10^4	
4	15	2.45	0.6125	2.58×10^3	2.78
	30	2.55	0.6375	5.16×10^3	
8	15	3.25	0.4062	1.29×10^3	5.56
	30	3.35	0.4188	2.58×10^3	
	60	3.45	0.4312	5.16×10^3	
16	15	3.35	0.2094	6.45×10^2	11.12
	30	3.45	0.2156	1.29×10^3	
	60	3.55	0.2218	2.58×10^3	

Table 11.--SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 1

Series 8

$V = 19.35$; $w_m = 0.955$; $\frac{V}{w_m} = 20.25$; $A = 2.06$ in.^{2};
$\sqrt{A} = 1.435$; $Q = 0.2762$; $T = 62.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	3.50	1.75	5.16×10^3	1.39
	30	3.70	1.85	1.03×10^4	
	60	3.90	1.95	2.06×10^4	
	120	4.10	2.05	4.12×10^4	
4	7.5	3.55	0.8875	1.29×10^3	2.78
	15	3.75	0.9375	2.58×10^3	
	30	3.95	0.9875	5.16×10^3	
	60	4.15	1.0375	1.03×10^4	
	120	4.35	1.0875	2.06×10^4	
8	15	4.00	0.5000	1.29×10^3	5.56
	30	4.20	0.5250	2.58×10^3	
	60	4.40	0.5500	5.16×10^3	
	120	4.60	0.5750	1.03×10^4	
16	15	4.70	0.2934	6.45×10^2	11.12
	30	5.00	0.3125	1.29×10^3	
	60	5.30	0.3312	2.58×10^3	
	120	5.60	0.3500	5.16×10^3	

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Table 12.--SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 9

$V = 9.33$; $w_m = 0.719$; $\frac{V}{w_m} = 13.8$; $A = 2.06$ in.^{2};
$\sqrt{A} = 1.435$; $Q = 0.1420$; $T = 60.8$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	3.20	1.600	3.88×10^3	1.39
	30	3.33	1.665	7.76×10^3	
	60	3.46	1.730	1.55×10^4	
4	15	3.23	0.8075	1.94×10^3	2.78
	60	3.49	0.8725	7.76×10^3	
8	15	3.40	0.4250	9.70×10^2	5.56
	60	3.66	0.4575	3.88×10^3	
16	15	3.45	0.2156	4.85×10^2	11.12
	30	3.58	0.2238	9.70×10^2	
	60	3.71	0.2320	1.94×10^3	

Table 13.--SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 10

$V = 15.20$; $w_m = 0.719$; $\frac{V}{w_m} = 21.15$; $A = 2.06$ in.^{2};

$\sqrt{A} = 1.435$; $Q = 0.2170$; $T = 60.8$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	4.10	2.050	3.88×10^3	1.39
	30	4.31	2.155	7.76×10^3	
	60	4.52	2.260	1.55×10^4	
	120	4.73	2.365	3.10×10^4	
4	15	4.20	1.0500	1.94×10^3	2.78
	30	4.41	1.1025	3.88×10^3	
	60	4.62	1.1550	7.76×10^3	
	120	4.83	1.2075	1.55×10^4	
8	15	4.25	0.5312	9.70×10^2	5.56
	30	4.46	0.5575	1.94×10^3	
	60	4.67	0.5812	3.88×10^3	
	120	4.88	0.6100	7.76×10^3	
16	15	4.20	0.2625	4.85×10^2	11.12
	30	5.30	0.3312	9.70×10^2	
	60	5.51	0.3440	1.94×10^3	
	120	5.72	0.3575	3.88×10^3	

Table 14.--SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 11

$V = 19.35$; $w_m = 0.719$; $\frac{V}{w_m} = 26.92$; $A = 2.06$ in.^{2};

$\sqrt{A} = 1.435$; $Q = 0.2762$; $T = 60.8$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	4.60	2.300	3.88×10^3	1.39
	30	4.87	2.435	7.76×10^3	
	60	5.14	2.570	1.55×10^4	
	120	5.41	2.705	3.10×10^4	
4	7.5	4.65	1.1625	9.70×10^2	2.78
	15	4.92	1.2300	1.94×10^3	
	30	5.19	1.2975	3.88×10^3	
	60	5.46	1.3650	7.76×10^3	
	120	5.73	1.4325	1.55×10^4	
8	15	5.10	0.6375	9.70×10^2	5.56
	30	5.37	0.6712	1.94×10^3	
	60	5.67	0.7090	3.88×10^3	
	120	5.94	0.7300	7.76×10^3	
16	15	5.50	0.3440	4.85×10^2	11.12
	30	5.77	0.3606	9.70×10^2	
	60	6.04	0.3775	1.94×10^3	
	120	6.31	0.3944	3.88×10^3	

Table 15.--SCOUR CAUSED BY 1.02-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 12

$V = 20.20$; $w_m = 0.719$; $\frac{V}{w_m} = 28.10$; $A = 1.02$ in.^{2};

$\sqrt{A} = 1.011$; $Q = 0.1420$; $T = 55.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{b}{\sqrt{A}}$
2	15	3.90	1.95	3.88×10^3	1.98
	30	4.10	2.05	7.76×10^3	
	60	4.30	2.15	1.55×10^4	
4	15	4.00	1.00	1.94×10^3	3.96
	30	4.20	1.05	3.88×10^3	
	60	4.40	1.10	7.76×10^3	
8	15	3.50	0.4375	9.70×10^2	7.92
	30	3.70	0.4625	1.94×10^3	
	60	3.90	0.4875	3.88×10^3	
16	15	4.30	0.2688	4.85×10^2	15.84
	30	4.50	0.2813	9.70×10^2	
	60	4.70	0.2938	1.94×10^3	

Table 16.--SCOUR CAUSED BY 1.02-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 13

$V = 36.42$; $w_m = 0.719$; $\frac{V}{w_m} = 50.70$; $A = 1.02$ in.^{2};

$\sqrt{A} = 1.011$; $Q = 0.1420$; $T = 55.6$ F.

b in.	t min	h in.	$\frac{h}{b}$	$T = \frac{w_m t}{b}$	$\frac{h}{\sqrt{A}}$
2	15	5.25	2.625	3.88×10^3	1.98
	30	5.75	2.875	7.76×10^3	
	60	6.25	3.125	1.55×10^4	
4	15	5.80	1.450	1.94×10^3	3.96
	30	6.30	1.575	3.88×10^3	
	60	6.80	1.700	7.76×10^3	
8	15	6.30	0.7875	9.70×10^2	7.92
	30	6.80	0.8500	1.94×10^3	
	60	7.30	0.9125	3.88×10^3	
16	3.75	5.00	0.3125	1.22×10^2	15.84
	7.50	5.40	0.3375	2.43×10^2	
	15	5.80	0.3625	4.85×10^2	
	30	6.20	0.3875	9.70×10^2	

Table 17.--VALUES OF COEFFICIENT c_1 AND SLOPES m AND m_1--
2.06-SQ.IN. HOLLOW JET

Series	$\frac{V}{w_m}$	b in.	m	c_1	$\frac{b}{\sqrt{A}}$	m_1
1	10.40	2	0.167	0.780	1.39	0.0178
		4	0.083	0.500		
		8	0.044	0.300		
		16	0.021	0.140		
2	19.60	2	0.336	0.530	2.78	0.0083
		4	0.167	0.330		
		8	0.086	0.330		
		16	0.055	0.130		
3	21.12	2	0.367	0.634	5.56	0.0041
		4	0.183	0.370		
		8	0.093	0.300		
		16	0.043	0.103		
4	26.01	2	0.417	0.570	11.12	0.0021
		4	0.207	0.533		
		8	0.104	0.337		
		16	0.052	0.170		

Table 18.--VALUES OF COEFFICIENT c_1 AND SLOPES m AND m_1--
2.06-SQ.IN. SOLID JET

Series	$\frac{V}{w_m}$	b in.	m	c_1	$\frac{b}{\sqrt{A}}$	m_1
7	10.40	2 4 8 16	0.167 0.083 0.042 0.021	0.580 0.330 0.275 0.150	1.39	0.0178
8	19.35	2 4 8 16	0.330 0.167 0.083 0.064	0.529 0.368 0.241 0.113	2.78	0.0083
9	13.80	2 4 8 16	0.217 0.108 0.053 0.027	0.820 0.450 0.250 0.142	5.56	0.0041
10	21.15	2 4 8 16	0.350 0.175 0.088 0.044	0.759 0.474 0.269 0.202	11.12	0.0021
11	26.92	2 4 8 16	0.450 0.225 0.112 0.055	0.685 0.489 0.301 0.195		

Appendix C.--Tables 19-31

LIST OF TABLES

LIST OF TABLES--Continued

Table 19.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 1

Series 1

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-0.66	0.0	-0.19	0.0	-0.66	0.0	-1.79
	+2.0	-0.91	+1.0	+0.03	+3.0	-0.91	+2.0	-1.54
	+3.0	-0.47	+2.0	-0.22	+4.5	-0.54	+4.0	-0.54
	+4.5	-0.16	+3.0	-0.47	+6.0	+0.46	+6.0	+1.46
	+6.0	+0.43	+4.0	-0.54	-3.0	-1.35	-2.0	-1.04
	-2.0	-0.60	+5.0	-0.41	-4.5	-1.04	-4.0	-0.66
	-3.0	-0.66	+6.0	-0.04	-6.0	-0.79	-6.0	+0.21
	-3.5	-0.72	+7.0	+0.15	-7.5	+0.59		
	-4.5	-0.41	-1.0	-1.29				
	-6.7	+0.59	-2.0	-0.41				
			-3.0	-0.41				
			-4.0	-0.29				
			-5.0	-0.16				
			-6.0	+0.28				
30	0.0	-0.47	0.0	-0.66	0.0	+0.15	0.0	-1.10
	+2.0	-0.29	+1.0	-0.47	+3.0	-0.60	+2.0	-0.79
	+3.0	-0.35	+2.0	-0.97	+4.5	-0.85	+4.0	-0.66
	+4.5	-0.04	+3.0	-0.72	+6.0	-0.54	+6.0	-0.04
	+6.0	+0.46	+4.0	-0.66	+8.1	+0.84	+7.5	+0.78
	-2.0	-0.79	+5.0	-0.54	-3.0	-0.54	-1.0	-1.35
	-3.0	-0.72	+6.0	-0.10	-4.5	-0.79	-2.0	-1.79
	-4.5	-0.29	+7.0	+0.34	-6.0	-0.60	-3.0	-1.66
	-6.0	+0.09	-1.0	-0.85	-8.0	+0.53	-4.0	-1.16
			-2.0	-0.60			-5.0	-0.79
			-3.0	-0.91			-6.0	-0.16
			-4.0	-1.10			-7.0	+0.09
			-5.0	-0.54				
			-6.0	-0.10				
			-7.0	+0.53				

*Origin at intersection of jet center line with original surface of bed material.

Table 19.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 1--Continued

Series 1

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
60	0.0	-1.60	0.0	-0.57	0.0	-0.34	0.0	-2.29
	+2.0	-1.66	+1.0	-0.82	+2.0	+0.65	+1.0	-2.35
	+3.0	-1.29	+2.0	-0.79	+3.0	+0.59	+2.0	-1.79
	+4.0	-0.54	+3.0	-0.85	+4.0	+0.46	+3.0	-1.29
	+5.0	-0.04	+4.0	-0.66	+5.0	-0.03	+4.0	-0.97
	+6.0	+0.40	+5.0	-0.54	+6.0	0.00	+5.0	-0.66
	-2.0	-1.60	+6.0	-0.04	+7.0	-0.07	+6.0	-0.16
	-3.0	-1.12	+7.0	+0.78	+8.0	+0.34	+7.0	+0.78
	-4.0	-0.54	-1.0	-0.54	-1.0	+0.15	-1.0	-2.29
	-5.0	-0.29	-2.0	-0.85	-2.0	-0.22	-2.0	-1.91
	-6.0	+0.15	-3.0	-0.60	-3.0	-0.60	-3.0	-1.29
			-4.0	-0.66	-4.0	-0.91	-4.0	-0.94
			-5.0	-0.60	-5.0	-0.66	-5.0	-0.60
			-6.0	-0.13	-6.0	-0.47	-6.0	-0.41
			-7.0	+0.34	-7.0	+0.09	-7.0	+0.03
120	0.0	-0.66	0.0	-0.60	0.0	-0.16	0.0	-1.97
	+2.0	-0.60	+1.0	-0.79	+1.0	+0.09	+1.0	-1.91
	+4.0	-0.47	+2.0	-0.35	+2.0	-0.41	+2.0	-1.35
	+6.0	-0.16	+3.0	-1.60	+3.0	-0.60	+3.0	-0.97
	+7.0	+0.34	+4.0	-1.29	+4.0	-0.79	+4.0	-0.66
	-2.0	-0.54	+5.0	-0.79	+5.0	-0.54	+5.0	-0.47
	-4.0	-0.29	+6.0	-0.06	+6.0	-0.16	+6.0	-0.07
	-6.0	+0.11	+7.0	+0.34	+7.0	+0.21	+7.0	+0.28
			-1.0	-0.41	-1.0	-0.10	-1.0	-1.91
			-2.0	-0.60	-2.0	-0.22	-2.0	-1.79
			-3.0	-0.72	-3.0	-0.66	-3.0	-1.54
			-4.0	-0.72	-4.0	-1.16	-4.0	-1.41
			-5.0	-0.54	-5.0	-0.91	-5.0	-0.91
			-6.0	-0.22	-6.0	-0.66	-6.0	-0.35
			-7.0	+0.28	-7.0	+0.09	-7.0	+0.15

*Origin at intersection of jet center line with original surface of bed material.

Table 20.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 1

Series 2

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
7.5	0.0	-3.16	0.0	-3.25	0.0	-4.28	0.0	-3.19
	+3.0	-1.79	+2.8	-1.56	+3.0	-2.50	+3.0	-2.50
	+6.0	-0.22	+4.8	-0.38	+6.0	-1.25	+6.0	-0.81
	+8.3	+0.96	+8.5	+1.25	+9.0	+0.69	+9.0	+0.50
	-3.0	-1.85	-3.3	-2.06	-3.0	-2.63	-3.0	-2.31
	-6.0	-0.09	-5.3	-0.75	-6.0	-0.94	-6.0	-0.75
	-8.1	+0.78	-9.0	+1.25	-9.0	+0.81	-9.0	+0.56
15	0.0	-2.97	0.0	-3.13	0.0	-4.63	0.0	-4.13
	+3.0	-1.69	+2.8	-1.81	+3.0	-2.81	+3.0	-3.00
	+6.0	+0.03	+4.5	-0.50	+6.0	-1.00	+6.0	-1.06
	-3.0	-2.16	+9.1	+1.50	+9.0	+0.72	+9.0	+0.50
	-6.0	-0.41	-2.3	-2.19	-3.0	-3.06	-3.0	-2.56
	-8.5	+0.78	-6.3	0.00	-6.0	-1.25	-6.0	-0.75
			-9.3	+1.25	-9.0	+0.37	-9.0	+0.25
30	0.0	-2.91	0.0	-3.00	0.0	-4.63	0.0	-3.50
	+3.0	-1.94	+2.8	-1.69	+3.0	-3.13	+3.0	-3.00
	+6.0	-0.16	+4.8	-0.50	+6.0	-1.56	+6.0	-1.50
	+8.3	+0.84	+9.0	+0.94	+9.0	+0.31	+9.0	-0.13
	-3.0	-2.25	-3.3	-1.69	-3.0	-3.31	+11.5	+1.25
	-6.0	-0.59	-7.3	+0.50	-6.0	-1.56	-3.0	-2.88
	-8.5	+0.59			-9.0	-0.06	-6.0	-1.69
					-12.2	+1.62	-9.0	-0.19
							-11.6	+0.62
60	0.0	-3.16	0.0	-3.00	0.0	-4.88	0.0	-4.10
	+3.0	-2.22	+2.8	-2.25	+3.0	-3.38	+3.0	-3.35
	+6.0	-0.25	+4.8	-0.94	+6.0	-1.88	+6.0	-1.54
	+7.9	+1.00	+9.5	+1.25	+9.0	+0.31	+9.0	-0.16
							+12.5	+1.40

*Origin at intersection of jet center line with original surface of bed material.

Table 20.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 1--Continued

Series 2

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
	-3.0	-2.29	-2.2	-2.44	-3.0	-3.69	-3.0	-2.29
	-6.0	-0.29	-5.2	-0.75	-6.0	-1.92	-6.0	-1.62
	-7.4	+0.46	-9.6	+0.97	-9.0	+0.06	-9.0	-0.54
					-12.8	+2.04	-12.6	+0.59
120	0.0	-3.46	0.0	-3.63			0.0	-[illegible].41
	+3.0	-2.06	+2.8	-2.19			+3.0	-3.16
	+6.0	-0.46	+4.8	-0.94			+6.0	-2.04
	+7.7	+0.50	+7.8	+0.91			+9.0	-0.41
	-3.0	-2.00	-2.3	-2.56			+13.1	+1.65
	-6.0	-0.52	-5.3	-0.89			-3.0	-3.41
	-7.8	+0.63	-10.0	+1.25			-6.0	-2.29
							-9.0	-0.91
							-13.2	+0.96
240							0.0	-3.97
							+3.0	-3.41
							+6.0	-2.16
							+9.0	-0.66
							+14.1	+1.84
							-3.0	-3.75
							-6.0	-2.26
							-9.0	-1.10
							-14.1	+1.06

*Origin at intersection of jet center line with original surface of bed material.

Table 21.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 2

Series 3

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-0.84	0.0	-2.14	0.0	-2.31	0.0	-2.53
	+2.0	-1.09	+2.0	-1.59	+2.0	-2.03	+1.0	-1.93
	+4.0	-0.97	+4.0	-1.28	+4.0	-1.65	+2.0	-1.90
	+5.0	-0.90	+5.0	-0.78	+6.0	-1.15	+4.0	-1.15
	+6.0	-0.59	+6.0	-0.90	+8.0	-0.47	+6.0	-0.40
	+7.5	0.00	+8.0	0.00	+8.6	0.00	+6.9	0.00
	-2.0	-1.03	-2.0	-2.09	-2.0	-2.40	-1.0	-2.43
	-4.0	-1.22	-4.0	-1.59	-4.0	-2.22	-2.0	-2.03
	-5.0	-0.97	-5.0	-1.47	-5.0	-2.03	-4.0	-1.34
	-6.0	-0.78	-6.0	-1.09	-6.0	-1.47	-5.0	-0.84
	-7.7	0.00	-8.4	0.00	-8.0	-0.59	-6.0	-0.28
					-9.0	0.00	-7.0	0.00
30	0.0	-1.84	0.0	-1.65	0.0	-2.78	0.0	-2.78
	+1.0	-1.72	+2.0	-1.53	+2.0	-2.84	+1.0	-2.40
	+2.5	-2.18	+4.0	-1.47	+4.0	-2.47	+2.0	-2.22
	+4.0	-1.59	+5.0	-1.22	+6.0	-1.59	+4.0	-1.15
	+6.0	-0.53	+6.0	-1.03	+8.0	-0.47	+6.0	-0.28
	+7.5	0.00	+8.1	0.00	+9.1	0.00	+7.2	0.00
	-1.0	-2.03	-2.0	-1.72	-2.0	-2.78	-1.0	-2.47
	-2.0	-2.34	-4.0	-1.84	-4.0	-2.47	-2.0	-2.28
	-4.0	-1.78	-5.0	-1.53	-5.0	-2.40	-4.0	-1.47
	-6.0	-0.84	-6.0	-1.15	-6.0	-1.84	-6.0	-0.72
	-7.9	0.00	-8.4	0.00	-8.0	-0.59	-7.4	0.00
					-9.1	0.00		

*Origin at intersection of jet center line with original surface of bed material.

Table 21.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 2--Continued

Series 3

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
60	0.0	-1.22	0.0	-1.34	0.0	-1.22	0.0	-2.65
	+2.0	-1.28	+2.0	-1.78	+2.0	-0.78	+1.0	-2.28
	+4.0	-1.09	+4.0	-1.47	+4.0	-0.84	+2.0	-2.28
	+6.0	-1.56	+5.0	-1.40	+6.0	-0.90	+4.0	-1.65
	+7.8	0.00	+6.0	-1.03	+7.0	-0.84	+6.0	-0.78
	-2.0	-1.78	+8.0	-0.40	+8.0	-0.59	+7.7	0.00
	-4.0	-1.78	+8.6	0.00	+9.6	0.00	-1.0	-2.65
	-6.0	-1.03	-2.0	-1.28	-2.0	-1.47	-2.0	-2.22
	-8.5	0.00	-4.0	-1.78	-4.0	-1.72	-3.0	-1.84
			-5.0	-1.53	-5.0	-1.59	-4.0	-1.47
			-6.0	-1.28	-6.0	-1.28	-6.0	-0.53
			-8.0	-0.34	-8.0	-0.72	-7.0	-0.28
			-8.6	0.00	-9.4	0.00	-8.0	0.00

*Origin at intersection of jet center line with original surface of bed material.

Table 22.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO 2

Series 4

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-3.03	0.0	-3.90	0.0	-4.72	0.0	-4.09
	+2.0	-2.84	+1.0	-3.72	+1.0	-4.03	+1.0	-3.84
	+4.0	-1.84	+2.0	-3.59	+2.0	-3.53	+2.0	-3.22
	+6.0	-0.90	+4.0	-2.40	+4.0	-2.72	+4.0	-2.34
	+7.7	0.00	+6.0	-1.47	+6.0	-1.78	+6.0	-1.47
	-2.0	-2.84	+8.0	-0.65	+8.0	-0.59	+8.0	-0.65
	-4.0	-2.15	+9.2	0.00	+9.2	0.00	+10.0	0.00
	-6.0	-1.09	-1.0	-3.78	-1.0	-4.34	-1.0	-4.09
	-7.7	0.00	-2.0	-3.47	-2.0	-3.72	-2.0	-3.65
			-4.0	-2.47	-4.0	-2.84	-4.0	-2.72
			-6.0	-1.15	-6.0	-1.65	-6.0	-1.84
			-8.3	0.00	-8.0	-0.53	-8.0	-0.86
					-9.2	0.00	-9.6	0.00
30	0.0	-3.09	0.0	-4.62	0.0	-5.22	0.0	-4.34
	+2.0	-3.15	+1.0	-4.22	+1.0	-4.78	+1.0	-3.84
	+4.0	-2.09	+2.0	-3.65	+2.0	-3.97	+2.0	-3.34
	+6.0	-0.90	+4.0	-2.59	+3.0	-3.22	+4.0	-2.84
	+7.9	0.00	+6.0	-1.28	+4.0	-2.84	+8.0	-1.97
	-2.0	-3.34	+8.0	-0.53	+6.0	-2.03	+6.0	-1.15
	-3.0	-2.97	+9.3	0.00	+8.0	-0.97	+10.0	-0.34
	-4.0	-2.28	-1.0	-4.03	+9.8	0.00	+11.0	0.00
	-6.0	-1.22	-2.0	-3.65	-1.0	-4.65	-1.0	-3.90
	-8.3	0.00	-4.0	-2.84	-2.0	-3.97	-2.0	-3.59
			-6.0	-0.59	-4.0	-2.84	-3.0	-3.03
			-8.0	-0.59	-6.0	-2.90	-4.0	-2.78
			-9.2	0.00	-8.0	-0.97	-6.0	-1.78
					-9.7	0.00	-8.0	-0.97
							-10.0	0.00

*Origin at intersection of jet center line with original surface of bed material.

Table 22.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. HOLLOW JET IN GRAVEL NO. 2--Continued

Series 4

Duration of test t min	Depth of stilling pool b in inches							
	2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
60	0.0	-3.34	0.0	-4.47	0.0	-5.34	0.0	-4.72
	+2.0	-3.09	+1.0	-4.22	+1.0	-4.34	+1.0	-4.34
	+3.0	-2.72	+2.0	-3.78	+2.0	-4.34	+2.0	-4.09
	+4.0	-2.15	+4.0	-2.65	+3.0	-3.59	+4.0	-3.03
	+6.0	-1.03	+6.0	-1.78	+4.0	-3.03	+6.0	-2.15
	+8.0	-0.34	+8.0	-0.84	+6.0	-2.15	+8.0	-1.03
	+9.2	0.00	+9.6	0.00	+8.0	-0.93	+10.0	-0.40
	-2.0	-3.22	-1.0	-4.03	+10.1	0.00	+11.3	0.00
	-3.0	-2.65	-2.0	-3.72	-1.0	-4.72	-1.0	-4.47
	-4.0	-2.34	-4.0	-2.78	-2.0	-4.15	-2.0	-4.15
	-6.0	-1.15	-6.0	-1.59	-3.0	-3.40	-4.0	-3.03
	-8.0	-0.28	-8.0	-0.93	-4.0	-3.03	-6.0	-2.09
	-8.8	0.00	-9.7	0.00	-6.0	-1.97	-8.0	-1.34
					-8.0	-0.93	-10.0	-0.59
					-10.1	0.00	-11.0	0.00

*Origin at intersection of jet center line with original surface of bed material.

Table 23.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 1

Series 5

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
3.75							0.0	-4.61
							+3.0	-3.80
							+6.0	-2.49
							+9.0	-0.92
							+12.0	+0.51
							-3.0	-4.30
							-6.0	-3.11
							-9.0	-1.36
							-12.0	+0.26
7.5							0.0	-4.86
							+3.0	-4.36
							+6.0	-4.11
							+9.0	-6.67
							+12.0	-0.01
							+15.0	+1.70
							-3.0	-4.86
							-6.0	-3.11
							-9.0	-1.61
							-12.0	-0.01
							-15.2	+2.11
15	0.0	-1.87	0.0	-2.40	0.0	-4.13	0.0	-5.07
	+2.8	-2.25	+2.8	-2.25	+3.0	-3.69	+3.0	-4.78
	+6.0	-0.75	+4.5	-1.75	+6.0	-2.57	+6.0	-3.28
	+9.9	+1.35	+8.0	-0.19	+9.0	-0.88	+9.0	-1.90
	-2.5	-2.25	+9.2	+0.50	+12.0	+0.62	+12.0	-0.28
	-6.0	-0.87	-3.1	-2.19	-3.0	-3.88	+15.0	+1.06
	-9.6	+1.19	-4.5	-1.69	-6.0	-2.63	-3.0	-4.82
			-6.0	-1.00	-9.0	-1.13	-6.0	-3.63
			-9.0	+0.81	-12.0	+0.56	-9.0	-2.07
							-12.0	-0.69
							-15.0	+1.18

*Origin at intersection of jet center line with original surface of bed material.

Table 23.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 1--Continued

Series 5

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
30	0.0	-2.18	0.0	-2.19	0.0	-4.38		
	+1.8	-2.37	+2.8	-2.12	+3.0	-3.88		
	+4.5	-1.75	+4.0	-1.94	+6.0	-2.44		
	+9.0	+0.88	+6.0	-1.00	+9.0	-1.28		
	-2.2	-2.46	+9.0	+0.25	+12.0	+0.60		
	-4.5	-1.56	-2.5	-2.44	-3.0	-4.38		
	-9.0	+0.75	-4.0	-1.81	-6.0	-3.13		
			-6.0	-0.69	-9.0	-1.57		
			-9.0	+0.88	-12.0	+0.13		
60	0.0	-2.19	0.0	-2.63	0.0	-4.88		
	+2.6	-2.39	+2.5	-2.63	+3.0	-4.19		
	+4.3	-1.94	+4.0	-2.33	+6.0	-2.69		
	+6.0	-1.00	+6.0	-1.44	+9.0	-0.32		
	+9.0	+0.60	+9.0	+0.13	+12.0	+0.06		
	-2.5	-2.81	-3.0	-2.82	-3.0	-4.69		
	-3.3	-2.27	-4.0	-2.32	-6.0	-3.13		
	-4.5	-1.94	-6.0	-1.13	-9.0	-1.38		
	-6.0	-1.19	-9.0	+0.56	-12.0	0.00		
	-9.0	+0.60						
120	0.0	-2.31	0.0	-2.63	0.0	-4.97		
	+2.4	-2.19	+2.8	-2.69	+3.0	-4.22		
	+4.0	-1.87	+4.0	-2.50	+6.0	-3.13		
	+7.0	-0.19	+6.0	-1.57	+9.0	-1.59		
	+9.0	+0.81	+9.0	-0.38	+12.0	+0.16		
	-3.3	-2.69	+12.5	+0.50	-3.0	-4.50		
	-4.0	-2.31	-2.7	-2.82	-6.0	-3.15		
	-7.0	-0.81	-4.0	-2.38	-9.0	-2.07		
	-10.0	+0.69	-6.0	-1.32	-12.0	-0.34		
			-9.0	+0.37	-15.0	+1.25		

*Origin at intersection of jet center line with original surface of bed material.

Table 23.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 1--Continued

Series 5

Duration of test t min	Depth of stilling pool b in inches							
	2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
240					0.0	-5.38		
					+3.0	-4.63		
					+6.0	-3.38		
					+9.0	-1.88		
					+12.0	-0.13		
					+15.0	+0.93		
					-3.0	-4.94		
					-6.0	-3.57		
					-9.0	-2.00		
					-12.0	-0.32		
					-15.0	+1.25		

*Origin at intersection of jet center line with original surface of bed material.

Table 24.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 2

Series 6

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole* x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
3.75							0.0	-6.03
							+2.0	-5.47
							+4.0	-5.02
							+6.0	-3.97
							+8.0	-3.22
							+10.0	-2.34
							+12.0	-1.15
							+14.1	0.00
							-2.0	-5.97
							-4.0	-5.03
							-6.0	-4.09
							-8.0	-3.09
							-10.0	-2.15
							-12.0	-1.09
							-13.2	0.00
7.5							0.0	-5.15
							+2.0	-4.59
							+4.0	-3.90
							+6.0	-3.09
							+8.0	-2.22
							+10.0	-1.22
							+12.4	0.00
							-2.0	-5.03
							-4.0	-3.97
							-6.0	-2.97
							-8.0	-2.09
							-10.0	-1.15
							-12.1	0.00

*Origin at intersection of jet center line with original surface of bed material.

Table 24.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 2--Continued

Series 6

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-3.34	0.0	-4.03	0.0	-4.09	0.0	-5.34
	+2.0	-3.90	+2.0	-4.78	+2.0	-4.28	+2.0	-5.28
	+3.0	-3.97	+4.0	-4.09	+4.0	-3.97	+4.0	-4.59
	+4.0	-3.34	+6.0	-3.15	+6.0	-2.65	+6.0	-3.59
	+6.0	-2.59	+8.0	-2.09	+8.0	-1.97	+8.0	-2.62
	+8.0	-1.65	+10.0	-1.15	+10.0	-0.90	+10.0	-1.90
	+10.0	-0.84	+12.5	0.00	+12.4	0.00	+12.0	-0.65
	+12.0	0.00	-2.0	-4.97	-2.0	-4.65	+13.0	0.00
	-2.0	-3.84	-4.0	-4.09	-4.0	-4.28	-2.0	-5.09
	-3.0	-3.78	-6.0	-3.15	-6.0	-2.90	-4.0	-4.59
	-4.0	-3.49	-8.0	-2.15	-8.0	-1.72	-6.0	-3.59
	-6.0	-2.47	-10.0	-1.15	-10.0	-0.78	-8.0	-2.59
	-8.0	-1.34	-13.0	0.00	-12.0	0.00	-10.0	-1.65
	-10.0	-0.47					-12.0	-0.65
	-11.0	0.00					-13.1	0.00
30	0.0	-3.59			0.0	-4.65		
	+2.3	-4.65			+2.0	-4.65		
	+4.0	-3.84			+4.0	-4.15		
	+6.0	-2.78			+6.0	-3.15		
	+8.0	-2.03			+8.0	-2.15		
	+10.0	-1.22			+10.0	-1.15		
	+12.5	0.00			+12.5	0.00		
	-2.5	-4.47			-2.0	-5.03		
	-4.0	-3.90			-4.0	-5.15		
	-6.0	-2.78			-6.0	-3.15		
	-8.0	-1.59			-8.0	-2.28		
	-10.0	-0.59			-10.0	-1.34		
	-11.8	0.00			-12.0	-0.34		
					-12.8	0.00		

*Origin at intersection of jet center line with original surface of bed material.

Table 24.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 0.90-SQ.IN. HOLLOW JET IN GRAVEL NO. 2--Continued

Series 6

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
60	0.0	-4.00	0.0	-5.28	0.0	-4.97		
	+2.0	-4.59	+1.5	-5.65	+2.5	-5.15		
	+4.0	-4.00	+4.0	-4.40	+4.0	-4.28		
	+6.0	-2.90	+6.0	-3.22	+6.0	-3.40		
	+8.0	-2.00	+8.0	-2.65	+8.0	-2.40		
	+10.0	-1.28	+10.0	-1.90	+10.0	-1.53		
	+12.0	-0.53	+12.0	-1.15	+12.0	-0.53		
	+13.2	0.00	+14.3	0.00	+13.1	0.00		
	-2.0	-4.72	-1.5	-5.28	-2.0	-4.97		
	-4.0	-3.97	-4.0	-4.09	-4.0	-4.53		
	-6.0	-2.84	-6.0	-3.22	-6.0	-3.53		
	-8.0	-1.78	-8.0	-2.34	-8.0	-2.53		
	-10.0	-0.84	-10.0	-1.47	-10.0	-1.53		
	-12.0	0.00	-13.7	0.00	-12.0	-0.53		
					-13.1	0.00		

*Origin at intersection of jet center line with original surface of bed material.

Table 25.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 1

Series 7

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-1.16	0.0	-1.10	0.0	-0.16	0.0	-2.04
	+1.0	-0.85	+1.0	-0.88	+2.0	+0.03	+1.0	-1.85
	+2.0	-0.60	+2.0	-0.66	+4.0	0.00	+2.0	-1.66
	+3.0	-0.35	+4.0	-0.10	+6.0	+0.03	+4.0	-1.16
	+4.5	+0.15	+5.3	+0.34	-2.0	+0.09	+6.0	+0.03
	-1.0	-0.97	-1.0	-0.94	-3.5	-0.60	-1.0	-2.16
	-2.0	-0.79	-2.0	-0.91	-5.0	-0.35	-2.0	-2.10
	-3.0	-0.47	-4.0	-0.29	-7.0	+0.15	-4.0	-1.16
	-4.5	+0.03	-5.3	+0.15			-6.0	-0.16
							-7.7	+0.71
30	0.0	-1.41	0.0	-1.41	0.0	-0.04	0.0	-0.54
	+1.0	-0.91	+1.0	-0.91	+2.0	+0.21	+1.0	-0.41
	+2.0	-0.66	+2.0	-0.60	+4.0	-0.22	+2.0	-0.41
	+3.0	-0.41	+3.0	-0.29	+6.0	-0.16	+4.0	-0.66
	+4.0	-0.04	+4.0	-0.10	+8.0	+0.34	+5.5	-0.72
	+5.0	+0.09	+5.5	+0.34	-2.0	-0.60	+8.0	+0.53
	-1.0	-1.04	-1.0	-1.10	-4.0	-0.35	-1.0	-0.79
	-2.0	-0.79	-2.0	-0.85	-6.0	-0.04	-2.0	-1.00
	-3.0	-0.54	-3.0	-0.47	-8.0	+0.34	-3.5	-1.85
	-4.0	-0.29	-4.0	-0.16			-6.0	-0.41
	-5.0	+0.09	-5.3	+0.28			-8.0	+0.40
60	0.0	-1.35			0.0	-0.22	0.0	-0.66
	+1.0	-1.04			+2.0	-0.16	+1.0	-0.72
	+2.0	-0.79			+4.0	-0.22	+2.0	-1.22
	+3.0	-0.41			+5.0	-0.22	+3.5	-1.35
	+4.0	-0.16			+6.0	+0.03	+6.0	-0.35
	+5.0	+0.15						

*Origin at intersection of jet center line with original surface of bed material.

Table 25.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 1--Continued

Series 7

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
	-1.0	-1.07			-2.0	-0.10	+8.0	+0.65
	-2.0	-0.79			-4.0	-0.91	-1.0	+0.28
	-3.0	-0.47			-6.0	-0.35	-2.0	+0.09
	-4.0	-0.22			-8.0	+0.34	-3.5	-0.29
	-5.0	-0.07					-6.0	+0.78
	-6.6	0.00						

*Origin at intersection of jet center line with original surface of bed material.

Table 26.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 1

Series 8

Duration of test t min	Depth of stilling pool b in inches							
	2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
7.5			0.0	-3.22				
			+2.0	-2.22				
			+4.0	-1.10				
			+6.0	+0.20				
			-2.0	-2.60				
			-4.0	-1.00				
			-6.0	-0.04				
			-7.0	-0.04				
			-8.0	-0.00				
15	0.0	-3.16	0.0	-2.82	0.0	-3.79	0.0	-3.91
	+2.0	-2.41	+1.0	-2.25	+2.0	-2.66	+1.0	-3.41
	+4.0	-1.10	+2.0	-2.12	+4.0	-1.60	+2.0	-2.29
	+6.0	+0.21	+4.0	-1.07	+6.0	-0.47	+4.0	-0.97
	-2.0	-2.41	+6.0	+0.15	+7.8	+0.34	+6.0	-0.16
	-4.0	-1.41	-1.0	-2.82	-2.0	-2.85	+8.0	+1.84
	-6.0	+0.15	-2.0	-2.47	-4.0	-1.47	-1.0	-3.79
			-4.0	-1.10	-6.0	-0.35	-2.0	-3.41
			-6.0	0.00	-7.8	+0.59	-4.0	-2.66
							-6.0	-1.35
							-8.0	-0.29
							-10.0	+0.71
30	0.0	-3.22	0.0	-3.29	0.0	-4.00	0.0	-4.29
	+2.0	-2.19	+1.0	-2.72	+2.0	-2.72	+1.0	-3.97
	+4.0	-1.10	+2.0	-2.22	+4.0	-1.47	+2.0	-3.47
	+6.0	+0.15	+3.0	-1.66	+6.0	-0.47	+4.0	-2.41
	-2.0	-2.35	+4.0	-1.10	+7.8	+0.28	+6.0	-1.66
	-4.0	-1.10	+6.4	+0.21	-2.0	-2.72	+8.0	-0.41
	-6.0	-0.16	-1.0	-3.04	-4.0	-1.47	+10.0	+0.71
	-6.5	+0.46	-2.0	-2.54	-7.8	+0.40	-1.0	-4.41
			-3.0	-1.79			-2.0	-3.85

*Origin at intersection of jet center line with original surface of bed material.

Table 26.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06 SQ.IN. SOLID JET IN GRAVEL NO. 1--Continued

Series 8

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
			-4.0	-1.29			-4.0	-2.85
			-6.0	+0.03			-6.0	-1.54
							-8.0	-0.60
							-10.0	+0.59
60	0.0	-3.50	0.0	-3.66	0.0	-4.35	0.0	-5.10
	+2.0	-2.16	+2.0	-2.47	+2.0	-2.72	+1.0	-4.66
	+4.0	-1.10	+4.0	-1.29	+4.0	-1.66	+2.5	-3.54
	+6.0	+0.09	+6.0	-0.12	+6.0	-0.72	+4.0	-2.72
	-2.0	-2.82	+8.0	+0.03	+8.0	+0.21	+6.0	-1.85
	-4.0	-1.35	-2.0	-2.91	-2.0	-3.04	+8.0	-0.72
	-6.0	0.00	-4.0	-1.10	-4.0	-1.54	+10.0	+0.46
			-6.0	+0.09	-6.0	-0.66	-1.0	-4.66
					-8.0	-0.28	-2.5	-3.79
							-4.0	-2.86
							-6.0	-1.91
							-8.0	-0.79
							-10.0	+0.21
120	0.0	-3.54	0.0	-3.72	0.0	-4.60	0.0	-5.29
	+1.0	-3.00	+2.0	-2.60	+1.0	-3.79	+1.0	-4.97
	+2.0	-2.29	+4.0	-1.29	+2.0	-3.04	+2.0	-4.10
	+4.0	-1.41	+5.0	-0.62	+4.0	-1.85	+4.0	-3.29
	+6.0	-0.16	+6.3	-0.04	+6.0	-0.66	+6.0	-2.16
	+7.0	+0.03	+11.9	0.00	+8.0	+0.34	+8.0	-0.91
	-1.0	-2.91	-2.0	-2.97	-1.0	-4.29	+10.0	+0.06
	-2.0	-2.41	-4.0	-1.35	-2.0	-3.16	-1.0	-4.85
	-4.0	-1.35	-5.0	-0.91	-4.0	-1.85	-2.0	-4.54
	-6.0	+0.35	-6.4	-0.03	-6.0	-0.66	-4.0	-3.60
	-7.0	0.00			-8.0	+0.21	-6.0	-2.29
							-8.0	-1.29
							-10.0	+0.09

*Origin at intersection of jet center line with original surface of bed material.

Table 27.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 9

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-1.97	0.0	-1.04	0.0	-0.47	0.0	-0.91
	+2.0	-1.35	+2.0	-0.47	+1.0	-0.29	+1.0	-0.85
	+3.0	-1.54	+4.0	-0.35	+2.0	-0.29	+2.0	-0.85
	+4.0	-1.29	+6.0	-0.16	+4.0	-0.54	+4.0	-0.41
	+5.0	-0.91	+8.0	+0.28	+5.0	-0.79	+6.0	-0.60
	+6.0	-0.47	-2.0	-0.79	+6.0	-0.47	+8.5	+0.46
	+7.0	-0.16	-4.0	-0.35	+9.0	+0.21	-1.0	-1.22
	-1.0	-1.66	-6.0	+0.09	-2.0	-0.29	-2.0	-1.54
	-2.0	-1.29			-4.0	-0.22	-3.0	-1.16
	-3.0	-1.16			-6.0	-0.16	-4.0	-0.97
	-4.0	-1.04			-8.0	+0.46	-6.0	-0.22
	-6.0	-0.29					-8.5	+0.28
	-7.0	+0.15						
30	0.0	-1.47					0.0	-1.16
	+2.0	-0.91					+2.0	-1.16
	+4.0	-0.47					+4.0	-0.97
	+6.0	-0.29					+6.0	-1.04
	+8.0	-0.35					+8.0	-0.35
	+10.0	0.00					+9.2	+0.09
	-2.0	-0.85					-1.0	-1.22
	-4.0	-0.66					-2.0	-1.16
	-6.0	-0.16					-4.0	-1.35
	-8.0	+0.46					-5.0	-1.4.
							-6.0	-1.04
							-8.0	-0.16
							-9.0	+0.15

*Origin at intersection of jet center line with original surface of bed material.

Table 27.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2--Continued

Series 9

Duration of test t min	Depth of stilling pool b in inches							
	2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
60	0.0	-1.85	0.0	-1.41	0.0	-0.66	0.0	-1.16
	+2.0	-1.25	+2.0	-0.66	+2.0	-0.35	+1.0	-1.10
	+4.0	-0.82	+4.0	-0.29	+4.0	-0.72	+2.0	-1.04
	+6.0	-0.16	+6.0	+0.03	+5.0	-0.91	+4.0	-0.74
	+8.0	-0.53	+8.0	+0.28	+6.0	-0.79	+6.0	-0.35
	+9.3	0.00	-2.0	-0.66	+8.0	+0.09	+8.0	-0.04
	-2.0	-1.16	-4.0	-0.79	-2.0	-0.85	+9.0	+0.26
	-3.0	-1.29	-6.0	-0.29	-4.0	-1.16	-1.0	-1.35
	-4.0	-1.10	-7.0	+0.15	-4.5	-1.29	-2.0	-1.29
	-6.0	-0.60			-6.0	-0.79	-4.0	-1.29
	-8.0	+0.46			-8.0	+0.09	-6.0	-0.66
							-8.0	-0.04
							-9.30	+0.34

*Origin at intersection of jet center line with original surface of bed material.

Table 28.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 10

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-2.22	0.0	-2.00	0.0	-1.35	0.0	-5.00
	+1.0	-1.79	+2.0	-1.60	+2.0	-1.29	+1.0	-4.75
	+2.0	-1.29	+4.0	-1.41	+4.0	-1.22	+2.0	-4.25
	+3.0	-1.60	+6.0	-1.04	+6.0	-1.00	+3.0	-3.54
	+4.0	-1.60	+8.0	-0.07	+8.0	-0.10	+4.0	-2.85
	+5.0	-1.35	+10.0	+0.78	+10.0	+1.00	+6.0	-1.35
	+6.0	-1.22	-2.0	-1.41	-2.0	-1.10	+8.0	-0.64
	+8.0	-0.29	-4.0	-0.97	-4.0	-1.41	+10.0	+0.65
	+9.0	+0.09	-6.0	-0.91	-5.0	-1.47	-1.0	-4.79
	-1.0	-2.22	-8.0	-0.06	-6.0	-1.16	-2.0	-4.22
	-2.0	-1.85	-9.0	+0.28	-8.0	-0.16	-3.0	-3.41
	-3.0	-1.72			-10.0	+0.78	-4.0	-2.79
	-4.0	-1.97					-6.0	-1.35
	-5.0	-1.60					-8.0	-0.47
	-6.0	-1.16					-10.0	+0.59
	-8.0	-0.22						
	-9.0	+0.09						
30	0.0	-2.41	0.0	-2.22	0.0	-1.47	0.0	-3.16
	+2.0	-1.85	+2.0	-1.47	+1.0	-1.41	+1.0	-3.22
	+4.0	-1.94	+4.0	-1.29	+3.5	-0.97	+2.0	-3.22
	+6.0	-1.29	+6.0	-1.16	+5.0	-1.35	+3.0	-3.22
	+8.0	-0.41	+8.0	-0.35	+8.0	-0.35	+4.0	-3.16
	+9.0	-0.16	+10.0	+0.40	+10.0	+0.59	+6.0	-2.35
	+11.2	+0.40	-2.0	-1.91	-1.0	-1.41	+8.0	-1.04
	-1.0	-2.22	-3.0	-2.04	-2.0	-1.82	+10.0	+0.28
	-2.0	-1.94	-4.0	-1.79	-4.0	-2.16	-1.0	-3.41
	-4.0	-1.72	-6.0	-0.85	-6.0	-1.41	-2.0	-3.60
	-6.0	-0.91	-8.0	+0.03	-8.0	-0.22	-3.0	-3.60
	-8.0	-0.04			-10.5	+0.78	-4.0	-3.22
	-9.0	+0.34					-6.0	-2.16
							-8.0	-0.97
							-10.0	+0.24

*Origin at intersection of jet center line with original surface of bed material.

Table 28.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2--Continued

Series 10

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
60	0.0	-2.54			0.0	-1.57	0.0	-3.82
	+1.0	-2.16			+2.0	-1.85	+1.0	-3.57
	+2.0	-2.10			+4.0	-2.16	+2.0	-3.29
	+4.0	-1.97			+5.0	-1.79	+3.0	-3.22
	+6.0	-1.41			+6.0	-1.47	+4.0	-3.04
	+8.0	-0.54			+8.0	-0.47	+6.0	-2.47
	+9.0	-0.29			+10.0	+0.46	+8.0	-1.60
	+11.0	+0.09			-2.0	-1.60	+10.0	-0.35
	-2.0	-1.79			-4.0	-1.35	+12.0	+1.09
	-3.0	-1.54			-6.0	-1.41	-1.0	-3.15
	-4.5	-1.79			-8.0	-0.47	-2.0	-3.54
	-6.0	-1.16			-10.0	+0.21	-3.0	-3.22
	-8.0	-0.29					-4.0	-2.82
	-9.0	+0.28					-6.0	-1.97
							-8.0	-1.04
							-10.0	+0.18
120	0.0	-2.66	0.0	-3.35	0.0	-1.72	0.0	-4.16
	+2.0	-2.16	+2.0	-2.75	+2.0	-1.35	+2.0	-4.16
	+4.0	-1.79	+4.0	-2.07	+4.0	-1.29	+4.0	-3.79
	+6.0	-1.54	+6.0	-1.16	+6.0	-1.10	+6.0	-2.72
	+8.0	-0.82	+8.0	-0.29	+8.0	-0.41	+8.0	-1.66
	+9.0	-0.41	+9.0	0.00	+10.0	+0.40	+10.0	-0.47
	+10.5	0.00	+10.5	+0.09	-2.0	-1.97	+12.0	+0.65
	-2.0	-2.00	-2.0	-2.79	-4.0	-1.91	-2.0	-3.72
	-3.0	-1.72	-4.0	-2.22	-5.0	-1.35	-4.0	-3.10
	-4.5	-2.10	-6.0	-1.35	-6.0	-1.60	-6.0	-2.41
	-6.0	-1.41	-8.0	-0.35	-8.0	-0.50	-8.0	-1.41
	-8.0	-0.35	-9.0	+0.09	-10.0	+0.46	-10.0	-0.41
	-9.0	+0.09					-12.0	+1.03

*Origin at intersection of jet center line with original surface of bed material.

Table 29.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 11

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
7.5			0.0	-3.04				
			+2.0	-2.26				
			+3.0	-2.41				
			+4.0	-1.91				
			+6.0	-1.07				
			+8.0	-0.16				
			+10.0	+0.46				
			-1.0	-2.72				
			-2.0	-2.41				
			-3.0	-1.91				
			-4.0	-1.60				
			-6.0	-0.72				
			-8.0	+0.21				
15	0.0	-4.57	0.0	-4.60	0.0	-5.00	0.0	-4.75
	+1.0	-4.16	+2.0	-3.60	+1.0	-4.16	+1.0	-4.41
	+2.0	-3.60	+4.0	-2.41	+2.0	-3.41	+2.0	-4.29
	+3.0	-3.10	+6.0	-1.25	+3.0	-2.66	+3.0	-3.85
	+4.0	-2.16	+8.0	-0.25	+4.0	-2.16	+4.0	-3.41
	+6.0	-1.60	+11.0	+0.71	+6.0	-1.22	+6.0	-2.35
	+8.0	-0.60	-2.0	-2.54	+8.0	-0.60	+8.0	-1.16
	+9.5	0.00	-4.0	-1.91	+10.0	+0.25	+10.0	-1.04
	-1.0	-4.29	-6.0	-0.79	-1.0	-4.16	+12.0	+1.09
	-2.0	-3.60	-8.0	+0.15	-2.0	-3.41	-1.0	-4.35
	-3.0	-2.91			-3.0	-2.66	-2.0	-4.10
	-4.0	-2.16			-4.0	-2.00	-3.0	-3.85
	-6.0	-1.00			-6.0	-1.29	-4.0	-3.16
	-8.0	-0.04			-8.0	-0.24	-6.0	-1.97
	-10.0	+0.78			-10.0	+0.59	-8.0	-1.10
							-10.0	-0.04
							+12.0	+1.03

*Origin at intersection of jet center line with original surface of bed material.

Table 29.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO.2--Continued

Series 11

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
30	0.0	-4.72	0.0	-4.69	0.0	-4.79	0.0	-5.00
	+1.0	-4.29	+1.0	-4.35	+1.0	-4.29	+1.0	-4.91
	+2.0	-4.00	+2.0	-3.91	+2.0	-3.60	+2.0	-4.41
	+3.0	-3.47	+3.0	-3.16	+3.0	-2.94	+3.0	-3.85
	+4.0	-2.85	+4.0	-2.54	+4.0	-2.47	+4.0	-3.41
	+6.0	-1.60	+6.0	-1.79	+6.0	-1.60	+6.0	-2.72
	+8.0	-0.79	+8.0	-0.72	+8.0	-0.54	+8.0	-1.72
	+10.0	+0.15	+10.0	+0.09	+10.0	+0.43	+10.0	-0.41
	-1.0	-4.22	-1.0	-4.19	-1.0	-4.35	+12.0	+0.78
	-2.0	-3.79	-2.0	-3.50	-2.0	-3.57	-1.0	-5.00
	-3.0	-3.10	-3.0	-2.82	-3.0	-2.82	-2.0	-4.60
	-4.0	-2.54	-4.0	-2.16	-4.0	-2.32	-3.0	-4.16
	-6.0	-1.16	-6.0	-1.16	-6.0	-1.29	-4.0	-3.35
	-8.0	-0.16	-8.0	-0.41	-8.0	-0.44	-6.0	-2.22
	-10.0	+0.65	-10.0	+0.65	-10.0	+0.31	-8.0	-1.16
							-10.0	-0.29
							-12.0	+0.78
60	0.0	-4.66	0.0	-4.87	0.0	-5.10	0.0	-5.41
	+1.0	-4.41	+1.0	-4.66	+1.0	-4.22	+1.0	-5.16
	+2.0	-4.10	+2.0	-4.16	+2.0	-3.66	+2.0	-4.54
	+3.0	-3.47	+3.0	-3.32	+3.0	-2.97	+3.0	-4.13
	+4.0	-2.91	+4.0	-2.91	+4.0	-2.22	+4.0	-3.72
	+6.0	-1.91	+6.0	-1.72	+5.0	-1.72	+6.0	-2.60
	+8.0	-1.04	+8.0	-0.66	+6.0	-1.41	+8.0	-1.47
	+10.0	-0.41	+10.0	-0.07	+8.0	-0.47	+10.0	-0.54
	+12.0	0.00	+12.0	+0.53	+10.0	+0.25	+12.0	+0.78
	-1.0	-4.29	-1.0	-4.54	-1.0	-4.22	-1.0	-5.10
	-2.0	-3.79	-2.0	-3.88	-2.0	-3.54	-2.0	-4.75
	-3.0	-3.10	-3.0	-3.00	-3.0	-2.88	-3.0	-4.29
	-4.0	-2.60	-4.0	-2.44	-4.0	-2.35	-4.0	-3.79
	-6.0	-1.66	-6.0	-1.66	-5.0	-1.79	-6.0	-2.79
	-8.0	-0.60	-8.0	-0.16	-6.0	-1.47	-8.0	-1.63
	-10.0	+0.34	-10.0	+0.40	-8.0	-0.60	-10.0	-0.60
					-10.0	+0.28	-12.0	+0.40

*Origin at intersection of jet center line with original surface of bed material.

Table 29.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 2.06-SQ.IN. SOLID JET IN GRAVEL NO. 2--Continued

Series 11

Duration of test t min	Depth of stilling pool in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
120	0.0	-4.97	0.0	-4.79	0.0	-5.10	0.0	-5.79
	+1.0	-4.66	+1.0	-4.60	+1.0	-4.22	+1.0	-5.47
	+2.0	-4.04	+2.0	-3.97	+2.0	-3.66	+2.0	-4.88
	+3.0	-3.47	+3.0	-3.41	+3.0	-2.97	+3.0	-4.44
	+4.0	-2.91	+4.0	-2.91	+4.0	-2.22	+4.0	-4.04
	+6.0	-1.97	+6.0	-1.97	+5.0	-1.72	+6.0	-3.97
	+8.0	-1.16	+8.0	-0.89	+6.0	-1.41	+8.0	-1.91
	+10.0	-0.29	+10.0	-0.29	+8.0	-0.47	+10.0	-0.60
	+12.0	+0.28	+12.0	+0.15	+10.0	+0.25	+12.0	+0.21
	-1.0	-4.60	-1.0	-4.47	-1.0	-4.22	-1.0	-5.79
	-2.0	-4.00	-2.0	-3.85	-2.0	-3.54	-2.0	-5.44
	-3.0	-3.41	-3.0	-3.41	-3.0	-2.88	-3.0	-4.80
	-4.0	-2.72	-4.0	-2.75	-4.0	-2.35	-4.0	-4.10
	-6.0	-1.41	-6.0	-1.50	-5.0	-1.79	-6.0	-2.91
	-8.0	-0.47	-8.0	-0.63	-6.0	-1.47	-8.0	-1.97
	-10.0	+0.09	-10.0	+0.40	-8.0	-1.60	-10.0	-1.10
					-10.0	+0.28	-12.0	+0.15

*Origin at intersection of jet center line with original surface of bed material.

Table 30.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 1.02-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 12

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-1.65	0.0	-1.68	0.0	-1.54	0.0	-2.79
	+2.0	-1.87	+2.0	-1.47	+2.0	-1.54	+1.0	-2.66
	+4.0	-1.34	+4.0	-1.40	+4.0	-1.41	+2.0	-2.22
	+6.0	-0.65	+6.0	-0.84	+5.0	-1.10	+3.0	-2.07
	+8.0	0.00	+8.2	0.00	+6.0	-0.79	+4.0	-1.85
	-2.0	-1.40	-2.0	-2.03	+7.5	0.00	+6.0	-1.10
	-4.0	-1.28	-4.0	-1.72	-2.0	-0.91	+8.0	0.00
	-6.0	-0.53	-6.0	-1.09	-4.0	-0.66	-1.0	-2.60
	-7.5	0.00	-7.0	-0.15	-5.5	-0.85	-2.0	-2.47
			-9.0	0.00	-7.5	-0.10	-3.0	-2.29
					-7.8	0.00	-4.0	-1.79
							-6.0	-0.85
							-8.0	+0.09
30	0.0	-2.03	0.0	-1.84	0.0	-1.35	0.0	-3.16
	+2.0	-2.03	+2.0	-1.18	+2.0	-1.50	+1.0	-3.00
	+4.0	-1.47	+4.0	-1.34	+3.0	-1.66	+2.0	-2.72
	+6.0	-1.09	+6.0	-1.09	+4.0	-1.54	+3.0	-2.54
	+8.0	-0.37	+7.0	-0.84	+5.0	-1.22	+4.0	-2.10
	+12.0	0.00	+8.0	-0.34	+6.0	-0.79	+6.0	-1.54
	-2.0	-1.72	+9.5	0.00	+8.0	0.00	+8.0	-0.60
	-4.0	-1.47	-1.0	-1.84	-2.0	-1.47	+10.0	+1.00
	-6.0	-0.78	-2.0	-2.03	-4.0	-1.54	-1.0	-3.07
	-7.0	-0.47	-3.0	-1.78	-5.0	-1.29	-2.0	-2.72
	-8.0	0.00	-4.0	-1.40	-6.0	-0.91	-3.0	-2.66
			-6.0	-0.39	-8.0	0.00	-4.0	-2.22
			-7.6	-0.00			-6.0	-1.29
							-8.0	-0.22
							-10.1	+1.09

*Origin at intersection of jet center line with original surface of bed material.

Table 30.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 1.02-SQ.IN. SOLID JET IN GRAVEL NO. 2--Continued

Series 12

Duration of test t min	Depth of stilling pool b in inches							
	2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
60	0.0	-2.15	0.0	-1.47	0.0	-1.91	0.0	-2.79
	+2.0	-2.40	+2.0	-1.59	+2.0	-1.47	+1.0	-2.60
	+4.0	-1.84	+3.0	-1.84	+4.0	-1.41	+2.0	-2.54
	+6.0	-1.22	+4.0	-1.72	+6.0	-0.91	+4.0	-2.22
	+8.0	-0.84	+6.0	-1.34	+8.2	0.00	+5.0	-2.10
	+10.0	-0.34	+8.0	-0.34	-2.0	-2.29	+6.0	-1.91
	+13.0	0.00	+9.0	0.00	-3.0	-2.33	+8.0	-0.72
	-2.0	-2.15	-1.0	-1.22	-4.0	-1.85	+9.2	0.00
	-3.5	-2.22	-3.0	-1.72	-6.0	-0.85	-1.0	-3.00
	-6.0	-1.09	-6.0	-1.03	-8.2	0.00	-2.0	-3.00
	-8.0	-0.15	-8.0	-0.53			-4.0	-2.47
	-8.5	0.00	-9.8	0.00			-5.0	-2.04
							-6.0	-1.60
							-8.0	-0.35
							-8.9	0.00

*Origin at intersection of jet center line with original surface of bed material.

Table 31.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 1.02-SQ.IN. SOLID JET IN GRAVEL NO. 2

Series 13

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
3.75							0.0	-4.47
							+1.0	-4.00
							+2.0	-3.60
							+3.0	-3.16
							+4.0	-2.16
							+6.0	-1.47
							+8.0	-0.66
							+10.0	+0.09
							-1.0	-3.91
							-2.0	-3.60
							-3.0	-3.16
							-4.0	-2.54
							-6.0	-1.47
							-8.0	-0.66
							-10.0	+0.09
7.5							0.0	-4.22
							+1.0	-4.00
							+2.0	-3.54
							+3.0	-3.10
							+4.0	-2.35
							+6.0	-1.41
							+8.0	-0.85
							+10.0	-0.16
							+12.0	+0.71
							-1.0	-4.16
							-2.0	-3.72
							-3.0	-3.16
							-4.0	-2.72
							-6.0	-1.60
							-8.0	-0.72
							-10.0	0.00

*Origin at intersection of jet center line with original surface of bed material.

Table 31.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 1.02-SQ.IN. SOLID JET IN GRAVEL NO. 2--Continued

Series 13

Duration of test t min	Depth of stilling pool b in inches							
	2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
15	0.0	-3.53	0.0	-4.29	0.0	-4.79	0.0	-4.66
	+2.0	-3.22	+1.0	-4.22	+1.0	-4.72	+1.0	-4.22
	+4.0	-2.84	+2.0	-3.79	+2.0	-4.29	+2.0	-4.04
	+6.0	-2.00	+3.0	-3.41	+4.0	-3.60	+3.0	-3.54
	+7.0	-1.53	+4.0	-3.72	+6.0	-2.60	+4.0	-2.85
	+8.0	-1.22	+6.0	-2.29	+8.0	-2.16	+6.0	-1.72
	+9.0	-1.55	+8.0	-1.35	+10.0	-1.10	+8.0	-0.97
	+10.0	-0.78	+10.1	0.00	+11.5	-0.72	+10.0	-0.22
	+12.0	-0.75	-1.0	-4.29	+13.7	0.00	+12.0	+0.34
	+14.0	-0.53	-2.0	-3.91	-1.0	-4.66	-1.0	-4.66
	+16.0	0.00	-3.0	-3.79	-2.0	-4.77	-2.0	-4.04
	-2.0	-3.15	-4.0	-3.35	-4.0	-3.66	-3.0	-3.67
	-4.0	-2.53	-6.0	-2.35	-6.0	-2.47	-4.0	-3.04
	-6.0	-1.53	-8.0	-1.72	-8.0	-1.66	-6.0	-1.85
	-8.0	-0.40	-10.0	-0.79	-10.0	-0.66	-8.0	-1.04
	-8.9	0.00	-12.0	-0.29	-12.0	-0.16	-10.0	-0.16
			-13.0	-0.10	-14.0	+0.15	-12.0	+0.65
			-14.0	+0.34				
30	0.0	-4.15	0.0	-4.91	0.0	-4.91	0.0	-5.34
	+2.0	-3.90	+1.0	-4.72	+1.0	-4.79	+1.0	-4.78
	+4.0	-3.47	+2.0	-4.35	+2.0	-4.54	+2.0	-4.40
	+6.0	-2.59	+3.0	-4.04	+4.0	-3.47	+4.0	-3.22
	+8.0	-1.84	+4.0	-3.66	+6.0	-2.54	+6.0	-1.97
	+10.0	-1.15	+6.0	-2.54	+8.0	-1.69	+7.0	-1.40
	+12.0	-0.65	+8.0	-1.54	+10.0	-0.97	+8.0	-1.37
	+15.4	0.00	+10.5	0.00	+12.0	-0.41	+10.0	-0.84
	-2.0	-3.78	-1.0	-4.66	+13.5	0.00	+12.0	0.00
	-4.0	-3.22	-2.0	-4.35	-1.0	-4.66	-1.0	-4.97
	-6.0	-2.03	-3.0	-4.16	-2.0	-4.41	-2.0	-4.28
	-8.0	-0.97	-4.0	-3.72	-4.0	-3.79	-4.0	-3.15
	-10.0	0.00	-6.0	-2.79	-6.0	-2.91	-7.0	-1.47

*Origin at intersection of jet center line with original surface of bed material.

Table 31.--EXPERIMENTAL DATA OF SCOUR CAUSED BY 1.02-SQ.IN. SOLID JET IN GRAVEL NO. 2--Continued

Series 13

Duration of test t min	Depth of stilling pool b in inches: 2		4		8		16	
	Co-ordinates of scour hole*							
	x in.	y in.	x in.	y in.	x in.	y in.	x in.	y in.
			-8.0	-1.91	-8.0	-2.16	-8.0	-1.15
			-9.0	-1.47	-10.0	-1.29	-10.0	-0.53
			-10.0	-1.41	-12.0	-0.54	-11.0	0.00
			-12.0	-0.97	-14.4	0.00		
			-14.0	-0.54				
			-15.4	0.00				
60	0.0	-4.90	0.0	-5.41	0.0	-5.60		
	+2.0	-4.47	+1.0	-5.16	+1.0	-5.35		
	+4.0	-3.72	+2.0	-4.72	+2.0	-4.97		
	+6.0	-2.90	+3.0	-4.29	+3.0	-4.66		
	+8.0	-2.22	+4.0	-3.91	+4.0	-4.10		
	+10.0	-1.53	+6.0	-3.22	+6.0	-3.10		
	+11.0	-1.40	+7.0	-2.85	+8.0	-2.72		
	+12.0	-1.22	+8.0	-2.66	+10.0	-1.82		
	+14.0	-0.47	+10.0	-2.07	+12.0	-0.97		
	+15.1	0.00	+12.0	-1.72	+14.0	-0.60		
	-2.0	-4.34	+14.0	-0.72	+15.7	0.00		
	-4.0	-3.47	+15.5	0.00	-1.0	-5.29		
	-6.0	-2.47	-1.0	-4.10	-2.0	-4.85		
	-10.0	-0.40	-2.0	-4.72	-3.0	-4.41		
	-11.0	0.00	-3.0	-4.22	-4.0	-3.72		
			-4.0	-3.60	-6.0	-2.72		
			-6.0	-2.60	-8.0	-1.85		
			-8.0	-1.35	-10.0	-0.91		
			-10.0	0.00	-12.0	-0.60		
					-13.7	0.00		

*Origin at intersection of jet center line with original surface of bed material.

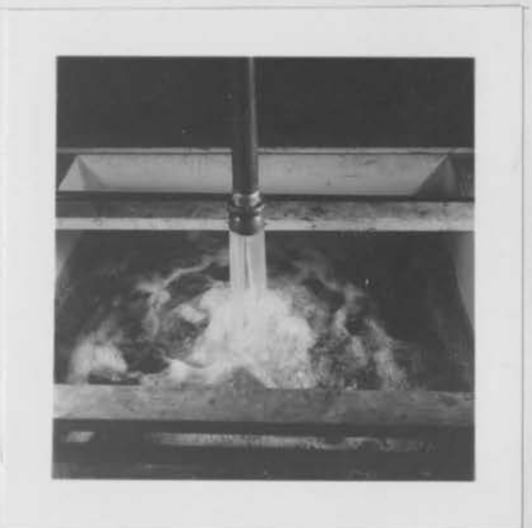
Appendix D.--Figures 16-19

LIST OF FIGURES

b = 2 IN.

b = 4 IN.

b = 8 IN.



b = 16 IN.

Fig. 16--Photographs showing the turbulent action increasing with increasing depth of stilling pool with 2.06-sq.in. hollow jet
Gravel No. 1 V = 9.93 Q = 0.1420

b = 2 IN.

b = 4 IN.

b = 8 IN.

b = 16 IN.

Fig. 17--Photographs showing the turbulent action increasing with increasing depth of stilling pool with 0.90-sq.in. hollow jet
Gravel No. 2 V = 41.40 Q = 0.2581

b = 8 IN.

b = 16 IN.

Fig. 18--Photographs showing the turbulent action increasing with increasing depth of stilling pool with 0.09-sq.in. hollow jet
Gravel No. 1 V = 41.40 Q = 0.2581

b= 2 IN.

b= 4 IN.

b= 8 IN.

b = 16 IN.

Fig. 19--Photographs showing the turbulent action increasing with increasing depth of stilling pool with 1.02-sq.in. solid jet
Gravel No. 2 V = 36.42 Q = 0.2581

Appendix E.--Figures 20-21

LIST OF FIGURES

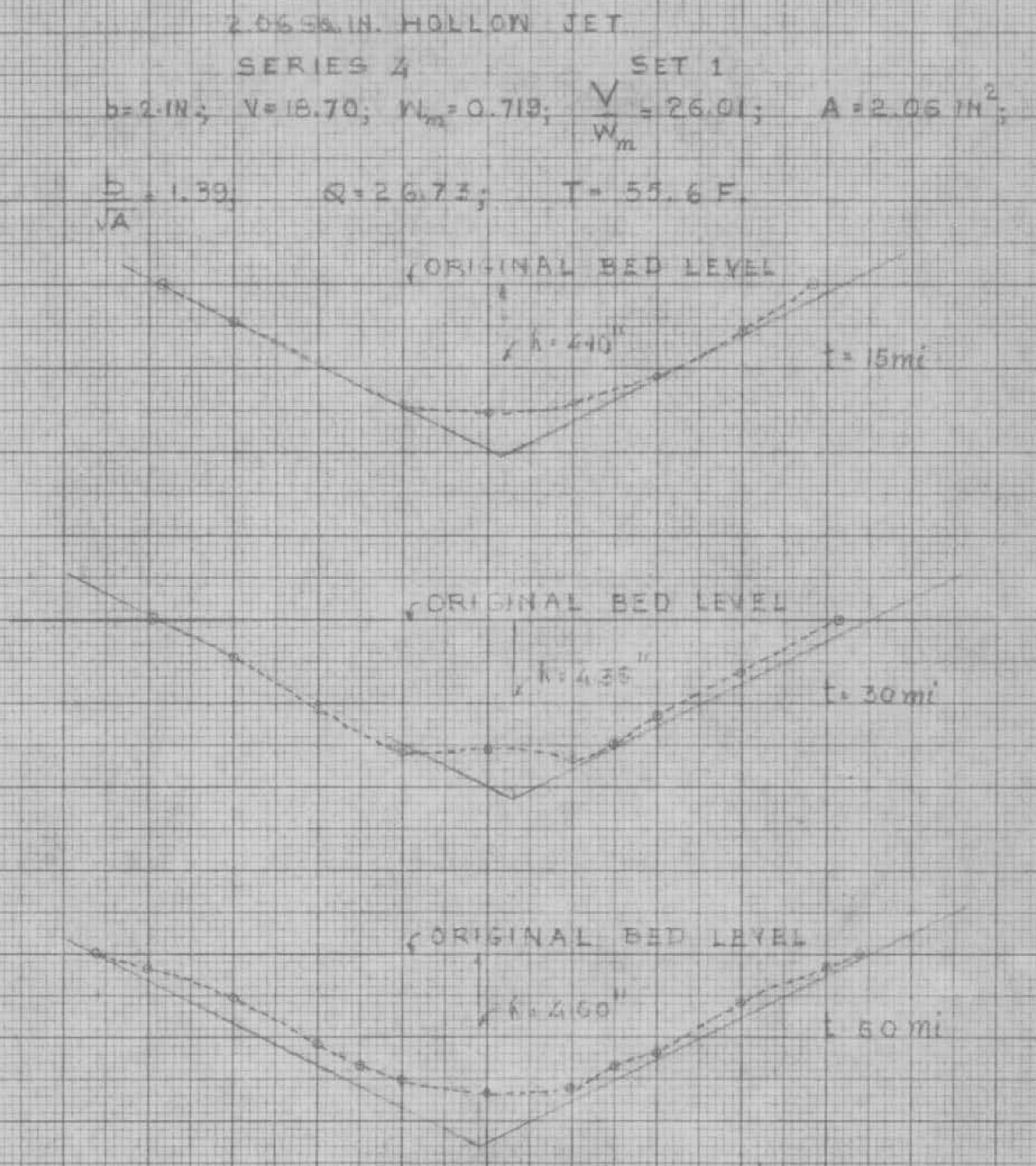


FIG. 20 TYPICAL CROSS SECTIONS OF SCOUR PATTERN WITH 2.06 SQ. IN. HOLLOW JET

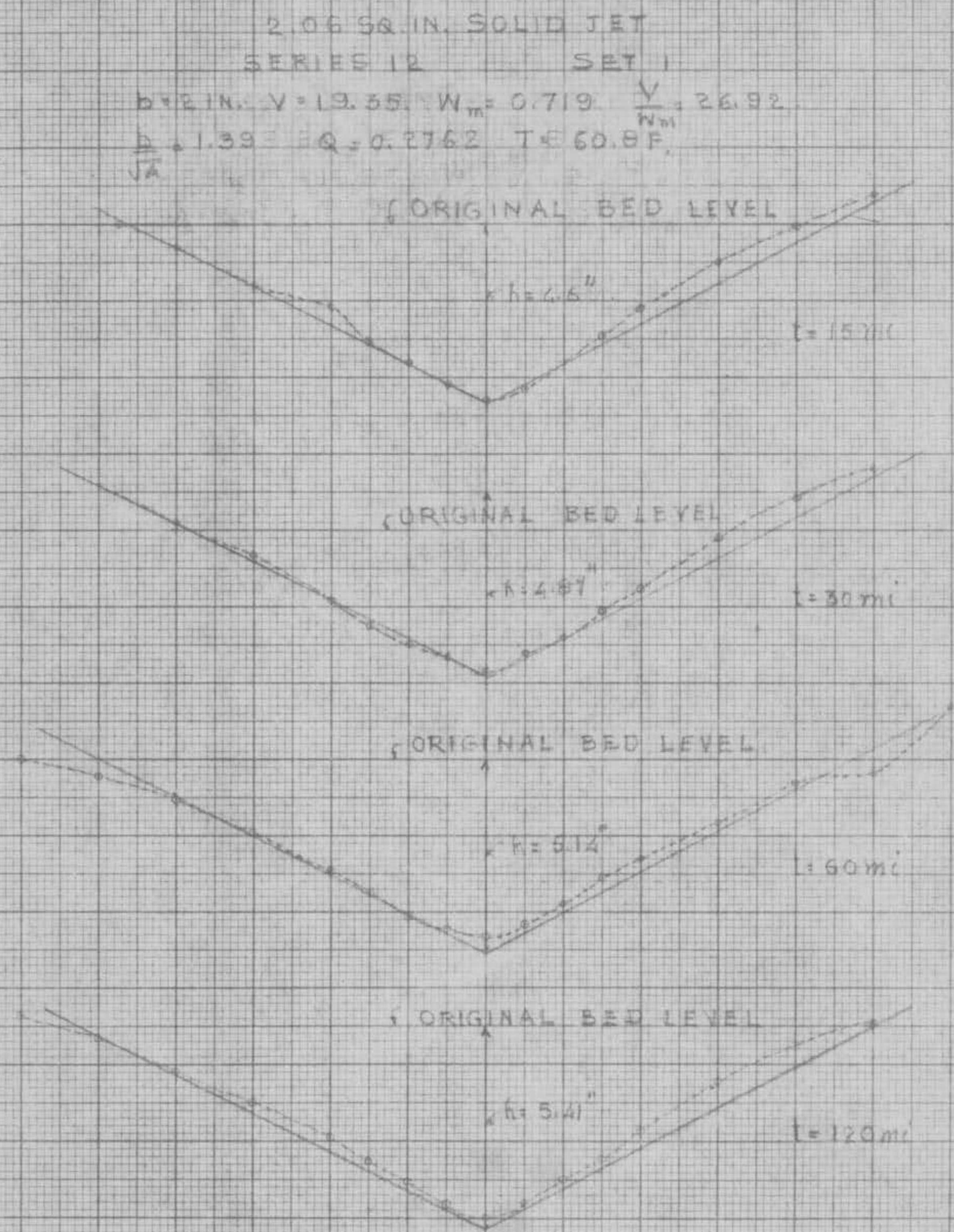


FIG. 21 TYPICAL CROSS SECTIONS OF SCOUR PATTERN WITH 2.06 SQ. IN SOLID JET.

Appendix F--Notation

NOTATION

A -- area of jet

a -- longest axis of a sediment particle

b -- depth of water over the levelled bed of sediment

b_1 -- intermediate axis of a sediment particle

c -- shortest axis of a sediment particle

f -- shape factor for jet

H -- height of the exit of the exit above the bed of sediment

h -- depth of scour

L -- length of pool

t -- duration of scouring action in minutes

V -- velocity

w -- fall-velocity of sediment

w_m -- geometric mean fall-velocity

θ -- angle of inclination of the tangent to the center line of the jet with the horizontal at the point where it strikes the original plane of the bed of sediment

ρ -- mass density of water

ρ_s -- mass density of sediment

ϕ -- function of

σ_w -- standard geometric deviation of w-frequency

ν -- kinematic viscosity of water

B I B L I O G R A P H Y

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