THE MANIFOLD STILLING BASIN

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Engineers are frequently confronted with the problem of dissipating the kinetic energy in water flowing at a great velocity. Certain standard design procedures for structures have been developed for this purpose but there is nearly always some aspect of the design, construction, or operation of the structure with which the engineer is not entirely satisfied. In this paper is presented the manifold stilling basin as a device for dissipating excess kinetic energy. This device has certain important advantages for some conditions. Two successful field installations of the manifold stilling basin have already been made. Both installations were made at the outlet ends of pipe drops in canals where the vertical drop of the water surface was several tens of feet.

Introduction

The dissipation of kinetic energy in hydraulic structures can take place either in the horizontal direction or in the vertical direction, or in a combination of both horizontal and vertical directions. Albertson and Smith (1) have analyzed this breakdown in some detail as illustrated in Fig. 1. From this figure it is evident that energy is dissipated in the:

1. Horizontal direction by
    a. Shear drag,
    b. Pressure drag,
    c. Increase in piezometric head.
2. Vertical direction by
    a. Diffusion of jets vertically downward, and
    b. Diffusion of jets vertically upward.

In this paper, consideration is given only to the dissipation of kinetic energy in the vertically-upward direction by means of a manifold type of structure, which is illustrated schematically in Fig. 1d. As discussed

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later in some detail, the use of a jet issuing vertically upward into the overhead tailwater has two important advantages:

1. The jet entrains a part of the surrounding fluid, and in so doing it distributes its energy throughout a greater mass. Furthermore, much of the kinetic energy is converted into heat from the resulting shear, either directly, or indirectly by the creation of relatively fine-grain turbulence.

2. The kinetic energy which remains in the diffused jet as it reaches the surface of the tailwater causes the jet to rise in a boil above the tailwater. The boil then spreads radially, causing a rapid reduction and dispersion of kinetic energy.

This type of device, see Fig. 1d and Fig. 2, was originally suggested by the second author and a laboratory model study was made to determine its effectiveness. Two field installations were later found to be so effective and economical it was decided to conduct a generalized laboratory investigation to obtain design data. Fiala (2) conducted the investigation and his data are reported in this paper. The design of the manifold stilling basin is based upon the manifold principle and the principles of diffusion of submerged jets.

Manifold Applications

Studies of various applications of manifold flow have been conducted by investigators since the early 1900's. A comprehensive study of gas-burner manifolds was conducted by Keller (4). The results of his study are of particular importance to this paper because he found that, for rectangular manifolds having a constant width, the contour of the bottom can be assumed to be linear for values of $L/\sqrt{A} \leq 10$, in which L is the length of the manifold, and A is the cross-sectional area of the manifold at the inlet end, see Fig. 2.

A series of investigations by McNown (5) and others at the Iowa Institute of Hydraulic Research has shown that certain aspects of the theoretical analysis of manifold flow are not sufficiently accurate for practical use except in a few instances.

Manifold flow in sprinkling systems for irrigation was summarized by Christianson (6) in 1942.

Considerable research has been conducted on various aspects of the flow in lock manifolds. As a result of experiments at the Panama Canal Laboratory in 1939 and 1940, Soucek and Zelnick (7) concluded that the design of a lock manifold is an indirect process so that the design must be assumed, analyzed, and then modified until the desired hydraulic behavior is obtained.

Studies conducted for lock emptying and filling systems by the United States Army Corps of Engineers (8) (9) are primarily for manifolds which operate under unusual circumstances. There is only limited application of these studies to manifold problems of a general nature.

Basic Requirements for a Manifold Design

The basic requirements for a manifold designed as an energy dissipator are:

1. The velocity and discharge per foot of length from the manifold must be the same at all points along the length of the manifold in order to have a uniform distribution of energy and momentum flux upward.

2. The shape, dimensions, and other design features must be practical, both for economic reasons and in order that the design can be fitted to the problem of construction in the field.

For the generalized laboratory investigation reported herein, consideration was given to various types of manifolds to find one which would best meet the basic requirements. The manifold design selected for this study had a rectangular cross section, a constant width, a linearly-varying height, and an $L/\sqrt{A}$ - ratio of 8. This design is basically the same as one of those discussed by Keller (4) and is similar to the successful prototype stilling basins previously mentioned.

With this manifold design, uniform efflux velocity and discharge can be obtained along the length of the manifold. The linear shape results in economical construction and the dimensions are practical for field installations.

Once the basic features of the design are decided, the variables influencing operation of the design can be grouped and treated by theoretical analysis and dimensional analysis to aid in the laboratory investigation.

Theoretical Shape of Manifold

The theoretical analysis for the simple manifold with uniform discharge conditions employs the energy equation

$$\frac{v^2}{2g} + \frac{p}{\gamma} + z = \text{constant} \qquad (1)$$

and the continuity equation

$$Q = AV \qquad (2)$$

in which

Q is the discharge across the section in the manifold where
A is the cross-sectional area,
V is the mean velocity across the section,
P is the pressure,
z is the elevation,
g is the acceleration of gravity,
γ is the specific weight of the water, and
v is the velocity at a point in the manifold.

The conditions which are imposed for manifold operation with a constant velocity and uniform discharge issuing along the manifold are:

1. Constant internal pressure to cause the constant efflux velocity along the length of the manifold.

2. A discharge of Q_o, entering the manifold at the upstream end, which is reduced linearly to a discharge of zero at the downstream end of the manifold.

Since the variation of elevation z in Eq 1 is relatively small compared with the magnitude of $v^2/2g$ and p/γ, it can be dropped from consideration. Therefore, with p/γ a constant, Eq 1 reduces to

$$v = \text{constant} \tag{3}$$

The discharge issuing from the manifold must be uniform along its length. Therefore, the discharge inside the manifold must vary linearly throughout the length of the manifold. Consequently,

$$Q = KS \tag{4}$$

in which S is the distance from the downstream end of the manifold. When $S = L$, $Q = Q_o$. Hence, Eq 4 becomes

$$\frac{Q}{Q_o} = \frac{S}{L} \tag{5}$$

in which L is the length of the manifold. By substituting Q from Eq 5, and h_1B for A in Eq 2; and by considering $V = Q_o/A_o = Q_o/HB$, Eq 2 becomes

$$Q_o \frac{S}{L} = h_1 B \frac{Q_o}{HB}$$

or

$$\frac{h_1}{H} = \frac{S}{L} \tag{6}$$

in which

h_1 is the height of the manifold at any point,
B is the width of the manifold, and
H is the height of the manifold at the entrance.

Eq 6 shows clearly that the shape of the manifold is composed of straight lines, since the height of the manifold varies directly with the distance from the downstream end, and that the shape is independent of flow and fluid properties if boundary resistance is assumed to be negligible.

Dimensional Analysis

Treatment of this problem of flow into and from a manifold by dimensional analysis is made in order to determine the dimensionless parameters which influence the phenomenon. The laboratory study of the problem can then be planned to determine the actual relationship of these parameters.

A definition sketch is shown in Fig. 2. The variables involved in the problem can be classified into three categories:

1. Variables describing the geometry of the manifold and flow system:

   L Length of manifold
   B Width of manifold
   H Height of manifold at entrance
   h_1 Height of manifold at a point
   w Width of opening
   s Size of cross bar
   b Tailwater depth
   x Distance along the jet
   λ Shape of cross bar

2. Variables describing the flow:

   v_o Mean velocity at entrance to manifold
   v_1 Initial velocity of jet issuing from manifold
   v Velocity at a point in the manifold
   v_{max} Centerline velocity in jet at point x
   p_o Pressure at entrance to manifold
   p Pressure at a point in the manifold
   a Boil height
   h Wave height
   B_o Effective initial width of jet issuing from manifold

3. Variables describing the fluid:

$\Delta\gamma$ Difference in specific weight across the air-water interface
μ Dynamic viscosity of water
ρ Density of water

Of the foregoing variables, v_1, p, p_o, a, h_1, v, v_{max}, and B_o can be considered as dependent while the others are independent. By selecting v_1 as the only dependent variable for the moment, and omitting the other dependent variables, application of the Pi-theorem gives

$$\frac{v_1}{v_o} = f_1\left(\frac{L}{B}, \frac{H}{B}, \frac{w}{B}, \frac{s}{B}, \lambda, \frac{b}{B}, \frac{v_o}{\sqrt{B\Delta\gamma/\rho}}, \frac{v_o B}{\mu/\rho}\right), \qquad (8)$$

in which B, v_o, and ρ are used as repeating variables.

For simplicity in equipment and experimentation, the parameters L/B and H/B can be selected to remain constant during the experiments, and therefore they can be deleted. Furthermore, the length ratios can be rearranged as w/s, b/B, and b/s; and b/B_o can be substituted for b/B and b/s can then be changed to B_o/w. Finally, the Froude number Fr can be substituted for $v_o/\sqrt{b\Delta\gamma/\rho}$ and Reynolds number Re for $v_oB/(\mu/\rho)$ to give

$$\frac{v_1}{v_o} = f_2\left(\frac{w}{s}, \frac{b}{B_o}, \frac{B_o}{w}, \lambda, Fr, Re\right) \qquad (9)$$

In a similar manner, the dimensionless parameters representing the remaining dependent variables are found to be $\Delta p/\rho v_o^2$ and $p_o/\rho v_o^2$; and the boil height a and wave height h (which are ultimately two of the principle criteria for design) can be related to the velocity head $v_1^2/2g$ to give $\dfrac{a}{v_1^2/2g}$ and $\dfrac{h}{v_1^2/2g}$. Each of these dependent parameters is equal to some function of the same independent parameters, as follows.

$$\frac{\Delta p}{\rho v_o^2} = f_3\left(\frac{w}{s}, \frac{b}{B_o}, \frac{B_o}{w}, \lambda, Fr, Re\right) \qquad (10)$$

$$\frac{p_o}{\rho v_o^2} = f_4\left(\frac{w}{s}, \frac{b}{B_o}, \frac{B_o}{w}, \lambda, Fr, Re\right) \qquad (11)$$

$$\frac{a}{v_1^2/2g} = f_5\left(\frac{w}{s}, \frac{b}{B_o}, \frac{B_o}{w}, \lambda, Fr, Re\right) \tag{12}$$

$$\frac{h}{v_1^2/2g} = f_6\left(\frac{w}{s}, \frac{b}{B_o}, \frac{B_o}{w}, \lambda, Fr, Re\right) \tag{13}$$

In one phase of the preliminary testing, a study of $\frac{\Delta p}{\rho v_1^2/2}$ (in which $\Delta p = p - p_o$) was made to ascertain the effect of gravity (as represented by the Froude number) and viscosity (Reynolds number). This pressure parameter is likewise a function of the same variables. When Fr and Re were varied, for given conditions of manifold geometry and tailwater depth over the range in which the experiments were conducted, the variation in the relative pressure change $\Delta p/\rho v_o^2$ was negligible except at low tailwater depths. Therefore, it was concluded that the effect of gravity (Fr) and viscosity (Re) was of secondary importance.

The relative thickness of the jet B_o/w (which is a form of contraction coefficient) was assumed to be constant for a given geometry and λ so that

$$\frac{a}{v_1^2/2g} = f_7\left(\frac{w}{s}, \frac{b}{B_o}\right) \tag{14}$$

A similar analysis can be made for $\frac{h}{v_1^2/2g}$ to yield

$$\frac{h}{v_1^2/2g} = f_8\left(\frac{w}{s}, \frac{b}{B_o}\right) \tag{15}$$

Eqs 14 and 15 were used to study the variation of relative boil height and relative wave height with respect to the geometry of the manifold and the tailwater depth.

Application of Submerged-Jet Relationships

Submerged jets are an integral part of energy dissipation in a vertical direction. The characteristics of the mean flow pattern of a single jet submerged in an infinite body of its own fluid were determined analytically and experimentally by Albertson and others (3) in 1950. Their experimental data provide the necessary empirical coefficients for flow from both slots and orifices. Fig. 3 is a plot of their experimental data for the centerline velocity of the jet flowing from a slot. Plots of the equations and data for the volume-flux ratio, the energy-flux ratio, and the momentum-flux ratio are shown in Fig. 4.

Dissipation of kinetic energy by a manifold stilling basin is brought about by diffusion of the jets of water issuing from the manifold into the tailwater above the manifold. Energy must be dissipated by the stilling basin so that a minimum amount of protection will be required on the bank and bed of the channel downstream. Therefore, the remaining energy of the flow (it is neither necessary nor practical to attempt to dissipate all of the kinetic energy) must be described in some physical manner so that eventually it can in turn be related to the resulting erosion.

Relationship between kinetic energy, boil height, wave height, and erosion: With a manifold stilling basin, erosion of the channel banks (neglecting the bed for this study) is primarily a function of wave height h. This is because the initial direction of flow (the jets) is vertically upward and at some distance from the banks. Through internal shear the velocity is reduced before flow begins outward at the surface of the tailwater. As the flow spreads outward over a relatively large area, the velocity is further reduced and no high-velocity flow is directed against the banks to cause erosion.

The wave height h at the boundary is a function of the boil height a, where the boil height is defined as the difference in height between the water surface over the jet opening and the mean tailwater surface.

Expression for boil height: An expression for boil height a can be derived in terms of the initial jet velocity v_1, the tailwater depth b, and the effective width of jet B_o, see Fig. 5. A relationship between wave height h, and boil height a can then be determined experimentally -- with the wave height being considered as a qualitative indication of the residual kinetic energy in the manifold stilling basin.

The following assumptions are necessary in deriving the expression for boil height:

1. The jet is diffused according to the theory developed by Albertson and others (3).

2. The velocity of the jet v_{max} at elevation b above the manifold causes a boil at the water surface which has a height a equal to the remaining velocity head of the jet $(v_{max})^2 / 2g$.

The second assumption can be expressed as

$$a = \frac{(v_{max})^2}{2g} \quad , \tag{16}$$

and the boil height a and the initial velocity head of the jet $v_1^2 / 2g$ as a ratio

$$\frac{a}{v_1^2 / g} = \frac{(v_{max})^2 / 2g}{v_1^2 / 2g} \tag{17}$$

Eq 17 can be combined with the equation developed by Albertson and others (3) which expresses the relationship between the velocity of the jet v_{max} (at a distance x from the slot of width B_o) in terms of the initial velocity of the jet v_1.

$$v_{max} = \frac{2.28\,v_1}{\sqrt{x/B_o}} \quad , \tag{18}$$

to yield

$$\frac{a}{v_1^{\,2}\,/\,2g} = \frac{\left(\dfrac{2.28\,v_1}{\sqrt{x/B_o}}\right)^2 \Big/ 2g}{v_1^{\,2}\,/\,2g} \tag{19}$$

Since $x = b$, this equation can be reduced to

$$\frac{a}{v_1^{\,2}\,/\,2g} = \frac{5.2}{b/B_o} \tag{20}$$

Eq 20 is of little value in this form, however, since the fundamental theory and investigations leading to Eq 18 were developed for a single jet of infinite length discharging into a medium of infinite extent; whereas in this study the tailwater surface confines the flow and adjacent jets interfere with each other. The coefficient 5.2 in Eq 20 will be shown not to have direct application to multiple adjacent jets.

Use of Single Jet Theory: In the case of a manifold having numerous jets issuing from it with certain boundary conditions imposed, the quantity of fluid surrounding the jet is limited, and the following can be expected to occur:

1. There will be mutual interference between patterns of jet diffusion.

2. The quantity of flow which can be entrained by the jet will be restricted by the boundary conditions.

Both of these factors will result in less efficient diffusion of the jet, which in turn will result in a greater magnitude of v_{max} and consequently a greater boil height for a given set of conditions. Therefore, an expression similar to Eq 20 can be written for a manifold with numerous jets and corresponding boundary conditions.

$$\frac{a}{v_1^{\,2}\,/\,2g} = \frac{C}{b/B_o} \tag{21}$$

Since the coefficient C reflects the residual kinetic energy, it can be expected to be larger than 5.2.

Limiting Conditions: Two limiting sets of conditions can be foreseen in which the manifold theory with numerous jets will approach the single jet theory. These are:

1. When the tailwater b is low, or the w/s-values are very small, very little interference will be expected between jet diffusion patterns and, consequently, data obtained under these conditions will approach the horizontal line at unity in Fig. 3.

2. At high tailwater and/or large values of w/s, the manifold behavior will approach single-jet conditions. In this case, however, the manifold will behave as one large jet rotated 90 degrees in the horizontal plane with the cross bar elements serving primarily as vanes to guide the flow in a vertical direction rather than creating a series of individual jets.

An expression is now derived for the limiting case of a manifold acting as a single large jet. The necessary assumptions for this development are:

1. A constant incoming flow Q.

2. The momentum flux m per unit area is the same whether the flow is coming through n_1 number of slots of B_{o_1} width, or through n_2 slots of B_{o_2} width.

Under these conditions $m_1 = m_2$

or $$\rho\, n_1 B_{o_1} v_1^2 = \rho\, n_2 B_{o_2} v_2^2 \qquad (22)$$

and solving for v_2

$$v_2 = \sqrt{\frac{n_1}{n_2}} \sqrt{\frac{B_{o_1}}{B_{o_2}}} \quad v_1 . \qquad (23)$$

If $B_{o_2} = 1$ ft and $n_2 = 1$ (representing an opening of one square foot)

$$v_2 = \sqrt{n_1 B_{o_1}} \quad v_1 . \qquad (24)$$

Now $v_{max} = v_2$ can be substituted in Eq 17 for b/B_o-values up to approximately 5.2 -- or, where $B_o = 1$ ft, to tailwater depths of approximately 5.2 ft -- to yield

$$\frac{a}{v_1^2 / 2g} = \frac{\dfrac{(\sqrt{n_1 B_{o_1}} \; v_1)^2}{2g}}{v_1^2 / 2g} \qquad (25)$$

or

$$\frac{a}{v_1^2 / 2g} = n_1 B_{o_1} \quad . \tag{26}$$

This expression for the single large jet is a horizontal line when located on a plot similar to Fig. 3, and is approached asymptotically by the curves for the manifold data for intermediate values of w/s and tailwater depth b .

The foregoing theory was tested and many of the desired relationships were obtained as a result of the laboratory investigation.

Experimental Equipment & Procedure

In accordance with the foregoing analysis of the problem, a generalized model study of a manifold stilling basin was conducted in the Hydraulics Laboratory of Colorado State University, Fort Collins, Colorado. The objectives of the experiments were:

1. To evaluate energy dissipation in a model manifold stilling basin in terms of boil height a and wave height h , at the boundary; and

2. To determine the validity of the general form of Eq 21 and values of the coefficient C when this equation is applied to a manifold under a given set of conditions.

Fig. 6 shows the general layout of the experimental equipment. The model of the manifold proper was constructed with a length of 8 ft, a width of 1 ft, and a depth of 1 ft at the inlet end. Along the manifold the width remained constant but the depth decreased linearly to zero at the downstream end. Initially, flow was brought horizontally into the manifold through a round-to-square transition. This method gave a non-uniform velocity distribution, however, and was abandoned in favor of a 1-ft square inlet section 8 ft long and installed on the same slope as the bottom of the manifold -- see Fig. 7 where arrow indicates direction of flow in square inlet section. With this shape of inlet section the velocity distribution into the manifold was considered satisfactory and flow from the manifold was also reasonably uniform, see Fig. 8.

Square cross bars 1, 2, and 4 in. across, and round cross bars of 2-in. diameter, were used in studying the effect of cross-bar size, shape, and spacing. Boundary conditions consisted of a simulated channel with sides installed on a 2:1 slope and a vertical bulkhead at the upstream end of the manifold.

The equipment and facilities used had the following limitations:

1. The model of the manifold had a fixed length, cross section, and bottom slope.

2. A maximum discharge of 3.5 cfs from the supply pump.

3. A maximum tailwater depth of 1.5 ft due to the depth of the box containing the model.

4. Difficulty in making precise measurements of:

    a. The average elevation of a rough water surface, and

    b. The average wave height at the given boundary wall.

During each experimental run measurements were made of the mean water-surface elevation (or tailwater elevation), velocity head of the jet, height of boil, height of waves, and pressure within the manifold.

The conditions under which this experiment was conducted were:

1. At a discharge of 3 cfs, the cross-bar size, shape, and spacing were varied for several values of tailwater elevation.

2. For several values of discharge, the tailwater elevation was held constant and the cross-bar size, shape, and spacing were varied.

The single discharge was used because preliminary experimentation had shown the ratio v_1/v_o to be constant for all values of discharge, if the geometry of the manifold and the height of the tailwater were held constant. Further experimentation, however, showed this ratio to vary somewhat under certain conditions. Consequently, for some conditions v_1/v_o cannot be considered constant -- particularly at low tailwater elevations.

Discussion of Results

The results of systematic laboratory experiments on a model of a manifold stilling basin have been analyzed as follows:

1. Velocity profiles and pressure distributions.
2. Water surface profiles.
3. Analysis of dimensionless plots.

Velocity profiles and pressure distributions: The first step toward accomplishing these objectives was to obtain flow conditions from the manifold which were as nearly ideal as possible. As previously mentioned, the model was first constructed with a horizontal round-to-square transition immediately upstream from the manifold. This arrangement proved unsatisfactory, however, because both the velocity distribution and pressure distribution inside the manifold were not uniform. The velocity varied considerably in both the horizontal and vertical directions at the inlet end and also in a longitudinal direction along the manifold. Furthermore, the pressure along the inside of the manifold had a steady increase in the downstream direction. These non-uniform flow conditions appeared to be caused by the relatively short round-to-square transition and the angle which the entering flow made with the bottom of the manifold. Both these problems were treated by abandoning the round-to-square transition in favor of a longer, square inlet section installed on the same slope as the bottom of the manifold.

Fig. 8 shows the velocity and pressure distributions obtained with this square and sloping inlet section. The velocity and pressure distributions obtained are considered as nearly ideal as practical for this experiment.

Water surface profiles: Throughout the experiment, water surface profiles were taken longitudinally along the center-line of the manifold and transversally to the manifold one foot distance downstream from the headwall.

With the square cross bars in place, the longitudinal water surface profile above the manifold had the shape of a smooth curve with a descending gradient in the downstream direction along the manifold. The slope of the water surface tended to flatten as the depth of tailwater increased.

With the round cross bars in place, the water surface above the manifold reached a maximum near the downstream end of the manifold. Water appeared to flow around the round cross bars, instead of being turned upward in a vertical direction, and thus retained a considerable component of velocity in the downstream direction. The performance of the manifold when using round cross bars was considered to be unsatisfactory and further tests with the round cross bars were abandoned.

Fig. 9 shows two water-surface profiles taken transversally to the manifold for square cross bars. The profiles are shown in relation to the manifold and sloping sidewalls. Note that the boil is largely dissipated long before it reaches the banks. A secondary flow is set up by the shear of the jet. This flow carries the water from the dissipated boil to the banks where a reduction of velocity causes a slight rise in elevation of the water surface.

Analysis of dimensionless plots: Although a relatively large number of dimensionless plots were prepared during the analysis of the data, only those having a direct application to the problem of manifold stilling basin design are discussed here. In Fig. 10 the relationship of the velocity of flow at the entrance of the manifold v_o to the initial velocity of the jet v_1 is shown as a function of the parameters b/s, and w/s in which

b is the depth of the tailwater
s is the size of the manifold crossbars
w is the width of the spacing between the manifold crossbars.

From Fig. 10 the following observations are made:

1. At relatively high tailwater depths the v_1/v_o - data have a trend toward a vertical asymptote which is shown in the figure.

2. As b/s decreases to $b/s \approx 5$, v_1/v_o becomes smaller. This trend is caused by the marked decrease in tailwater depth along the manifold. The lower hydrostatic head at the downstream end of the manifold then results in a greater discharge from this end and a consequent reduction in flow (and velocity) from the upstream part of the manifold.

3. As the magnitude of w/s increases, v_1/v_o becomes smaller. This appears logical, since it would be expected that the initial jet velocity would become smaller as the width of opening becomes larger with respect to the size of the cross-bar.

4. The data which plot to the right of the asymptote for $w/s = 1.0$ are for small values of Q. This inconsistency is attributed to the difficulty in measuring an average velocity of the jet at the small discharges.

5. The function of this plot, in manifold design, is to aid in determining the initial jet velocity v_1, when the entrance velocity v_o, the tailwater depth b, and the geometry of the manifold are known.

Fig. 11 shows the relationship between boil height a, initial velocity of the jet v_1, tailwater depth b, and the average width of the jet B_o, for various w/s - values. This figure is similar to Fig. 3. It contains three essential elements:

1. The horizontal line at $\dfrac{a}{v_1^2/2g} = 1.$

2. The straight line portion on a 1 to 1 slope.

3. The horizontal lines near $\frac{a}{v_1^2 / 2g} = 0.1$.

The horizontal line near $\frac{a}{v_1^2 / 2g} = 1$ represents the limiting condition when the tailwater depth becomes sufficiently low that the boil height a is equal to the initial velocity head $v_1^2 / 2g$ of the jet. As the depth increases, the data drift away from the horizontal line toward lines of 1 to 1 slope because the centerline velocity of the jets is being reduced by diffusion of the jet into the deeper tailwater. According to the jet theory (3), this drift away occurs where the tailwater depth is equal to 5.2 times the effective initial jet width B_o.

The straight line portion of the curves on the 1 to 1 slope is significant in that it:

1. Proves the validity of Eq 21.

2. Establishes the coefficient C in Eq 21 for specific w/s - values.

3. Supports the theory of less efficient diffusion of jets due to mutual interference. It does this by the fact that these curves indicate a greater boil height, for a given set of conditions, than does the single jet theory.

4. Shows the data tend to drift toward a horizontal asymptote near $\frac{a}{v_1^2 / 2g} = 0.1$ for high values of tailwater depth.

The horizontal lines near $\frac{a}{v_1^2 / 2g} = 0.1$ show the limiting operating conditions of the manifold as it tends to function as a single large two-dimensional jet with its axis parallel to the manifold. When these operating conditions are reached, the effective width of the jet changes from a fraction of the width of opening w to the entire width B of the manifold and has a velocity v_2. The large single jet is oriented at 90 degrees in the horizontal plane with respect to the small jets.

In Fig. 12 the w/s ratio is plotted against the coefficient for Eq 21 (multiple-jet flow), as determined from Fig. 11. The equation coefficient 5.2 for the single-jet flow is also plotted against w/s-values for comparative purposes. From Fig. 12 the following observations are made:

1. As the w/s - ratio becomes either large, or small, the behavior of the manifold approaches the single-jet flow. The lower protions of the curve have been determined by judgement since no data are available. As the size s of the manifold crossbar becomes large with respect to the width of the opening w, the jets are separated a sufficient distance to have a negligible effect upon one another.

2. The upper portion of the curve has a definite trend toward the single-jet coefficient. It is possible to imagine, however, a condition where the w/s-ratio is so large that the jets are no longer turned upward in a vertical direction with the result being a poor flow condition.

3. The bulge in the central portion of the curve is caused by mutual interference between the jets of the manifold and occurs between the two regimes described in item 1. From Fig. 12 it appears that part of this experiment was conducted near the point of maximum interference between jets.

Fig. 13 is the same type plot as Fig. 11 -- the only difference being that the parameter $\frac{h}{v_1^2/2g}$ is plotted as the ordinate. In this parameter h is the height of the waves at the boundary, and the other terms are identical to those defined in the discussion of Fig. 11. The basic curves (straight lines) are located in the same relative positions as the curves in Fig. 11 for respective values of w/s. The data at the ends of the curves appear to be approaching horizontal asymptotes as the data did in Fig. 11. This is to be expected since a direct relationship exists between wave height and boil height.

A primary value of this plot is that the wave height h can be determined, providing the other terms are known. In this way the erosion which takes place for a given wave height can be determined from other data relating erosion to wave height.

The foregoing information can be used to design a manifold stilling basin as follows:

1. The quantity of flow Q and tailwater depth b must be known.

2. The flow condition at the entrance of the manifold is assumed to be uniform -- for computation of v_o.

3. The geometry of the manifold is assumed following the criterion $L/\sqrt{A} = 8$ and then checked by the criteria presented in this paper to be sure of proper hydraulic design based upon the magnitude of wave height h which can be considered tolerable. The designer may wish to make minor modifications in the design to obtain an economical and practical shape.

Example Problem

The following example illustrates the use of the design criteria presented in this paper. The problem is to design a manifold stilling basin for the outlet of a pipe drop so that the wave height (run-up) on the 2:1 side slopes of the channel downstream does not exceed 1.5 feet.

Known: Discharge $Q = 300$ cfs, diameter of pipe = 72 in., and minimum tailwater depth $b = 8$ ft.

Assumed:

1. Uniform distribution of velocity at the entrance of the manifold.

2. For the geometry of the manifold, assume entrance dimensions of 6 ft by 6 ft and $L/\sqrt{A} = 4$. Then $L = 4\sqrt{A} = 4\sqrt{36} = 24$ ft. Also assume, for ease in construction, that $w = 12$ in. and $s = 12$ in. which makes the number of slots $n = 12$ and $w/s = 1.0$.

Computation:

$$v_o = Q/A = \frac{300}{\pi 6^2 / 4} = 10.6 \text{ fps}$$

$$b/s = 8/1 = 8$$

From Fig. 10, $v_1 / v_o = 1.24$

$$v_1 = 1.24 \times 10.6 = 13.2 \text{ fps.}$$

The area A_1 and discharge Q_1 of a single jet is

$$A_1 = 6\ B_o \text{ and}$$

$$Q_1 = Q/n = 300/12 = 25 \text{ cfs}$$

Since $A_1 = Q_1 / v_1$, the effective width of jet is $B_o = 25/(6)(13.2) = 0.316$ ft.

Then $b/B_o = 8/0.316 = 25.3$.

From Fig. 11, $\dfrac{a}{v_1{}^2 / 2g} = 0.3$, so that

$$a = 0.3\ \frac{(13.2)^2}{64.4} = \underline{\underline{0.81 \text{ ft}}}$$

From Fig. 13, $\dfrac{h}{v_1{}^2 / 2g} = 0.42$, and

$$h = 0.42\ \frac{(13.2)^2}{64.4} = \underline{\underline{1.14 \text{ ft}}}$$

which is considerably less than the allowable run-up of 1.5 ft. Therefore, the minimum tailwater could be decreased (by raising the manifold or lowering the downstream control) or the jet velocity could be increased if cost would thereby be reduced.

Summary

1. In general, the dissipation of kinetic energy is caused by shear resistance, pressure resistance, and the turbulence associated with shear and pressure resistance.

2. In some cases, real economies can be effected by dissipating energy in the vertical direction instead of the horizontal direction.

3. The dissipation of energy in a jet issuing vertically upward has two important advantages:

   a. The jet entrains a part of the surrounding fluid and in so doing it distributes its energy throughout a greater mass. Furthermore, much of the kinetic energy is converted into heat from the resulting shear, either directly or indirectly, by the creation of relatively fine-grained turbulence.

   b. The kinetic energy which remains in the diffused jet as it reaches the surface of the tailwater causes the jet to rise in a boil above the tailwater. The boil then spreads radially causing a rapid reduction and dispersion of the remaining kinetic energy.

4. The manifold stilling basin has been used as a low-cost structure for combining one stream of high-velocity flow with another stream of flow -- both in open channels and in closed conduits.

5. To be suitable as an energy dissipating device in the field of hydraulics, a manifold must have:

   a. A uniform distribution of flow issuing from the manifold along its entire length.

   b. Practical dimensions and shape to keep construction and maintenance costs as small as possible.

6. With the kinetic energy from a manifold being dissipated in a vertical direction, no high-velocity currents, or large concentrations of flow, are directed against either the bed or banks.

7. The design of the inlet section to the manifold is important in obtaining uniform flow from the manifold.

8. Equation 21

$$\frac{a}{v_1^2 / 2g} = \frac{C}{b/B_o} \qquad (21)$$

which is based on a single-jet theory with certain assumptions applied, is found to be valid over the anticipated range of conditions. The coefficient C has been determined for specific conditions of geometry and flow.

9. The functioning of the manifold which has been tested was found to approach two limits:

   a. The characteristics of a series of single small jets (of width B_o and length B) at low tailwater depths, or the characteristics of a single large jet (of width B and length L) at high tailwater depths.

   b. The characteristics of a single jet as the w/s -ratio becomes either large or small.

Acknowledgments

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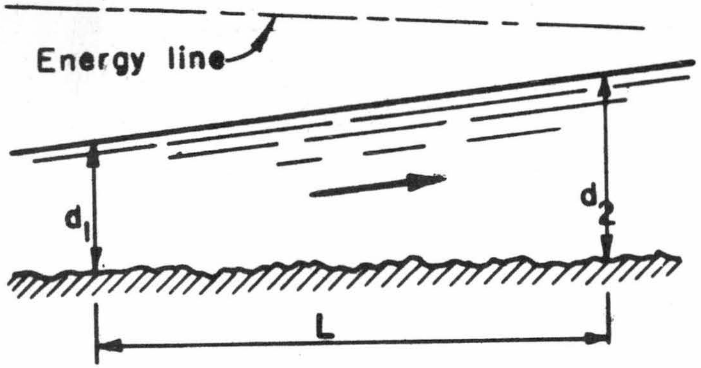
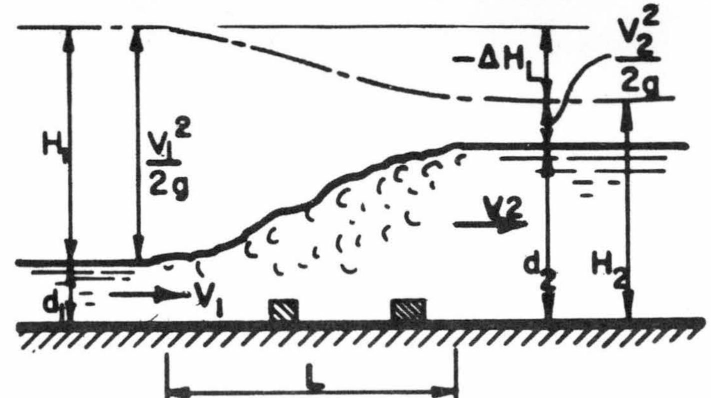
HORIZONTAL ENERGY DISSIPATION

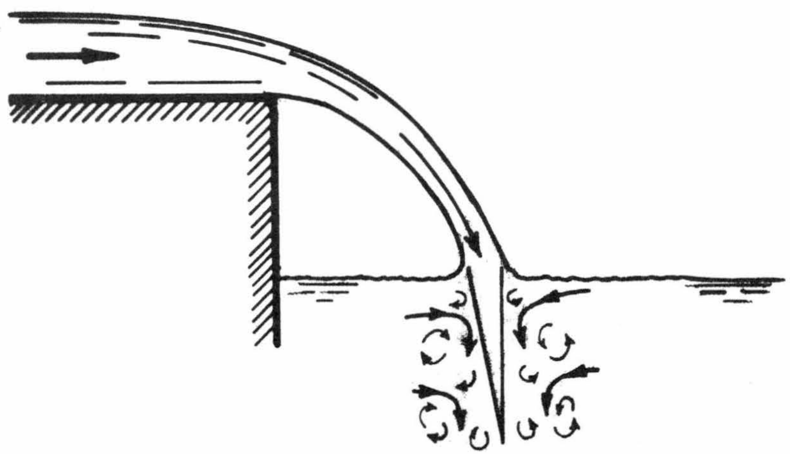


(a) Channel resistance

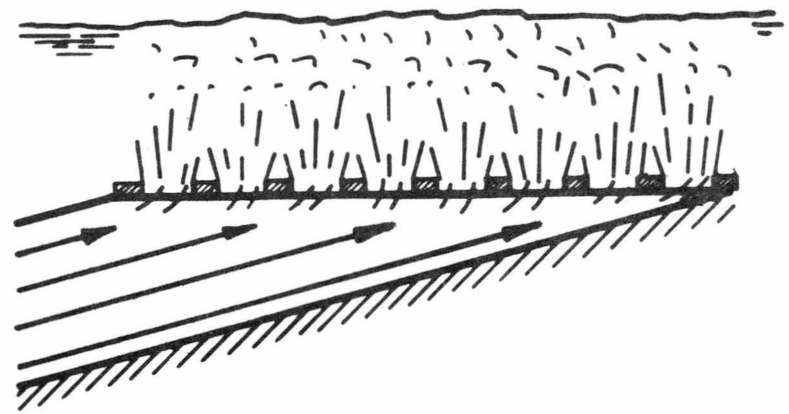


(b) Hydraulic jump and form resistance

VERTICAL ENERGY DISSIPATION



(c) Downward



(d) Upward

Fig. 1 Methods of dissipation of kinetic energy

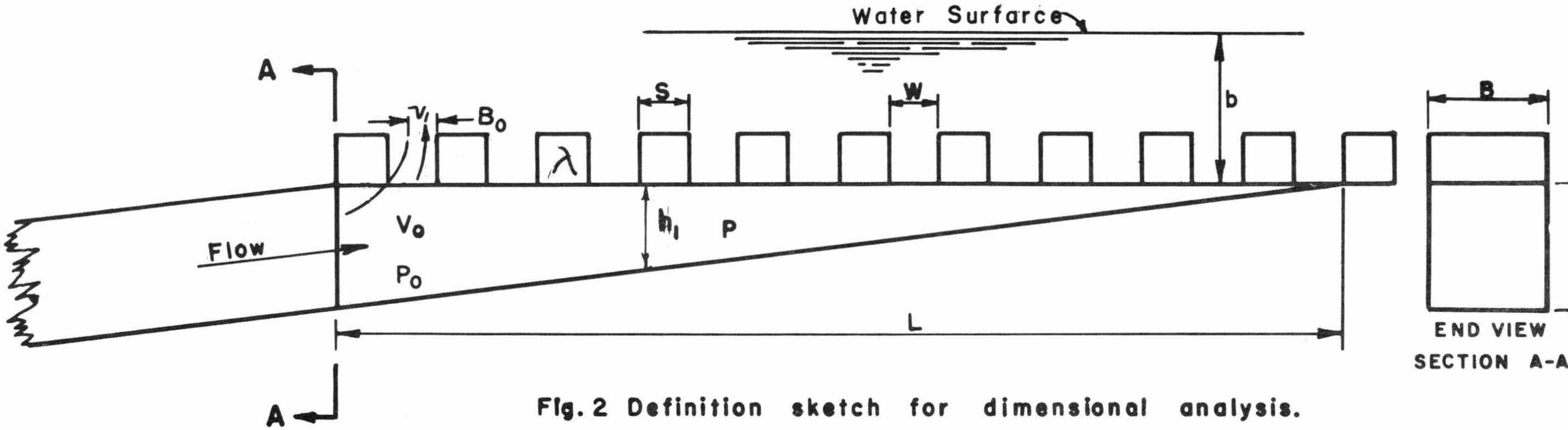


Fig. 2 Definition sketch for dimensional analysis.

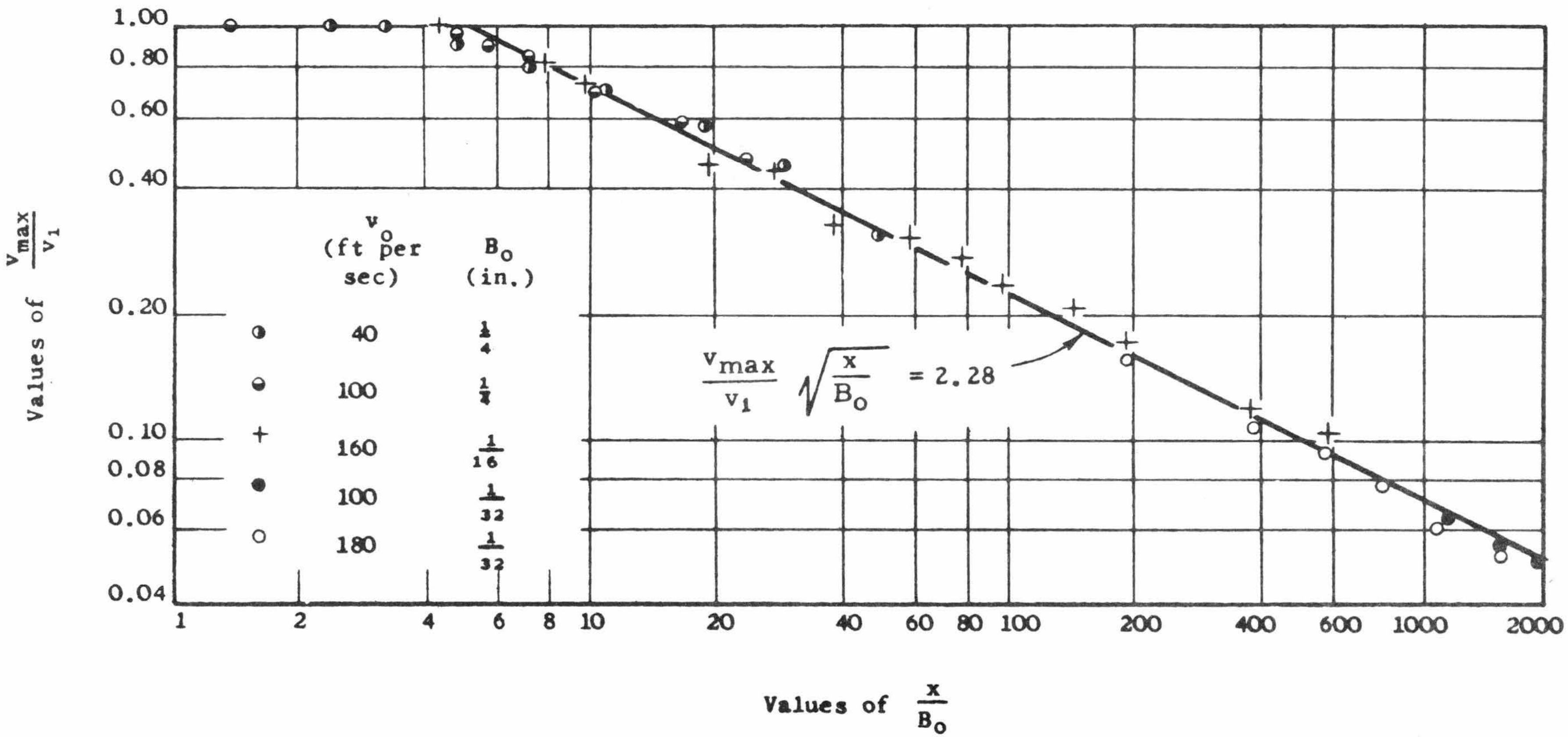


Fig. 3 Distribution of center line velocity for flow from slot.

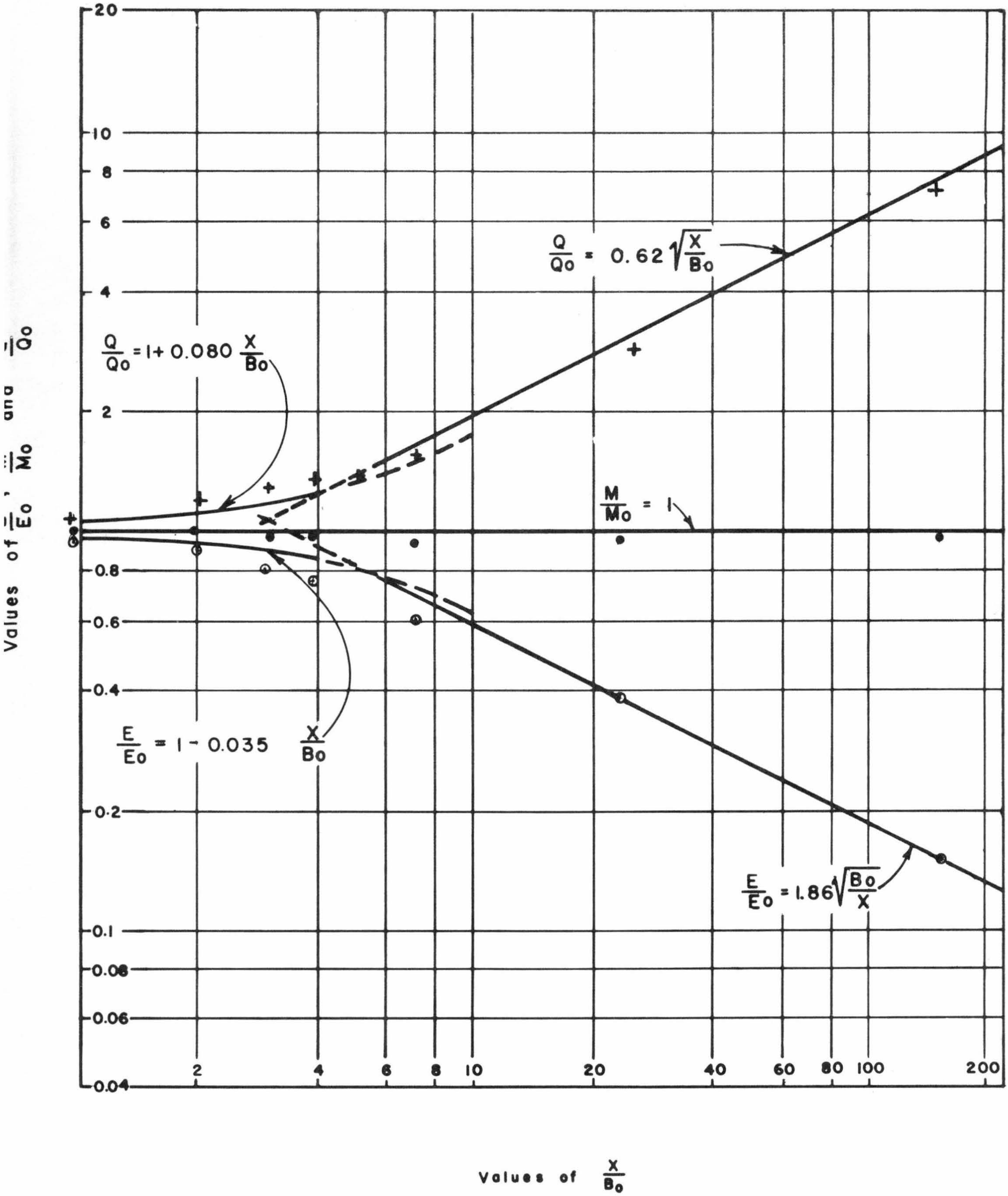


Fig. 4 Distribution of volume, momentum, and energy flux downstream from slot.

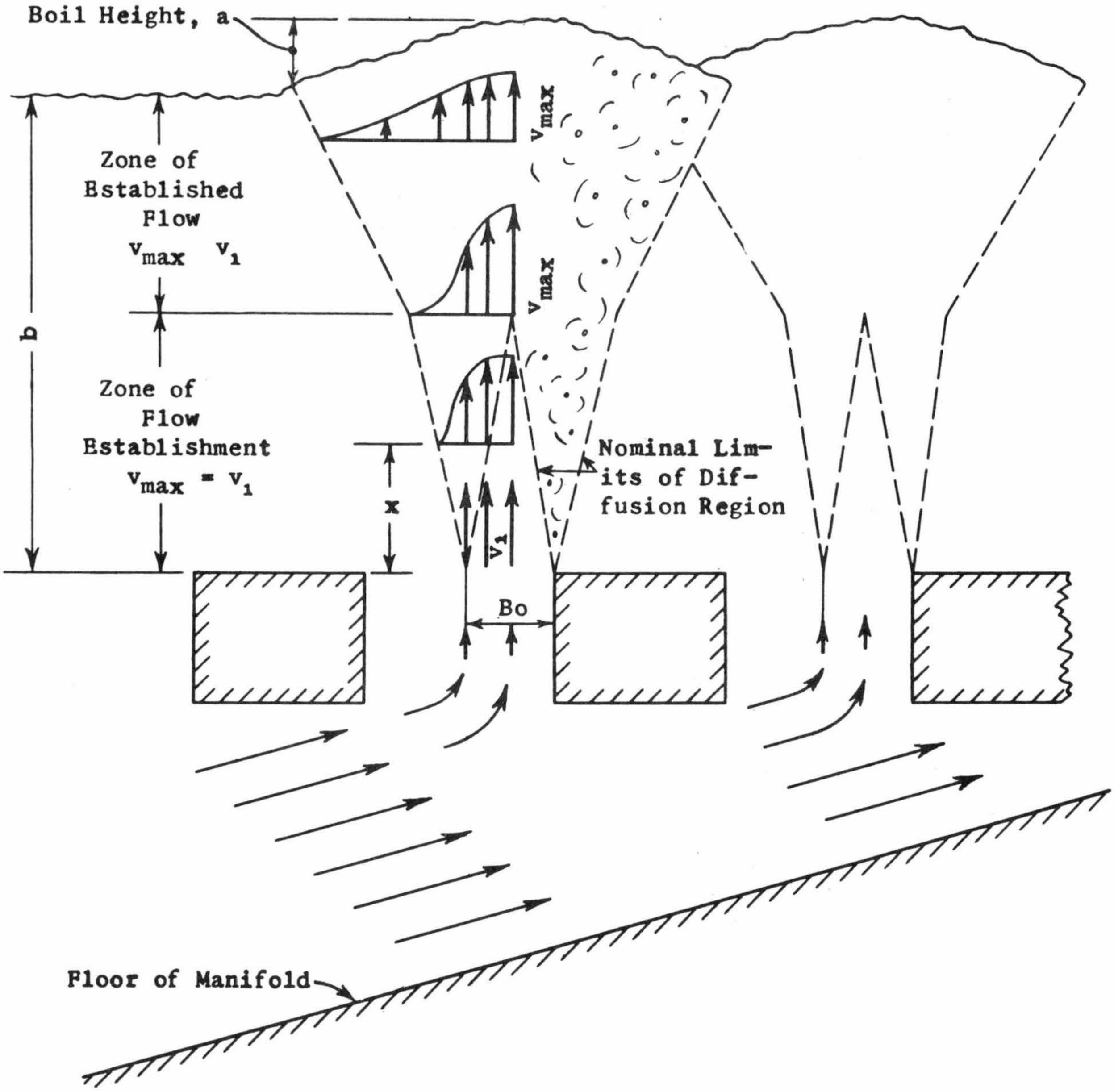


Fig. 5 Definition sketch for jet flow in a manifold stilling basin.

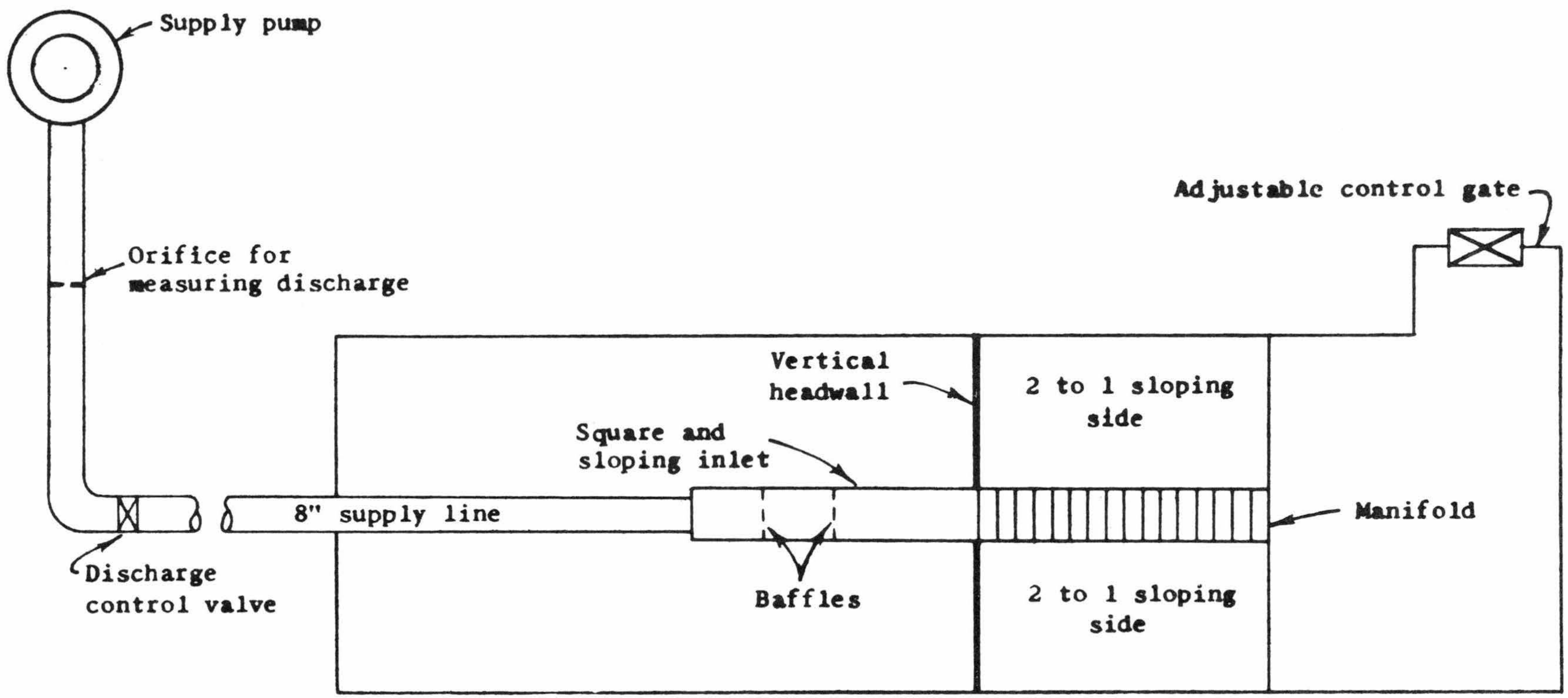


Fig. 6 Plan view of laboratory equipment.

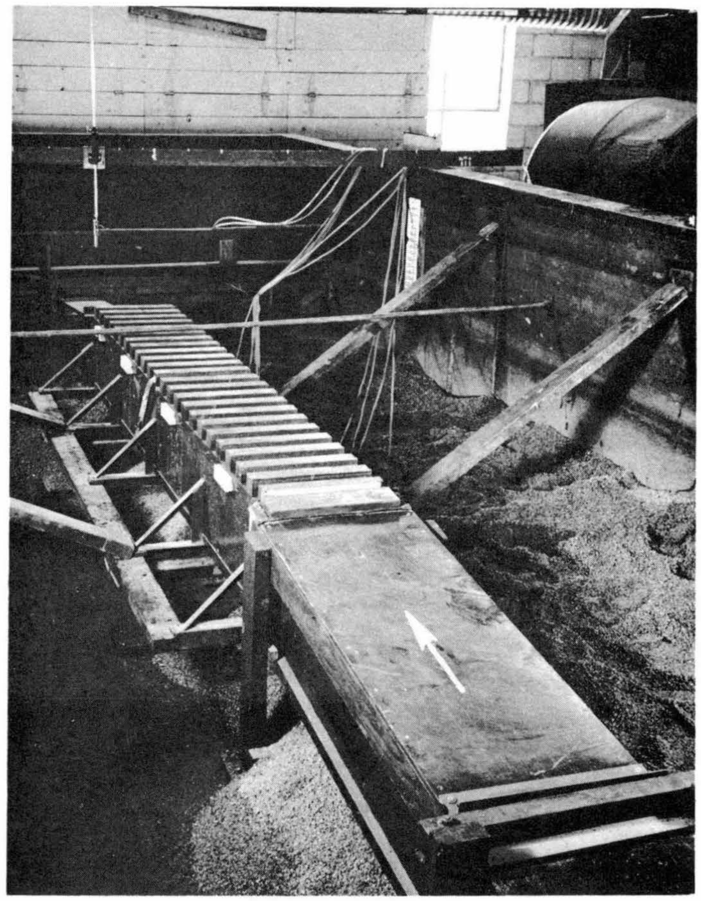
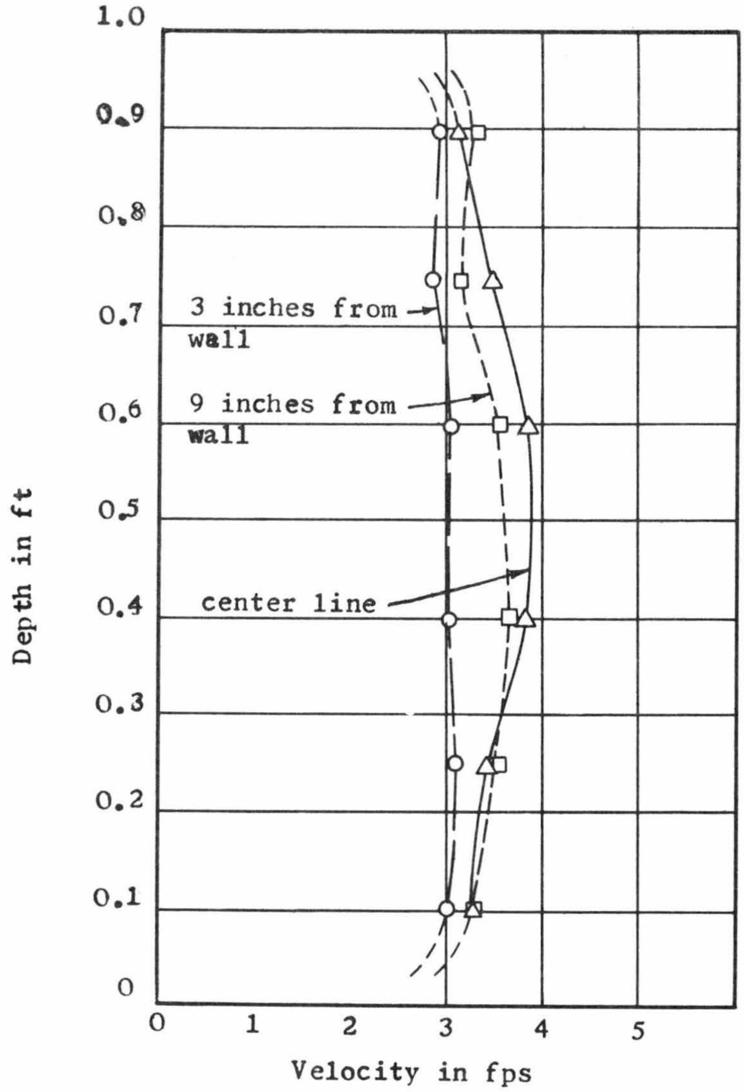
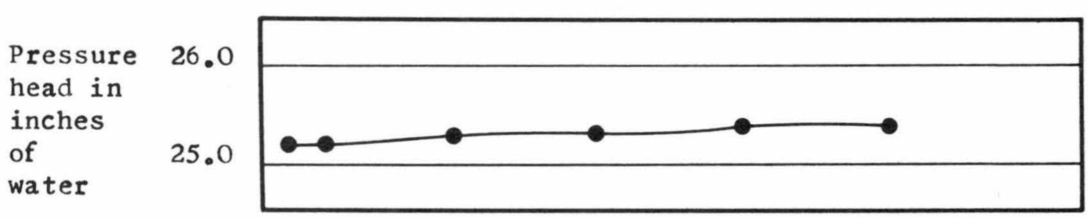


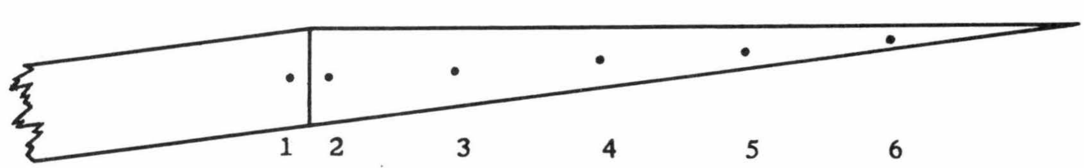
Fig. 7 Model of manifold with square and sloping inlet.



a. Velocity across manifold entrance



b. Pressure along side wall of manifold



c. Location of piezometers in manifold

Fig. 8 Distribution of velocity and pressure with the square and sloping inlet. Q = 3.0 cfs, b = 1.5 ft, S = 2 in., w = 2 in.

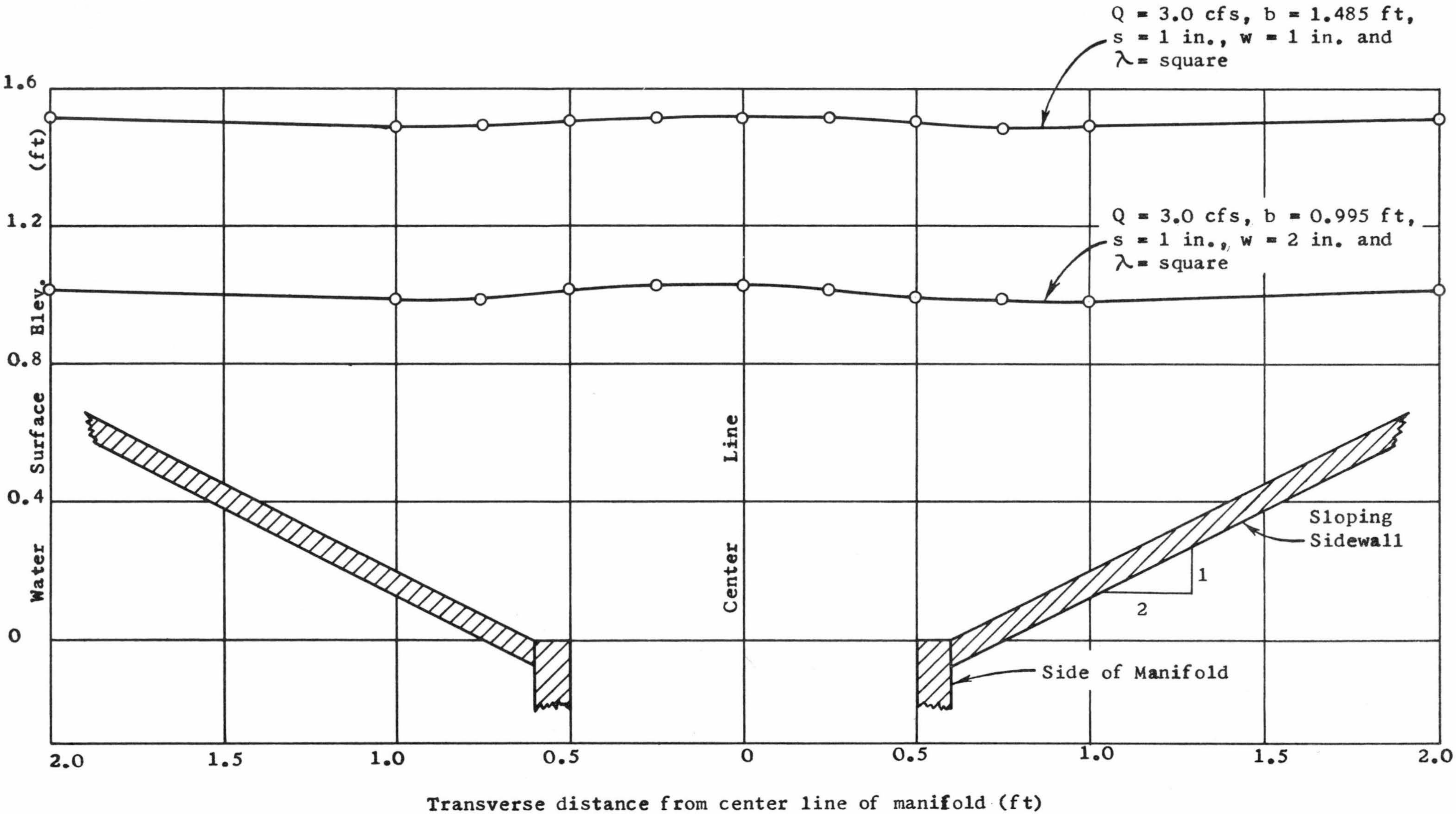


Fig. 9 Transverse water surface profile at 1 ft downstream from headwall.

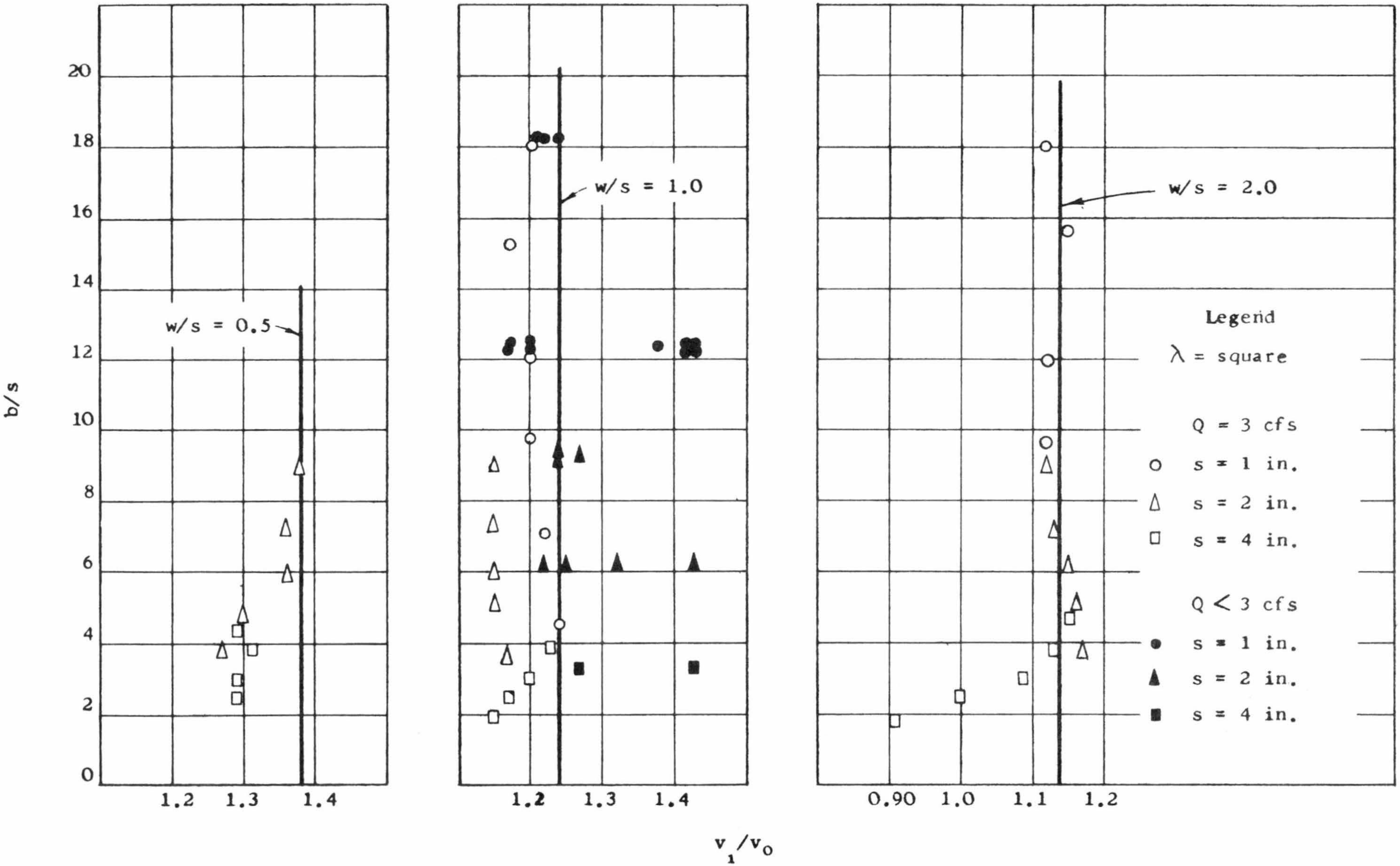


Fig. 10 Variation of b/s with v_1/v_0 and w/s .

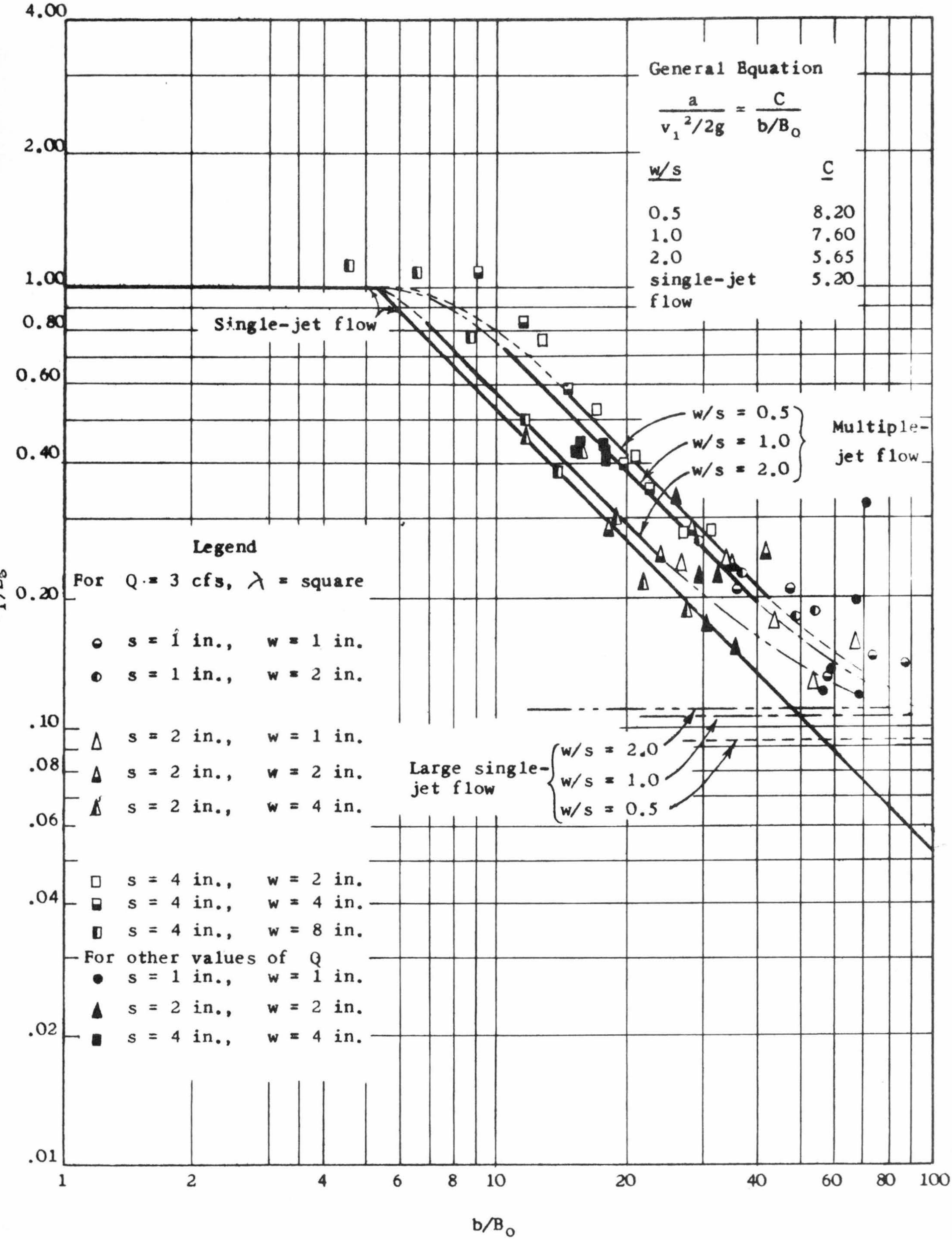


Fig. 11 Variation of $a/(v_1^2/2g)$ with b/B_o and w/s .

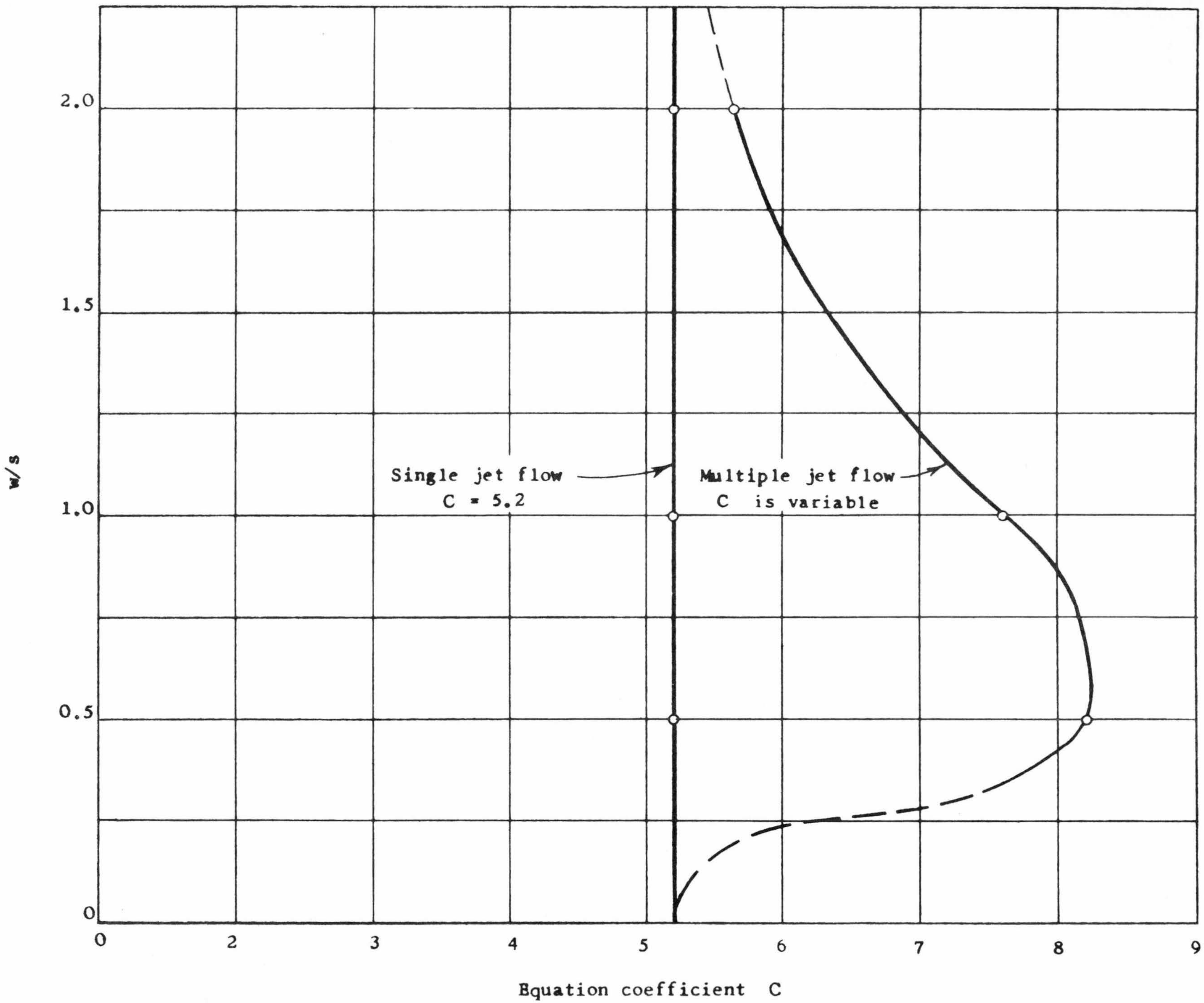


Fig. 12 Comparison of the variation of C with w/s for single-jet flow and multiple-jet flow.

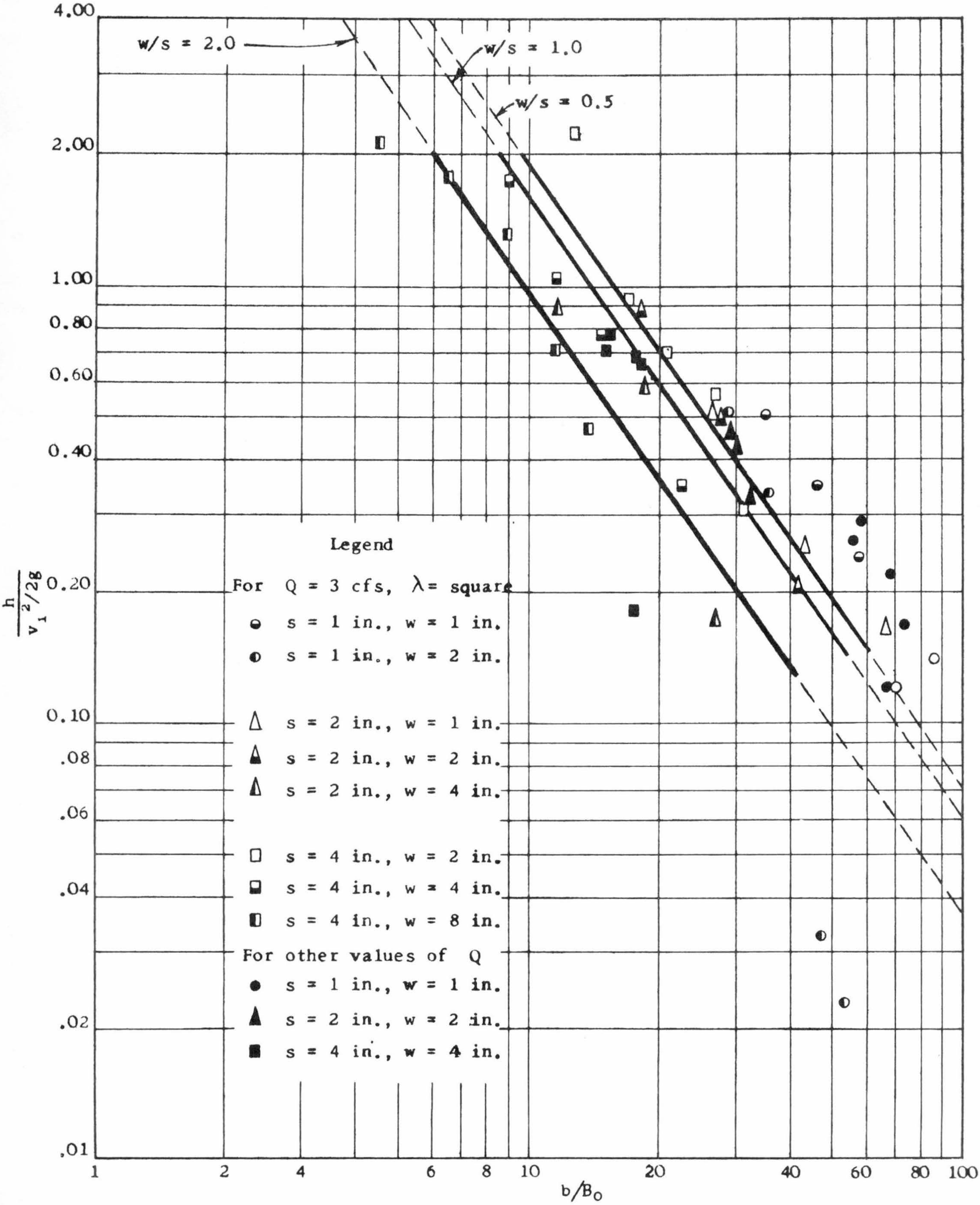


Fig. 13 Variation of $h/(v_1^2/2g)$ with b/B_o and w/s.