TECHNICAL REPORT H-73-4

SELECTIVE WITHDRAWAL FROM MAN-MADE LAKES

Hydraulic Laboratory Investigation

by

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March 1973

Sponsored by Office, Chief of Engineers, U. S. Army
U. S. Army Engineer Districts, Philadelphia, Savannah, Huntington
St. Louis, and Louisville

Conducted by U. S. Army Engineer Waterways Experiment Station
Hydraulics Laboratory
Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

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FOREWORD

This report is a compilation, with updated revisions, of the selective withdrawal techniques developed at the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi. The techniques were developed through experimental investigations conducted during the period July 1966 to the present (March 1973). The research was sponsored by several offices within the Corps of Engineers. These included the Office, Chief of Engineers, U. S. Army; the U. S. Army Engineer Districts, Philadelphia, Savannah, Huntington, St. Louis, and Louisville; and the WES. The studies were conducted in the Hydraulics Laboratory of the WES under the direction of Messrs. E. P. Fortson, Jr., and H. B. Simmons, former Chief and Chief of the Hydraulics Laboratory, respectively, and T. E. Murphy, Chief of the Structures Branch. The testing and data analysis were conducted by Mr. J. P. Bohan under the supervision of Mr. J. L. Grace, Jr., Chief of the Spillways and Channels Section. This report was prepared by Messrs. Bohan and Grace.

COL John R. Oswalt, Jr., CE, COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE, were Directors of the WES during the conduct of the investigation and the preparation and publication of this report. Messrs. J. B. Tiffany and F. R. Brown were Technical Directors.

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NOTATION

A	Cross-sectional area of the zone of withdrawal, sq ft
A_o	Area of the orifice opening, sq ft
b	Width of the lake at the cross section of interest, ft
C_D	Free flow discharge coefficient of the weir
D	Height of the orifice, ft
g	Acceleration due to gravity, ft/sec^2
h	Vertical distance of overlap of the velocity profiles, ft
H	Distance from the lower limit to the upper limit of the zone of withdrawal, ft
H_o	Vertical distance between the orifice center lines (℄'s), ft
H_w	Head on the weir for free flow or depth of flow over the weir for submerged flow, ft
p	Exponent that is a function of C_D
Q	Total discharge, cfs
t	Time, sec
v_1	Local velocity in the zone of withdrawal at a distance y_1 below the elevation of the maximum velocity V, fps
v_2	Local velocity in the zone of withdrawal at a distance y_2 below the elevation of the maximum velocity V, fps
V	Maximum velocity in the zone of withdrawal, fps
$\bar{V}$	Average velocity in the zone of withdrawal, fps
V_h	Average velocity in the zone of overlap of either the upper or lower withdrawal layer, fps
V_o	Average velocity through the orifice, fps
V_w	Average velocity over the weir, fps
y_1	Vertical distance from the elevation of the maximum velocity V to that of the corresponding local velocity v_1, ft

y_2 Vertical distance from the elevation of the maximum velocity V to that of the corresponding local velocity v_2, ft

Y_1 Vertical distance from the elevation of the maximum velocity V to the lower limit of the zone of withdrawal, ft

Y_2 Vertical distance from the elevation of the maximum velocity V to the upper limit of the zone of withdrawal, ft

Z_o Vertical distance from the elevation of the weir crest to the lower limit of the zone of withdrawal, ft

Z_1 Vertical distance from the elevation of the orifice ℄ to the lower limit of the zone of withdrawal, ft

Z_2 Vertical distance from the elevation of the orifice ℄ to the upper limit of the zone of withdrawal, ft

ΔH Head differential on the orifice, ft

ΔZ Vertical shift of the withdrawal limit, ft

$\Delta\rho_s$ Density difference of fluid between the elevations of the original withdrawal limit and the shifted withdrawal limit, g/cc

$\Delta\rho_w$ Density difference of fluid between the elevations of the weir crest and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_1$ Density difference of fluid between the elevations of the maximum velocity V and the corresponding local velocity v_1, g/cc

$\Delta\rho_2$ Density difference of fluid between the elevations of the maximum velocity V and the corresponding local velocity v_2, g/cc

$\Delta\rho_1'$ Density difference of fluid between the elevations of the orifice ℄ and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_2'$ Density difference of fluid between the elevations of the orifice ℄ and the upper limit of the zone of withdrawal, g/cc

$\Delta\rho_{1m}$ Density difference of fluid between the elevations of the maximum velocity V and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_{2m}$ Density difference of fluid between the elevations of the maximum velocity V and the upper limit of the zone of withdrawal, g/cc

ρ_o Fluid density at the elevation of the orifice ℄, g/cc

ρ_s Density of fluid at the elevation of the original withdrawal limit, g/cc

ρ_w Density of fluid at the elevation of the weir crest, g/cc

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
square feet	0.092903	square meters
cubic feet per second	0.0283168	cubic meters per second
feet per second	0.3048	meters per second
feet per second per second	0.3048	meters per second per second

SUMMARY

Laboratory investigations were conducted at the U. S. Army Engineer Waterways Experiment Station to determine the withdrawal-zone characteristics created in a randomly density-stratified impoundment by releasing flow through a submerged orifice, over a free and submerged weir, or through a combination of the above. Density stratification was generated in the experimental facilities by creating differentials in both temperature and salinity. Velocity profiles were obtained from movies of dye streak displacements.

Through the investigations, generalized relationships for describing the vertical limits of the withdrawal zone and the vertical velocity distribution within the zone have been developed. Techniques for handling conditions in which the water surface or bottom boundary controlled the limits of the withdrawal zone and for describing the composite velocity profile resulting from withdrawal zones which overlapped have also been developed. If the velocity profile and the reservoir width with respect to depth are known, a vertical flow rate distribution can be determined. This flow rate distribution can then be applied as a weighting function to the reservoir profile of any water-quality parameter to determine its value in the reservoir release.

SELECTIVE WITHDRAWAL FROM MAN-MADE LAKES

Hydraulic Laboratory Investigation

PART I: INTRODUCTION

1. The effective planning, design, management, and operation of one or more man-made lakes for optimum conservation and utilization of regional water and related resources for many purposes involve, among other things, the problems of predicting, monitoring, and controlling the physical and chemical quality of impounded waters and releases through spillways, powerhouses, and outlet works. An evaluation of the effectiveness of various structures in selectively withdrawing releases from various levels of stratified man-made lakes is urgently needed. This evaluation relative to multipurpose projects in which specific physical, chemical, and biological requirements of the releases are desired should be based on existing and future needs and objectives. The desire to release quality water requires monitoring the characteristics of water within lakes and knowledge of the flow patterns to be expected in the immediate and upstream vicinities of various regulating structures. Therefore, a determination of the effects on withdrawal of the size, shape, spacing, and number of multilevel openings is necessary to permit prediction and control of the stratum of a lake from which releases are made and to permit selection of effective locations for fixed monitoring stations. An evaluation of the effectiveness of submerged skimming weirs and walls or thermal barriers in preventing the intrusion of either cold or warm water into powerhouse intakes and single-level outlet works is also of primary concern.

2. During 1966, the Corps of Engineers initiated laboratory research at the U. S. Army Engineer Waterways Experiment Station (WES) to determine the characteristics of withdrawal zones resulting from release of flows through orifices and over weirs from randomly stratified lakes. This research program was designed to develop means of predicting and controlling the quality of water discharged through various regulating

structures. It was considered that any practical method for predicting the quality of water discharged through an inlet should be based upon the extent of the zone of withdrawal and the distribution of velocities within this zone. Then, if the distribution of one or more water-quality parameters was known, the resulting values of temperature, dissolved oxygen, or other parameters of the release could be computed. The facilities, experiments, test results, and data analyses utilized for determining generalized equations that describe the extent of the zone of withdrawal and the distribution of velocities therein are the basis of this report and are described in subsequent paragraphs.

PART II: EXPERIMENTAL FACILITIES

3. The experimental facilities (fig. 1) contained an orifice or a sharp-crested weir located in the center of a 1-ft-wide,* 2-ft-deep channel. A headbay, 40 ft long, 16 ft wide, and 4 ft deep, was provided upstream of the channel for the purpose of providing a relatively large supply of salt water. Stratification was generated by means of differentials in both temperature and dissolved salt concentrations. Fresh water was supplied by a pipe and weir box that extended across the full width of the headbay. The weir box was supported by screw jacks in order that the base or lip of the box could be set at the desired interface or surface of the saline water. The lower, denser stratum was generated by filling the headbay and channel to a predetermined level with fresh water and then mixing in salt and dye to give the desired density and red color. The weir box was placed at the surface of the saline water, and fresh water was slowly introduced through the box and over the broad-crested weir and saline water in order to establish the upper

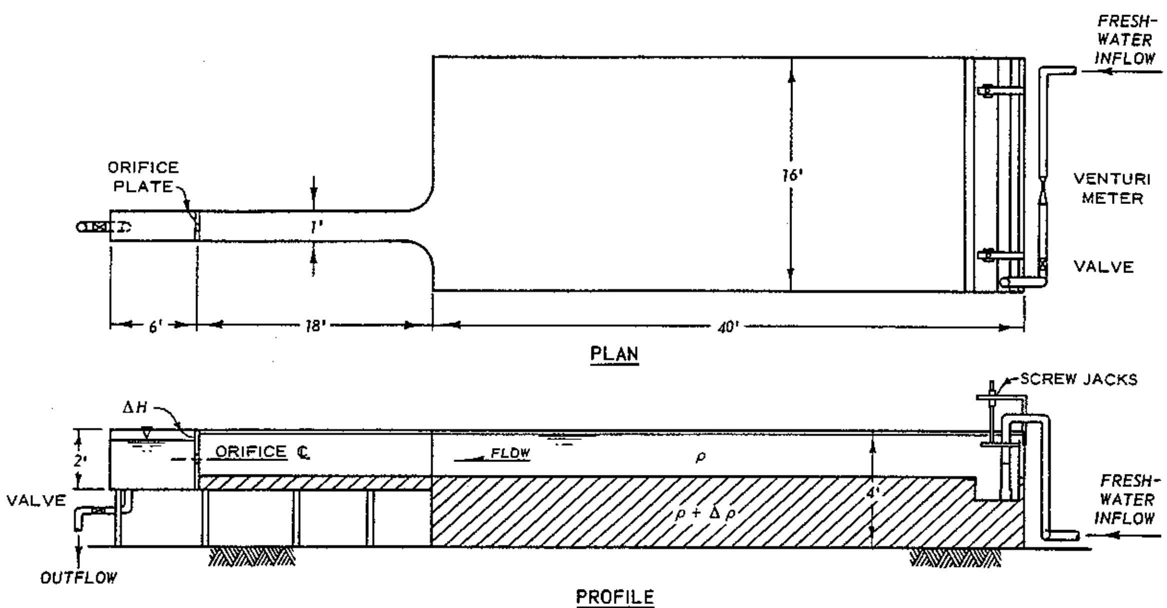

Fig. 1. Experimental facilities

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* A table of factors for converting British units of measurement to metric units is presented on page ix.

stratum. A drain pipe and valve were provided at the downstream end of the facilities for control of the head differential on the orifice and the depth of flow over the weir. A venturi meter was used to measure the rate of freshwater inflow. The valve in the drain pipe was adjusted to release an equivalent rate of outflow that was measured by means of a V-notch weir.

4. The density distributions were determined in place from measurements of temperature and conductivity using commercially available thermistors, conductivity probes, and indicators (fig. 2). The actual densities of the fresh and saline waters used in the facilities and for calibration purposes were determined by means of a gravimetric balance, since the sump water was not distilled water. Initially, a very distinct two-layer stratification existed; however, the variable temperature of the atmosphere generally heated and cooled the upper stratum during the day and night to the extent that it was necessary to monitor

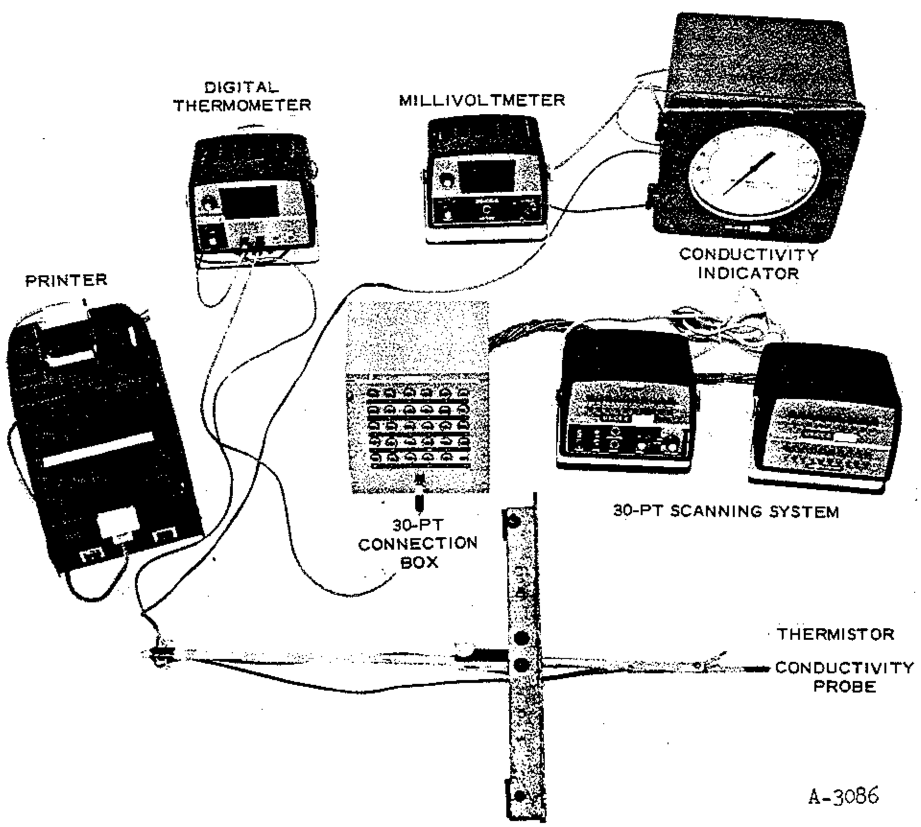


Fig. 2. Instrumentation used in experimental facilities

temperatures as well as salinity in order to determine an accurate measure of the density gradient in the experimental facilities. Velocity distributions were obtained by dropping dye particles into the flow and filming the displacement of the resulting streaks with movie cameras.

0.1 ft of depth was calculated by dividing the scaled horizontal distance between the traced streaks by the increment of time elapsed. Thus, three velocity distributions were obtained for each location upstream of both the orifice and weir, and these were averaged to yield one representative distribution.

7. Temperature and conductivity readings were converted to determine densities at various depths, and these values were plotted to determine the density profiles for the locations 1 and 8 ft upstream of both the orifice and the weir. A comparison of the density and velocity distributions at the different locations upstream of both the orifice and the weir showed very close agreement. It appeared that, for the orifice study, only those streaks that were within a distance of about three times the height of the orifice and, for the weir study, that were at a distance equal to the thickness of the withdrawal zone upstream of the weir were distorted materially by contractive effects. However, since the thickness of the zone of withdrawal did tend to increase very slightly in an upstream direction, only the density and velocity distributions obtained for the location 8 ft upstream of both the orifice and the weir were used in the data analyses. The basic data are shown in plates 1-4 for the orifice study and in plates 5-8 for the weir study.

Analysis of Orifice Data

8. General observations as well as those made of the dye streaks indicated the existence of a zone of withdrawal above and below which there was no flow (fig. 3). It was desirable and necessary to describe the upper and lower limits of this zone of withdrawal. The important variables appeared to be the size of the orifice, the velocity through the orifice, the density profile, and the vertical location of the orifice relative to the density profile. A definition sketch of the variables involved is shown in fig. 5. The data were plotted, as shown in plate 9, in terms of the densimetric Froude number and the ratio Z^2/A_o . The equation of the curve shown in plate 9 is

$$V_o = \frac{Z^2}{A_o}\sqrt{\left(\frac{\Delta\rho'}{\rho_o}\right)gZ} \qquad (1)$$

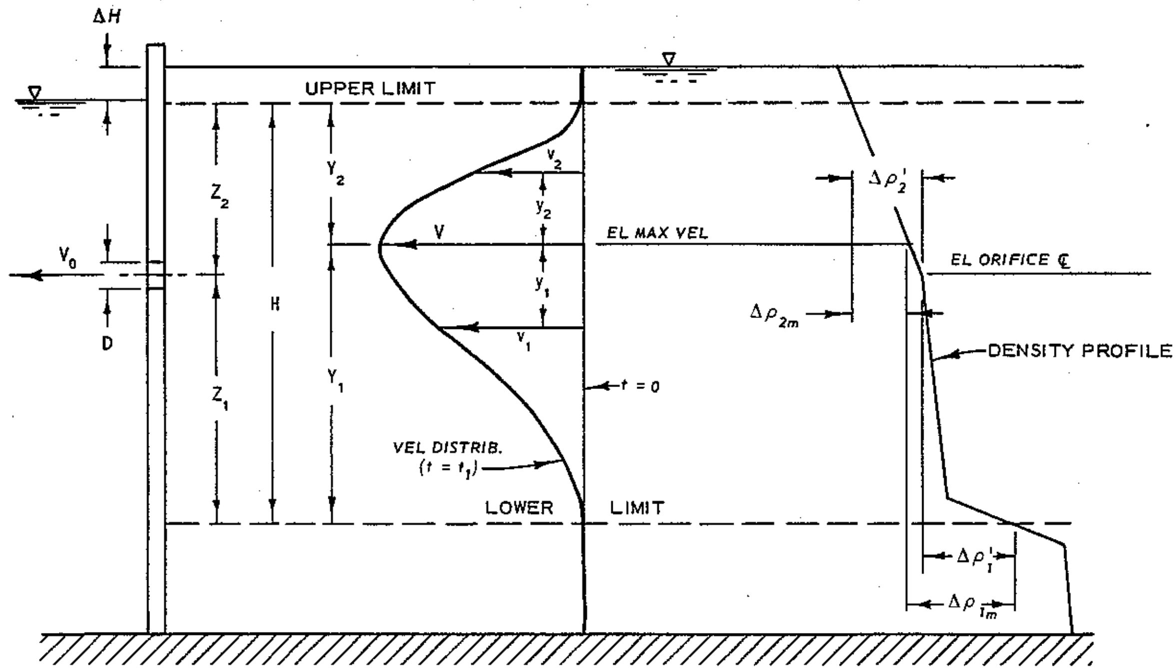


Fig. 5. Definition sketch of variables for orifice flow

where

V_o = average velocity through the orifice, fps

Z = vertical distance from the elevation of the orifice center line (℄) to the upper or lower limit of the zone of withdrawal, ft

A_o = area of the orifice opening, sq ft

$\Delta\rho'$ = density difference of fluid between the elevations of the orifice ℄ and the upper or lower limit of the zone of withdrawal, g/cc

ρ_o = fluid density at the elevation of the orifice ℄, g/cc

g = acceleration due to gravity, ft/sec^2

The quantity $V_o/\sqrt{(\Delta\rho'/\rho_o)gZ}$ is defined as the densimetric Froude number, where $(\Delta\rho'/\rho_o)g$ represents the modified gravitational effect. This relation is valid for both the upper and lower limits of the withdrawal zone, except in cases where the upper or lower limits of the zone intersect either the free surface or bottom boundary, respectively.

9. The initial tests were conducted using a square orifice, and the first plot constructed was one showing the relation of $V_o/\sqrt{(\Delta\rho'/\rho_o)gZ}$ versus Z/D, where D is the orifice height. This

plot indicated good correlation between the two different size square orifices tested (0.08 and 0.16 ft square). Several different shaped orifices (0.18-ft-diam circular, 0.11 ft high by 0.23 ft wide, and 0.11 ft wide by 0.23 ft high) were tested to determine whether the orifice shape had any effect on the zone of withdrawal. Plate 9 indicates good correlation between the various sizes and shapes of orifices tested. Since only the orifice area is used in this relation, it may be concluded that the orifice shape, at least within the limits of the shapes tested, has no effect on the zone of withdrawal.

10. During the testing program, conditions were encountered in which the upper limit of the withdrawal zone extended to the free surface. For these conditions, Z_2 and $\Delta\rho_2'$ are fixed by the presence of the free surface. When the densimetric Froude numbers were calculated and plotted on the graph in plate 9 for these conditions, the points fell to the left of the suggested curve. An examination of the parameters showed that restricting Z_2 would cause this effect. Therefore, for a given condition, the distance from the orifice ℄ to the free surface and the corresponding density difference can be used to plot a point in plate 9 to determine whether the withdrawal zone extended to the free surface. If the point falls on or to the left of the suggested curve, the withdrawal zone extended to the free surface. If the point falls to the right of the curve, the withdrawal zone did not extend to the free surface but was controlled by the relative distance and fluid density difference between the orifice ℄ and the upper limit. It is interesting to note that, for the conditions in which the upper limit of the withdrawal zone was limited by the free surface, the lower limit still satisfied the relation in plate 9 represented by equation 1. This fact indicates that the locations of the upper and lower limits of the withdrawal zone were independent of each other.

11. The movies of the dye streaks indicated that the maximum velocity within the zone of withdrawal, in most cases, did not occur at the elevation of the orifice ℄. The data shown in plate 9 indicate that the upper and lower extents of the zone of withdrawal were functions of the area and the densimetric Froude number of flow through the

orifice. Data analyses indicated that the maximum velocity occurred at the elevation of the orifice ℄ only when the withdrawal zone was vertically symmetrical about the elevation of the orifice ℄. The maximum velocity occurred below the orifice ℄ when the vertical extent of the lower limit of the withdrawal zone was less than that of the upper limit. Similarly, the maximum velocity occurred above the orifice ℄ when the distance from the orifice ℄ to the lower limit was greater than the distance from the orifice ℄ to the upper limit (fig. 6). A plot indicating

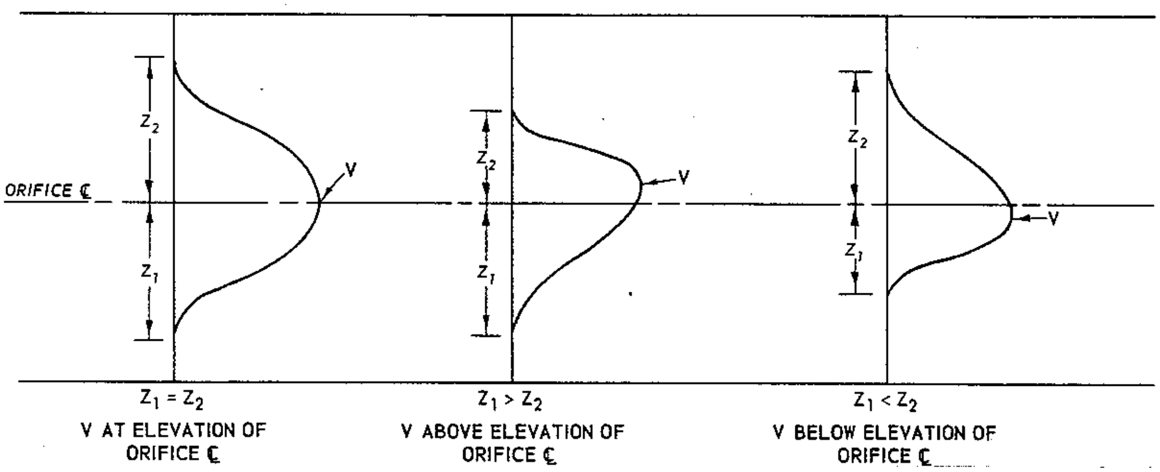


Fig. 6. Location of maximum velocity relative to elevation of orifice ℄

the relative position of the maximum velocity in terms of Y_1/H and Z_1/H is shown in plate 10. The variables, illustrated in fig. 5, are defined as follows:

Y_1 = vertical distance from the elevation of the maximum velocity V to the lower limit of the zone of withdrawal, ft

H = thickness of the withdrawal zone $(Z_1 + Z_2)$, ft

Plate 10 can be used to determine where the maximum velocity will occur after Z_1 and Z_2 have been determined from equation 1.

12. The next objective was to develop a dimensionless velocity distribution so that for any given situation the velocity distribution could be described. The problem was approached by first plotting the ratios y_1/Y_1 and y_2/Y_2 against v_1/V and v_2/V, respectively,

where

y_1 = vertical distance from the elevation of the maximum velocity V to that of the corresponding local velocity v_1, ft

y_2 = vertical distance from the elevation of the maximum velocity V to that of the corresponding local velocity v_2, ft

Y_1 = vertical distance from the elevation of the maximum velocity V to the lower limit of the zone of withdrawal, ft

Y_2 = vertical distance from the elevation of the maximum velocity V to the upper limit of the zone of withdrawal, ft

v_1 = local velocity in the zone of withdrawal at a distance y_1 below the elevation of the maximum velocity V, fps

v_2 = local velocity in the zone of withdrawal at a distance y_2 below the elevation of the maximum velocity V, fps

V = maximum velocity in the zone of withdrawal, fps

These plots (not shown herein) produced various unsymmetrical shapes that indicated the need for incorporating the effects of density. Observations of the velocity and density distributions indicated that a sudden reduction in velocity was always associated with an abrupt change in density. Since density and pressure are directly related and pressure and velocity are indirectly related, it seemed quite logical that the observed phenomenon should occur and thus distort the velocity distributions. The most satisfactory fit of the experimental data was obtained by plotting $y_1\Delta\rho_1/Y_1\Delta\rho_{1m}$ and $y_2\Delta\rho_2/Y_2\Delta\rho_{2m}$ against v_1/V and v_2/V, respectively,

where

$\Delta\rho_1$ = density difference of fluid between the elevations of the maximum velocity V and the corresponding local velocity v_1, g/cc

$\Delta\rho_2$ = density difference of fluid between the elevations of the maximum velocity V and the corresponding local velocity v_2, g/cc

$\Delta\rho_{1m}$ = density difference of fluid between the elevations of the maximum velocity V and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_{2m}$ = density difference of fluid between the elevations of the maximum velocity V and the upper limit of the zone of withdrawal, g/cc

This approach not only satisfied all of the test data, but also made the upper and lower sections of the dimensionless plot symmetrical about the axis, $v/V = 0$. The data, plotted in plate 11, were satisfied by the parabola

$$\frac{v}{V} = \left(1 - \frac{y\Delta\rho}{Y\Delta\rho_m}\right)^2 \qquad (2)$$

This equation can be used to describe both the upper and lower sections of a velocity distribution using the elevation of the maximum velocity V as the reference elevation, except for conditions in which the withdrawal zone is limited by either the free surface or the bottom boundary. The upper section of the velocity profiles, for the conditions in which the free surface limited the withdrawal zone, was best satisfied by the relation

$$\frac{v}{V} = 1 - \left(\frac{y\Delta\rho}{Y\Delta\rho_m}\right)^2 \qquad (3)$$

as shown in plate 12. For a situation in which only one limit (upper or lower) is affected by a boundary (free surface or bottom boundary), equation 2 can be used to determine the velocity distribution from the elevation of maximum velocity V to the limit unaffected by a boundary, and equation 3 can be used to determine the velocity distribution from the elevation of maximum velocity V to the limit affected by a boundary.

13. A comparison of the velocity distribution observed during a single test and that computed based upon equation 2 is shown in fig. 7. If the limits of the zone of withdrawal, the location of the maximum velocity V , and the density profile are known, this procedure can be applied to determine the relation between the local velocity v and the maximum velocity V at any vertical position within the zone of withdrawal.

14. However, the need for developing a method of determining the magnitude of the maximum velocity V for any given condition was apparent. Since the magnitudes of velocities at a given elevation across the experimental channel appeared to be the same except in the immediate vicinity of the side boundaries, it was assumed that the vertical distribution of velocities is constant throughout the full width of a stratified lake. Based upon this assumption, the relation between the

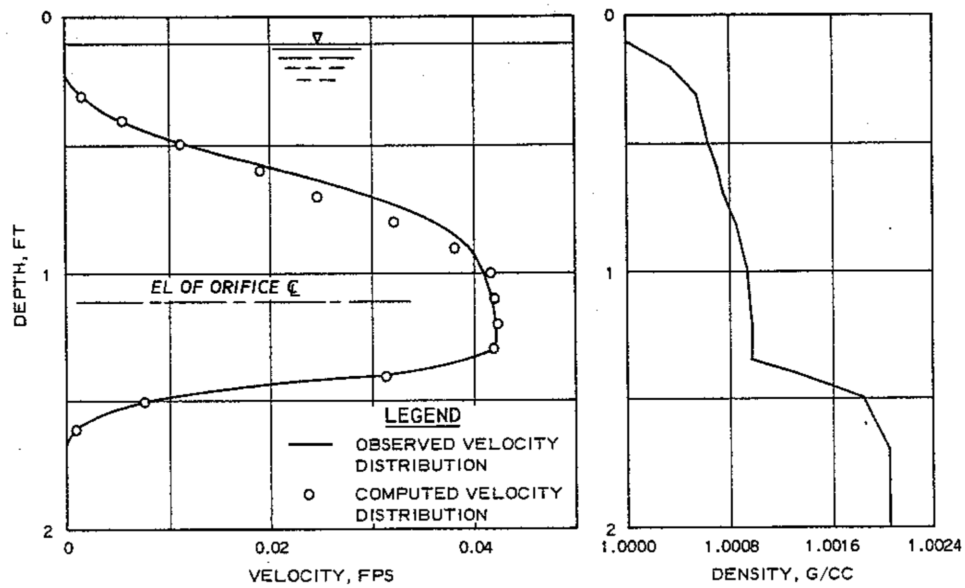


Fig. 7. Comparison of observed and computed velocity distributions for single test condition

average velocity $\bar{V}$ and the maximum velocity V in the zone of withdrawal and across any cross section of a stratified lake is expressed as

$$\frac{\bar{V}}{V} = \frac{Q}{AV} = \frac{\int_0^{Y_1} bv_1 \, dy_1 + \int_0^{Y_2} bv_2 \, dy_2}{AV} \tag{4}$$

where

$\bar{V}$ = average velocity in the zone of withdrawal, fps

Q = total discharge, cfs

A = cross-sectional area of the zone of withdrawal, sq ft

b = width of the lake at the cross section of interest at any depth Y , ft

This relation can also be written as

$$\frac{\bar{V}}{V} = \frac{1}{A}\left(\int_0^{Y_1} b \frac{v_1}{V} dy_1 + \int_0^{Y_2} b \frac{v_2}{V} dy_2\right) \tag{5}$$

The ratios of local v to maximum V velocities in equation 5 can be substituted with the appropriate relations of depth and density based on whether or not a boundary affected the withdrawal limits. In order to solve the above integrals, $\Delta\rho/\Delta\rho_m$ must be expressed as a function of y/Y, and b must be expressed as a function of y. If the density profile is known, the relation between $\Delta\rho/\Delta\rho_m$ and y/Y can be easily obtained. The ratio $\Delta\rho/\Delta\rho_m$ can be several different functions of y/Y in the zone of withdrawal, depending upon the density profile; thus, a separate integral must be written for each $\Delta\rho/\Delta\rho_m = f(y/Y)$. Each of these integrals can then be evaluated and all added together. Letting the sum of the integrals equal K, the equation can be written as

$$\frac{\overline{V}}{V} = \frac{K}{A} \tag{6}$$

where $\overline{V} = Q/A$. Then,

$$\frac{Q}{AV} = \frac{K}{A} \tag{7}$$

yielding

$$V = \frac{Q}{K} \tag{8}$$

It is then possible to determine the upper and lower limits of the zone of withdrawal and the velocity distribution within this zone. These results are taken from reference 1.

Analysis of Weir Data

15. In general, the data relative to the extent of the zone of withdrawal upstream of a vertical-faced, sharp-crested weir and the distribution of velocities therein were analyzed in a manner similar to that used with the orifice data. Observations of stratified flow over the weir indicated that the withdrawal zone always extended to the free surface, provided the vertical drain in the facilities downstream of the

weir was not permitted to control the vertical extent of withdrawal. The upper limit of the withdrawal zone over the weir could be restricted by releasing only relatively low rates of flow through the facilities with a relatively great depth of flow over the weir. Under similar conditions, the lower limit of withdrawal could be restricted by raising the drain outlet relative to the channel bottom and weir crest. Withdrawal characteristics of a vertical outlet are described by Harleman, Morgan, and Purple in reference 2. Although the free surface determines the upper limit of the withdrawal zone upstream of a weir that controls flow, it was necessary to describe the lower limit of this zone of withdrawal. The important variables appeared to be the velocity over the weir, the density profile, and the vertical location of the weir relative to the free surface and the density profile. A definition sketch of the variables for weir flow is shown in fig. 8. The data were plotted, as shown in plate 13, in terms of a densimetric Froude number and the ratio of the thickness of the withdrawal zone to the head on or depth of flow over the weir. The equation of the curve shown in plate 13 is

$$V_w = 0.32\left(\frac{Z_o + H_w}{H_w}\right)\sqrt{\left(\frac{\Delta\rho_w}{\rho_w}\right)gZ_o} \qquad (9)$$

where

V_w = average velocity over the weir, fps

Z_o = vertical distance from the elevation of the weir crest to the lower limit of the zone of withdrawal, ft

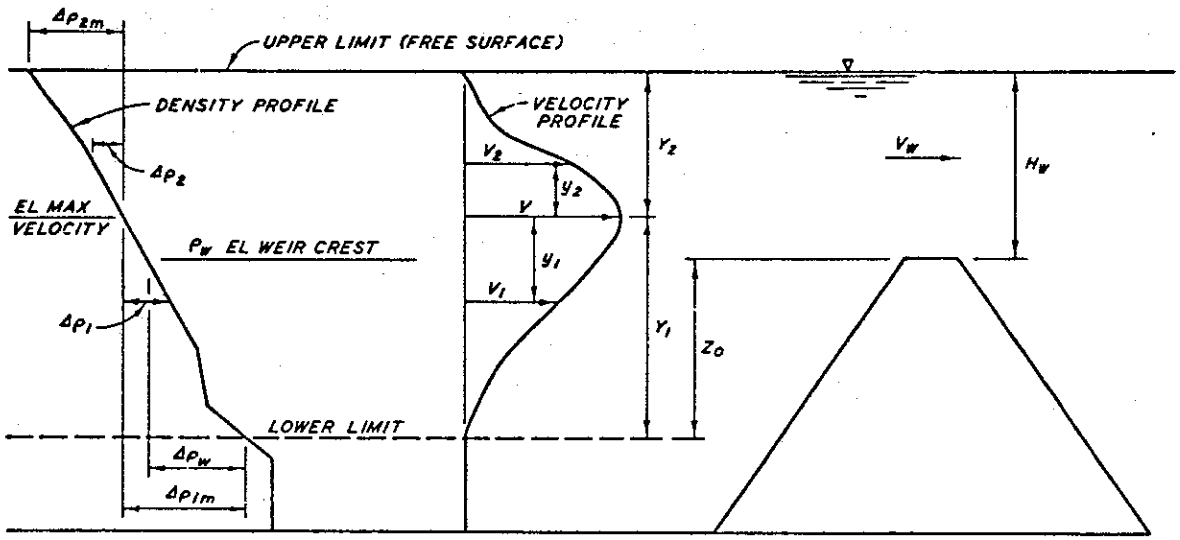
H_w = head on the weir for free flow or depth of flow over the weir for submerged flow, ft

$\Delta\rho_w$ = density difference of fluid between the elevations of the weir crest and the lower limit of the zone of withdrawal, g/cc

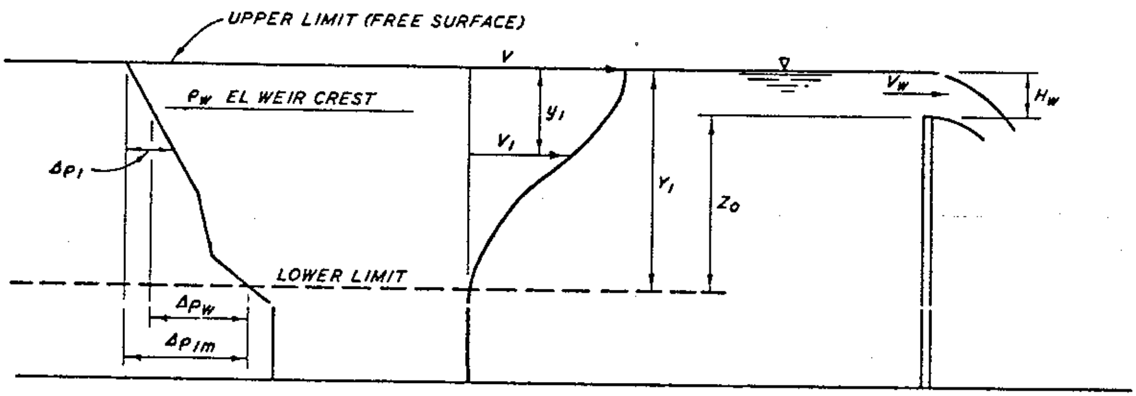
ρ_w = density of fluid at the elevation of the weir crest, g/cc

g = acceleration due to gravity, ft/sec^2

The data of Harleman and Elder,[3] for which not more than 1 percent of the total flow under a plane skimmer wall was withdrawn from the stratum above the interface of a stratified lake upstream of the wall, are also shown in plate 13. Plate 13 also shows a curve that reflects an average



a. Submerged weir flow



b. Free weir flow

Fig. 8. Definition sketch of variables for weir flow

of similar data obtained during WES investigations with three-dimensional models of specific proposed vertical-faced, sharp-crested and sloped-faced, broad-crested submerged weirs. These data correlated well with the relations determined in the subject study through observations of the withdrawal zone and velocities.

16. The movies of the dye streaks indicated that, in most cases with submerged weir flow, the maximum velocity V within the zone of withdrawal occurred below the water surface and either above or below the elevation of the weir crest. With free weir flow, the maximum

velocity, for all practical purposes, occurred at the free surface. A plot indicating the relative position of the maximum velocity V to both the weir crest and the lower limit of withdrawal is shown in plate 14. The variables shown therein are defined as follows:

Y_1 = vertical distance from the elevation of maximum velocity V to the lower limit of withdrawal, ft

Z_o = vertical distance from the elevation of the weir crest to the lower limit of withdrawal, ft

H_w = head on the weir for free flow or the depth of flow over the weir for submerged flow, ft

Plate 14 can be used to determine where the maximum velocity will occur after Z_o has been determined from equation 9.

17. Observations of the velocity and density distributions indicated that a reduction in velocity was always associated with a change in density, as was indicated with stratified flow through an orifice. The most satisfactory fit of the experimental data with submerged weir flow was obtained by plotting v_1/V and v_2/V against $y_1\Delta\rho_1/Y_1\Delta\rho_{1m}$ and $y_2\Delta\rho_2/Y_2\Delta\rho_{2m}$, respectively, as shown in plates 15 and 16, where

v_1 = local velocity in the zone of withdrawal at a distance y_1 below the elevation of the maximum velocity V , fps

v_2 = local velocity in the zone of withdrawal at a distance y_2 below the elevation of the maximum velocity V , fps

V = maximum velocity in the zone of withdrawal, fps

y_1 = vertical distance from the elevation of the maximum velocity V to that of the corresponding local velocity v_1 , ft

y_2 = vertical distance from the elevation of the maximum velocity V to that of the corresponding local velocity v_2 , ft

$\Delta\rho_1$ = density difference of fluid between the elevations of the maximum velocity V and the corresponding local velocity v_1 , g/cc

$\Delta\rho_2$ = density difference of fluid between the elevations of the maximum velocity V and the corresponding local velocity v_2 , g/cc

Y_1 = vertical distance from the elevation of the maximum velocity V to the lower limit of the zone of withdrawal, ft

Y_2 = vertical distance from the elevation of the maximum velocity V to the upper limit of the zone of withdrawal, ft

$\Delta\rho_{1m}$ = density difference of fluid between the elevations of the maximum velocity V and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_{2m}$ = density difference of fluid between the elevations of the maximum velocity V and the upper limit of the zone of withdrawal, g/cc

The equation describing the dimensionless velocity distribution for the portion below maximum velocity with submerged weir flow,

$$\frac{v_1}{V} = \left(1 - \frac{y_1\Delta\rho_1}{Y_1\Delta\rho_{1m}}\right)^3 \tag{10}$$

is of the same form as that used in the orifice study with negligible boundary effects.

18. The dimensionless velocity distribution for the portion above maximum velocity with submerged weir flow is described by

$$\frac{v_2}{V} = 1 - \left(\frac{y_2\Delta\rho_2}{Y_2\Delta\rho_{2m}}\right)^2 \tag{11}$$

This equation is of the same form as that used with the submerged orifice and the restricting, free surface boundary effect.

19. With free weir flow, the maximum velocity V occurred at the water surface, and the dimensionless velocity distributions observed were described by an equation of the form that satisfactorily described the distributions observed with either submerged orifice or submerged weir flow and the restricting, free surface boundary effect (see plates 17 and 18). However, different relations were required to satisfy the different velocity distributions observed as affected by a different value of the weir discharge coefficient with free flow conditions C_D. The following general equation describes the dimensionless velocity distributions observed with free weir flow and the free surface boundary effect:

$$\frac{v_1}{V} = 1 - \left(\frac{y_1\Delta\rho_1}{Y_1\Delta\rho_{1m}}\right)^p \tag{12}$$

where p is an exponent that is a function of the free flow discharge coefficient of the weir. Based on the available data, it appeared that p values of 3/2, 1/2, and 1/5 were indicated for C_D values of 3.00, 3.33, and 4.10, respectively.

20. Since the magnitudes of velocities at a given elevation appeared to be the same, except in the immediate vicinity of the side boundaries, it was assumed that the vertical distribution of velocities is constant throughout the full width of a stratified lake. Based upon this assumption, the relation between the average $\bar{V}$ and the maximum V velocities in the zone of withdrawal and across any cross section of a stratified lake is expressed by equations 4 and 5. The appropriate relations between the local v and maximum V velocities for submerged or free weir flow conditions (equations 10 and 11 or 12, respectively) can be substituted into equation 5, and the resulting integrals can be solved when b is expressed as a function of y and when $\Delta\rho/\Delta\rho_m$ is expressed as a function of y/Y. If the density profile in the lake is known, the relationship between $\Delta\rho/\Delta\rho_m$ and y/Y can be easily obtained. A separate integral must be written for each $\Delta\rho/\Delta\rho_m = f(y/Y)$ evaluated, and then all of the integrals must be summed to determine the appropriate value of K in equation 8, which can then be solved to determine the magnitude of the maximum velocity V within the zone of withdrawal. It is then possible to determine the upper and lower limits of the zone of withdrawal and the velocity distribution therein. With the capability of predicting the velocity distribution to be anticipated for any given density distribution upstream of an orifice or weir, the weighted-average technique can be applied to predict the value of any water-quality parameter of the outflow for which a profile in the lake is known. The results and the basic data of this investigation are presented in reference 4.

Analysis of Multiple-Outlet Operation

21. Tests were conducted at the WES[5] to determine the adequacy of superimposing velocity profiles calculated for single-outlet operation when two or more outlets were operating simultaneously at different

elevations. The tests were conducted in a 3-ft-wide flume in a manner similar to that used for the single orifice and single weir tests. The tests were conducted using two outlet ports to obtain results for different vertical spacings and flow distributions between the outlets.

22. The resulting density profiles, individual orifice discharges, and elevations were used to calculate the velocity profiles for single-orifice operation, based on the results presented earlier in this report. The two calculated profiles for each test were superimposed and compared with the observed velocity profiles for the corresponding tests. These comparisons are shown in the graphs on the left in plates 19-24. The comparisons did not appear adequate; therefore, further analyses of the data were conducted in order to develop a predictive technique that would give better agreement between the observed and predicted velocity profiles.

23. A comparison of the observed and predicted velocity profiles, based on simple superpositioning, indicates a consistent deviation in all of the tests. The observed velocities appeared greater than the predicted ones in the zone where the profiles overlap, and, in most cases, the predicted maximum velocities in each of the withdrawal zones were greater than the observed. In the zone where the profiles overlap, based on simple superpositioning, it is reasonable to assume that the velocities of one withdrawal zone influence the velocities of the other by reducing the shear force in any horizontal layer. The result of this influence is an increase in velocities of both withdrawal layers within this zone. By shifting the inner withdrawal limits to increase the depths of both zones, the velocities in the zone of overlap are increased. In order to maintain continuity, a decrease in the maximum velocity of each withdrawal zone will occur. Shifting the inner withdrawal limits will therefore provide both of the adjustments necessary to reduce the discrepancy in the simple superpositioning technique.

24. Several attempts were made to determine the appropriate amount of shift, and it was finally concluded that the shift should be a function of the amount of overlap of the two velocity profiles, based upon single-outlet operation, the vertical spacing between the outlets,

the density profile in the reservoir, and the average velocity of each withdrawal zone in the zone of overlap. (A large density gradient would tend to inhibit a shift of a withdrawal limit, while a small gradient would allow a greater shift.) This procedure led to the development of a satisfactory technique for shifting the inner withdrawal limits. The technique will be referred to as the "controlled-shift technique."

25. Fig. 9 is a definition sketch showing the terms used in the analysis. The final relationship developed to describe the amount of shift of the inner withdrawal limits involves a densimetric Froude number and the ratio of the vertical distance of overlap of the velocity profiles to the vertical distance between the orifice ℄'s. This relationship, as shown in plate 25, is expressed as

$$\frac{V_h}{\sqrt{\left(\frac{\Delta\rho_s}{\rho_s}\right) g\Delta Z}} = 0.7\left(\frac{h}{H_o}\right)^{1.25} \tag{13}$$

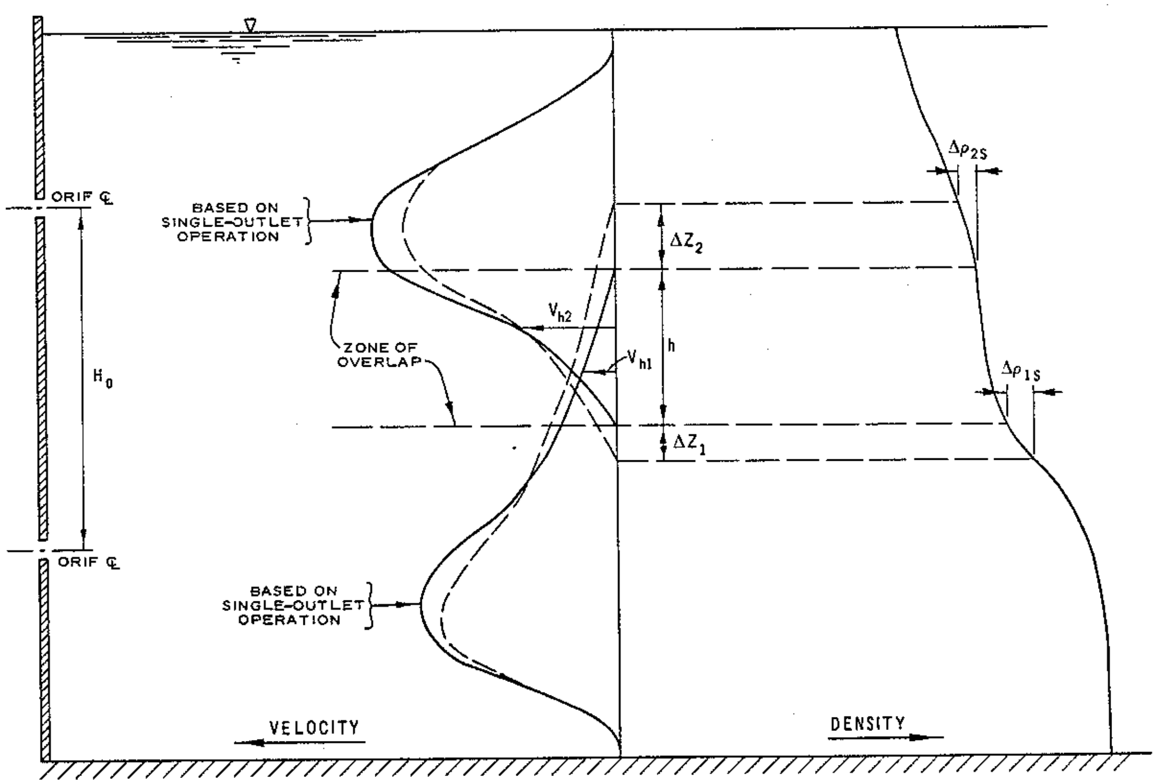


Fig. 9. Definition sketch of variables for controlled-shift technique

where

V_h = average velocity in the zone of overlap of either the upper or lower withdrawal layer, fps

$\Delta\rho_s$ = density difference of fluid between the elevations of the original withdrawal limit and the shifted withdrawal limit, g/cc

ρ_s = density of fluid at the elevation of the original withdrawal limit, g/cc

g = acceleration due to gravity, ft/sec^2

ΔZ = vertical shift of the withdrawal limit, ft

h = vertical distance of overlap of the velocity profiles, ft

H_o = vertical distance between the orifice ℄'s, ft

Since h/H_o is constant for any given flow condition, the value of the densimetric Froude number for the shift of both of the inner withdrawal limits for a given flow condition will be the same. The value of the densimetric Froude number for each flow condition was determined by adjusting the inner withdrawal limits of the predicted velocity profiles, based on single-orifice operation, and superimposing until good agreement was obtained between the observed and predicted velocity profiles and the value of the densimetric Froude number was the same for the shift of both of the inner withdrawal limits. A comparison of the observed and predicted velocity profiles based on the controlled-shift technique is shown in plates 19-24.

26. A computer program (a category C program as defined by Engineer Regulation 1110-1-10[6]) has been developed at WES for application of all of the results reported herein. The program is operational on the WES Time Sharing System and may be adapted for batch processing. The program can be used to analyze the withdrawal characteristics of flow from a randomly density-stratified reservoir through single- or multiple-level outlets. As many as six outlets can be operated simultaneously, and the top outlet can be a free or submerged weir.

PART IV: DISCUSSION OF RESULTS

27. The techniques described herein provide a means of predicting the limits of and the velocity distribution within the zone of withdrawal upstream of single- or multiple-level outlets. With this information known, the relative contribution of selected vertical extents of each layer to the total release can be determined. Then, with assumed or known gradients of temperature, dissolved oxygen content, and/or other water-quality parameters in the reservoir, the value of each parameter representative of the total release can be estimated by means of weighted averages. Application of these results through the use of a computer program is recommended for actual operation of prototype structures. If other pertinent meteorologic, hydrologic, and hydrographic data and methodology are know, these results can be applied to predict the effectiveness of proposed impoundments, selective withdrawal structures, and operation schedules for preserving and enhancing quality water and related resources.

28. Selective withdrawal tests have been conducted in rectangular shaped flumes with widths of 1, 3, and 4 ft, as well as in irregular shaped models of specific reservoirs. The observed and predicted withdrawal limits determined in these tests have shown good agreement. This correlation indicates that the assumption made in the analysis, i.e., that the width of the reservoir section being considered does not influence the withdrawal limits, is valid. The reservoir width does, however, as indicated by the analysis, affect the magnitudes of the velocities within the withdrawal zone.

29. The techniques presented for predicting the characteristics of selective withdrawal have been applied to Lucky Peak, Detroit, and other existing prototype impoundments by the U. S. Army Engineer Division, North Pacific, and have produced very good correlation with observed data. The techniques have also been verified by other Corps of Engineers offices. Some of the more extensive evaluations of the WES selective withdrawal techniques have been conducted by Clay and Fruh.[7-9]

30. The effects of geometry in the vicinity of an intake

structure have been observed to be significant, based on the results of specific model studies. For example, in tests of the 1:20-scale, three-dimensional model of the structure proposed for Lake New Hope,[10] the model indicated that an inlet located on the upstream face of the intake structure would permit releases approximately double those permitted through a side inlet located very close to the embankment, without initiating withdrawal below the interface or thermocline. Stratified flow patterns observed in the 1:40-scale, three-dimensional model of the outlet works proposed for Meramec Park Reservoir,[11] which reproduced approximately 400 to 500 ft of the reservoir topography and a curved, narrow approach channel upstream of a single, low-level intake, indicated that local geometry was also of importance. The narrow approach channel and shallow depth of the reservoir created shear along the interface that, during high flows, caused considerable mixing along the interface. Considerably greater mixing and/or blending of the warm and cold waters would be anticipated with an intake structure located in a relatively shallow narrow section of a man-made lake. The interface tends to be elevated and lowered, respectively, along the inner and outer portions of a curved approach channel. Based upon these observations, it is believed that the geometry adjacent to the intakes may have a significant effect upon the withdrawal limits.

31. It is furthermore believed that the use of physical hydraulic models to evaluate the effectiveness of specific proposed structures should be encouraged to ensure reasonably adequate and accurate performance of proposed projects, as well as to gain additional knowledge concerning the mechanics of stratified flow and refinements of the state-of-the-art. The model study of the Clarence Cannon control structure[12] indicated the inadequacy of the submerged, water-quality weir in meeting desired downstream objectives. This inadequacy was a result of a lack of appropriate design guidance at the time the weir was designed. The model was used to develop a weir design that would retain the hypolimnetic waters during normal power generation. Power generation at Clarence Cannon provides for a pumped-storage operation, with a reregulation dam downstream. The model was also used to investigate the

effect of the water-quality weir on the pumpback operation. Pumpback was simulated for a period of 9 hr, and a minimal amount of mixing occurred between the water in the hypolimnion and the pumpback water which was discharged into the epilimnion due to the presence of the submerged weir. However, it cannot be generally concluded that a pumpback operation under these conditions does not destroy stratification, since there are many factors, such as density gradient, flow rate, relative depths of the epilimnion and hypolimnion, local geometry, weir characteristics, etc., which may influence this type of operation.

32. An area of selective withdrawal design which has not received adequate acknowledgment and attention is that of the mechanics of stratified flow in manifold systems. It is appropriate to consider blending water at different reservoir elevations in order to satisfy downstream quality requirements. However, if water is simultaneously entering a common wet well from a high- and a low-level port, it is conceivable that the more dense water from the low-level port could partially or completely block the flow of the less dense water from the high-level port. This problem can be circumvented by discharging flows from different elevations into separate wells. In this case, it may be necessary to ensure that the separate flows are completely mixed prior to their release downstream so that a stratified flow condition does not exist in the downstream channel.

33. Three-dimensional models operated in such a manner that they can reproduce typical hydrologic records should be utilized to investigate the effects of unsteady and varied flow conditions due to variations in geometry, inflows, outflows, storage, and density that are characteristic of prototype reservoirs. The results of even limited tests in such models would be most beneficial in the development of mathematical simulations and computer programs for solution of the problems associated with the planning, design, and operation of reservoirs to achieve well-defined, desirable objectives.

LITERATURE CITED

1. Bohan, J. P. and Grace, J. L., Jr., "Mechanics of Flow from Stratified Reservoirs in the Interest of Water Quality; Hydraulic Laboratory Investigation," Technical Report H-69-10, Jul 1969, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

2. Harleman, D. R. F., Morgan, R. L., and Purple, R. A., "Selective Withdrawal from a Vertically Stratified Fluid," International Association for Hydraulic Research, Eighth Conference, Aug 1959.

3. Harleman, D. R. F. and Elder, R. A., "Withdrawal from Two-Layered Stratified Flows," Journal, Hydraulics Division, American Society of Civil Engineers, Vol 91, No. HY4, Jul 1965, pp 43-58.

4. Grace, J. L., Jr., "Selective Withdrawal Characteristics of Weirs; Hydraulic Laboratory Investigation," Technical Report H-71-4, Jun 1971, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

5. Bohan, J. P. and Gloriod, T. L., "Simultaneous, Multiple-Level Release from Stratified Reservoirs; Hydraulic Laboratory Investigation," Research Report H-72-3, Dec 1972, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

6. Office, Chief of Engineers, U. S. Army, "Development, Review, and Use of Computer Programs," Engineer Regulation 1110-1-10, 30 Jun 1970, U. S. Government Printing Office, Washington, D. C.

7. Clay, H. M., Jr., and Fruh, E. G., "Management of Water Quality in Releases from Southwestern Impoundments," Sixth American Water Resources Conference of American Water Resources Association, Oct 1970, Las Vegas, Nev.

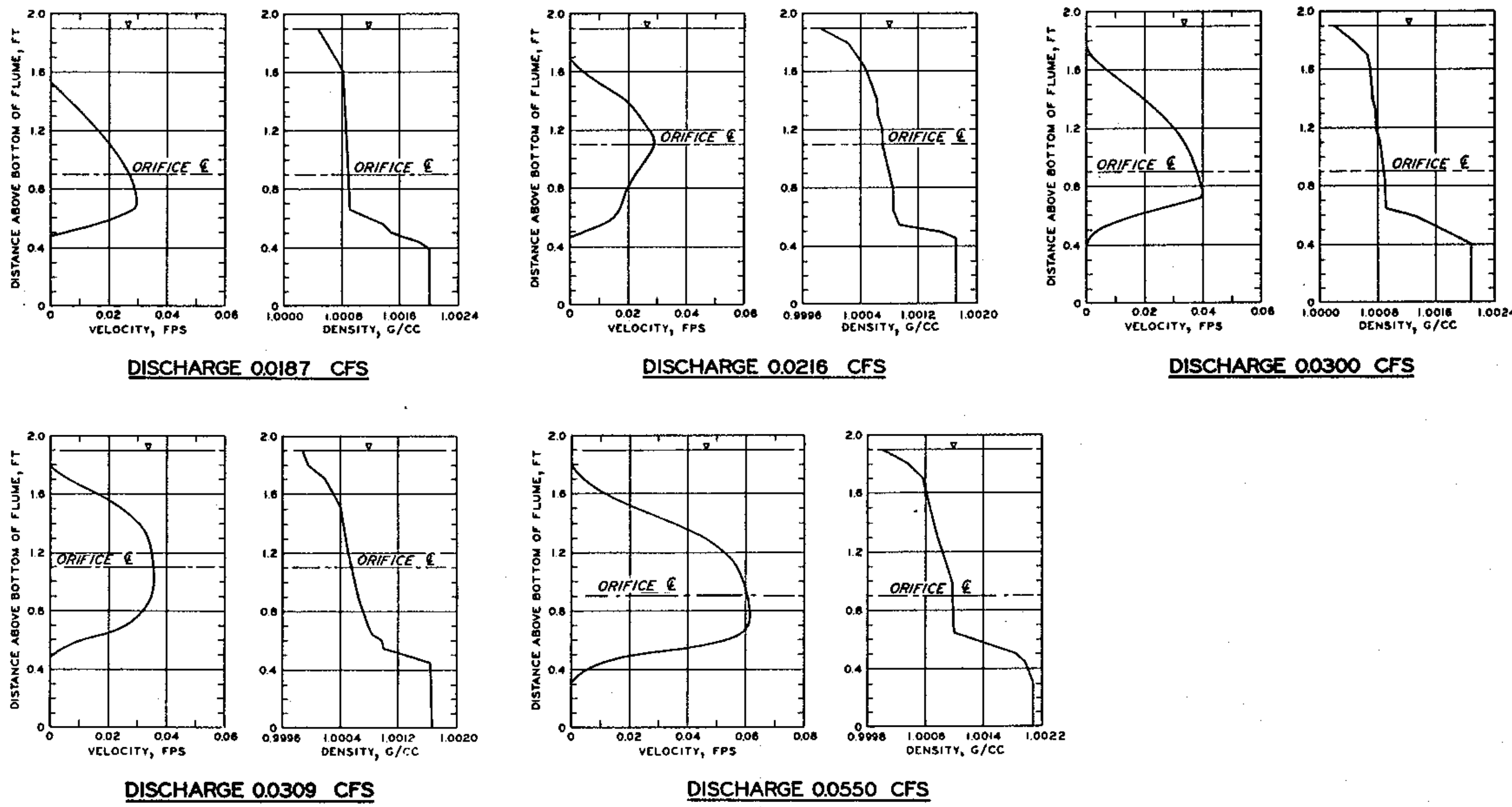
8. __________, "Selective Withdrawal at Lake Livingston; An Impoundment Water Quality Model Emphasizing Selective Withdrawal," Progress Report EHE 70-18, CRWR 66, Nov 1970, University of Texas, Austin, Tex.

9. Fruh, E. G., "Selective Withdrawal at Lake Livingston," Final Report EHE 72-15, CRWR 91, May 1972, University of Texas, Austin, Tex.

10. Melsheimer, E. S. and Oswalt, N. R., "Outlet Works for New Hope Reservoir, Cape Fear River Basin, North Carolina; Hydraulic Model Investigation," Technical Report H-69-14, Oct 1969, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

11. Bohan, J. P., "Water Temperature Control Weir for Meramec Park Dam, Meramec River, Missouri; Hydraulic Model Investigation," Technical Report H-70-1, Feb 1970, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

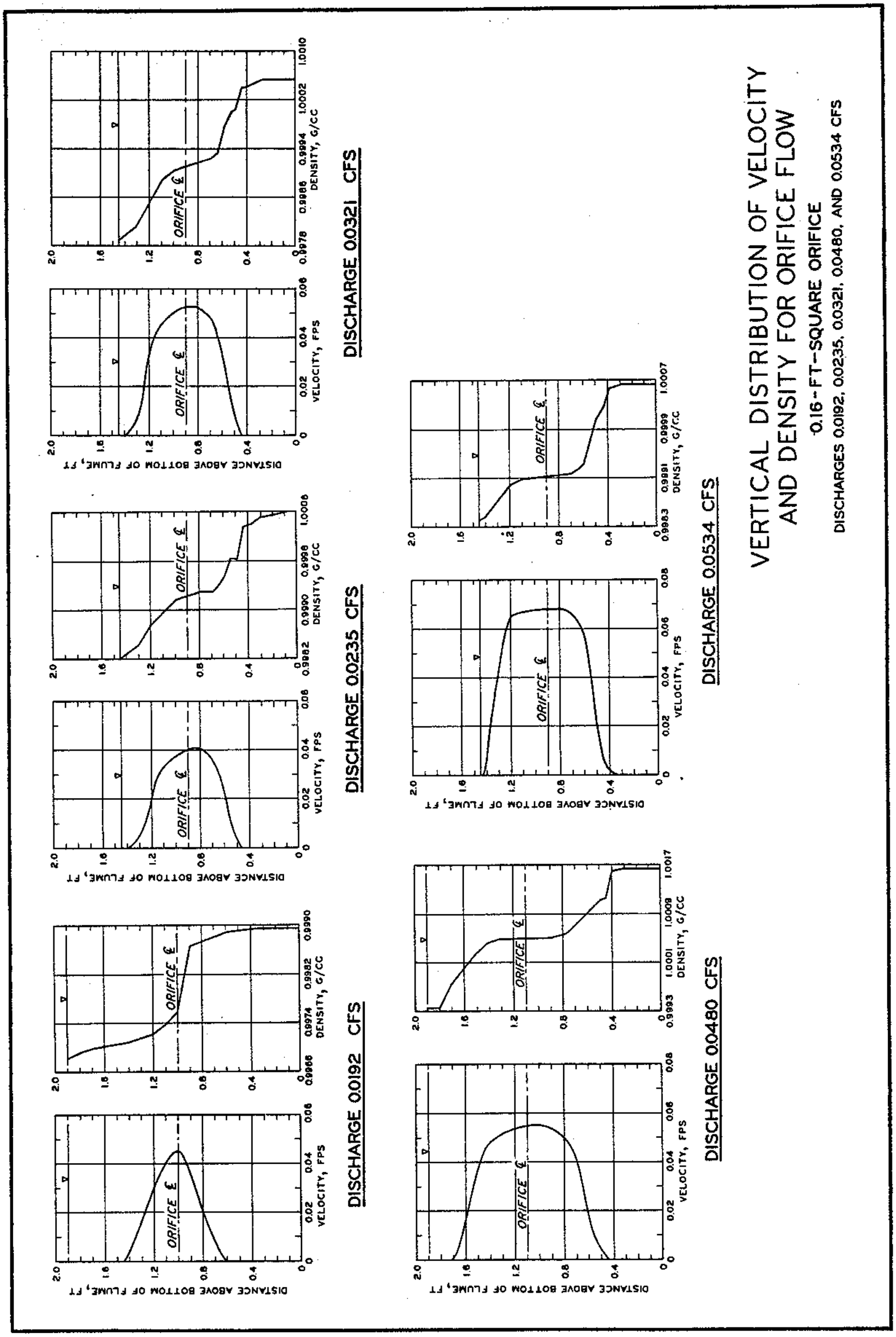
12. Fletcher, B. P., "Spillway for Clarence Cannon Dam, Salt River, Missouri; Hydraulic Model Investigation," Technical Report H-71-7, Oct 1971, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.



VERTICAL DISTRIBUTION OF VELOCITY AND DENSITY FOR ORIFICE FLOW

0.16-FT-SQUARE ORIFICE

DISCHARGES 0.0187, 0.0216, 0.0300, 0.0309, AND 0.0550 CFS

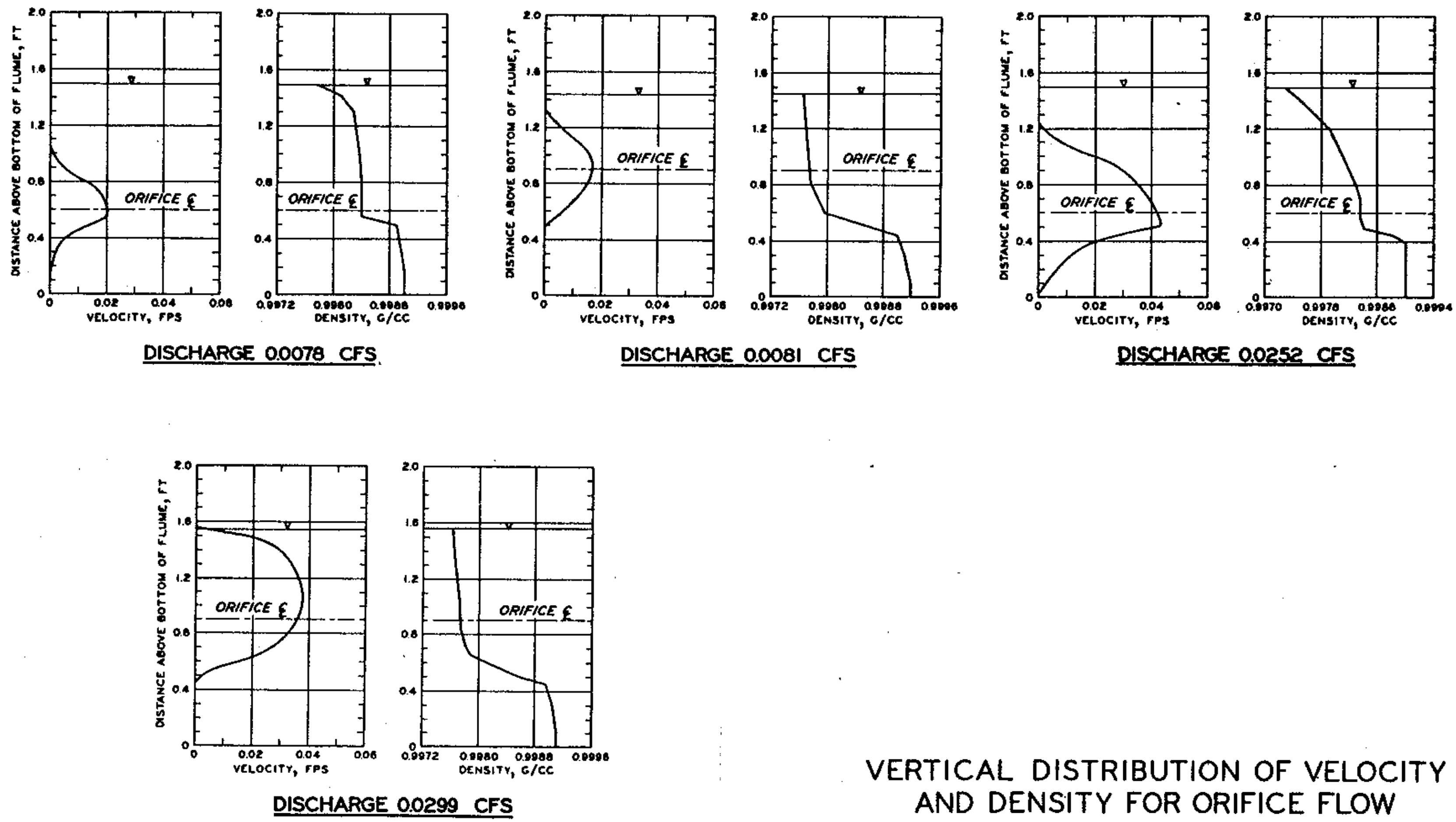


VERTICAL DISTRIBUTION OF VELOCITY AND DENSITY FOR ORIFICE FLOW

0.16-FT-SQUARE ORIFICE

DISCHARGES 0.0192, 0.0235, 0.0321, 0.0480, AND 0.0534 CFS

PLATE 2

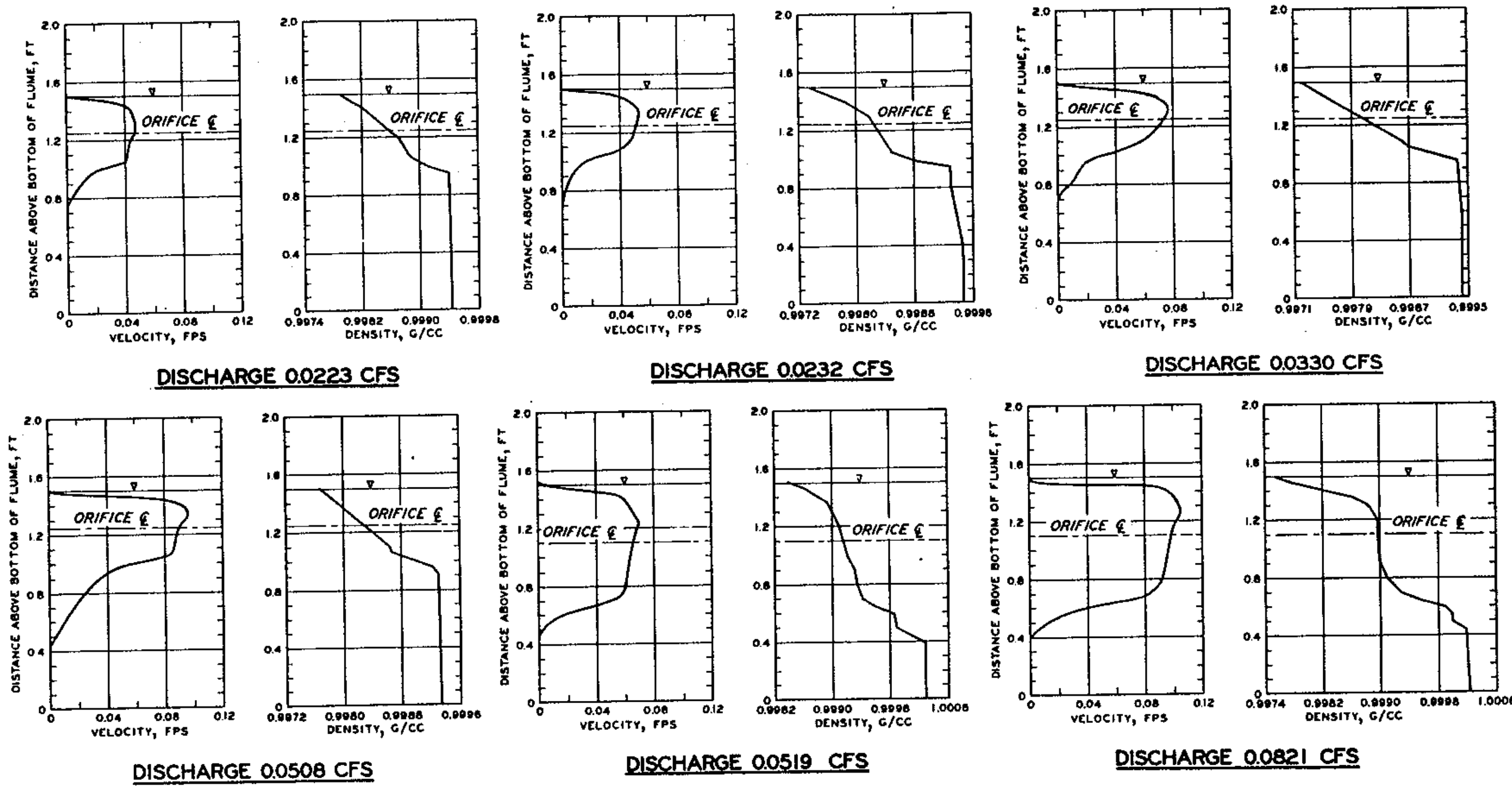


VERTICAL DISTRIBUTION OF VELOCITY AND DENSITY FOR ORIFICE FLOW

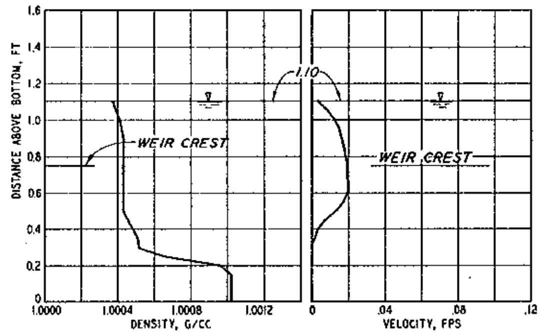
0.08-FT-SQUARE ORIFICE

DISCHARGES 0.0078, 0.0081, 0.0252, AND 0.0299 CFS

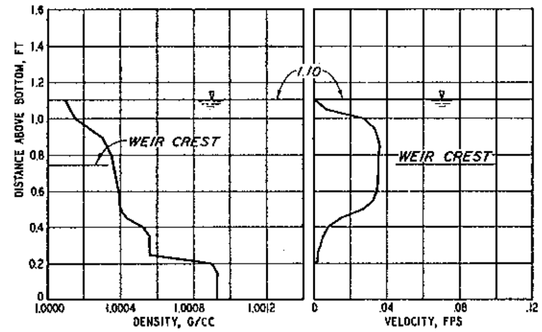
PLATE 4



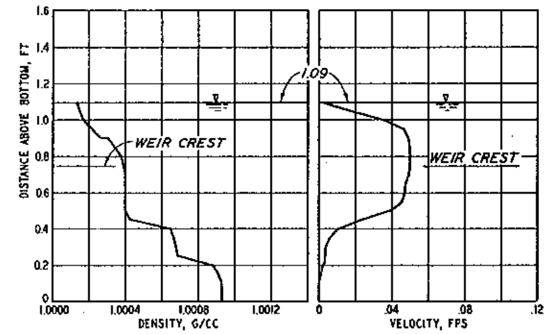
VERTICAL DISTRIBUTION OF VELOCITY AND DENSITY FOR ORIFICE FLOW
(WATER SURFACE CONTROLS UPPER WITHDRAWAL LIMIT)
0.16-FT-SQUARE ORIFICE
DISCHARGES 0.0223, 0.0232, 0.0330, 0.0508, 0.0519, AND 0.0821 CFS



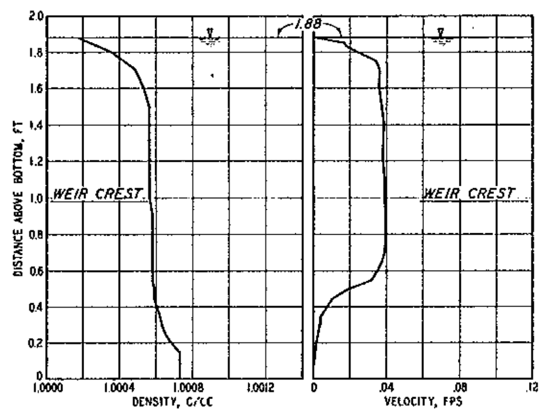
DISCHARGE 0.00646 CFS
<u>WEIR CREST EL 0.750</u>



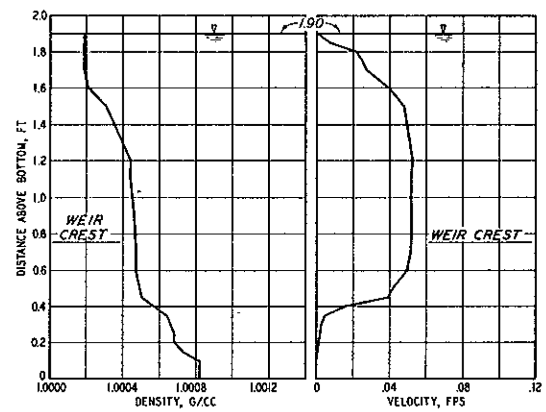
DISCHARGE 0.0136 CFS
<u>WEIR CREST EL 0.750</u>



DISCHARGE 0.0203 CFS
<u>WEIR CREST EL 0.750</u>

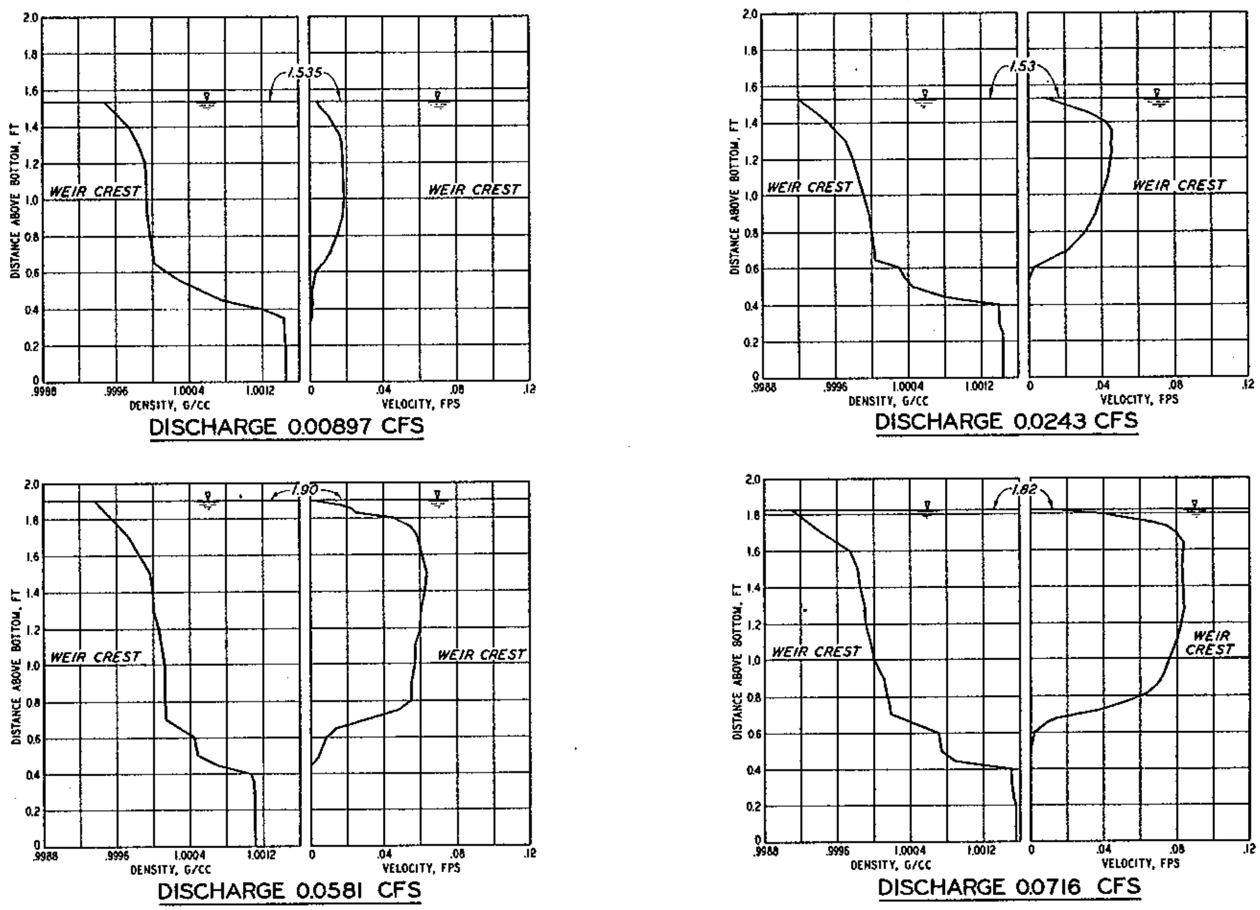


DISCHARGE 0.0370 CFS
<u>WEIR CREST EL 0.980</u>



DISCHARGE 0.0516 CFS
<u>WEIR CREST EL 0.750</u>

VERTICAL DISTRIBUTION OF
DENSITY AND VELOCITY
FOR SUBMERGED WEIR FLOW
DISCHARGES 0.00646, 0.0136, 0.0203,
0.0370, AND 0.0516 CFS

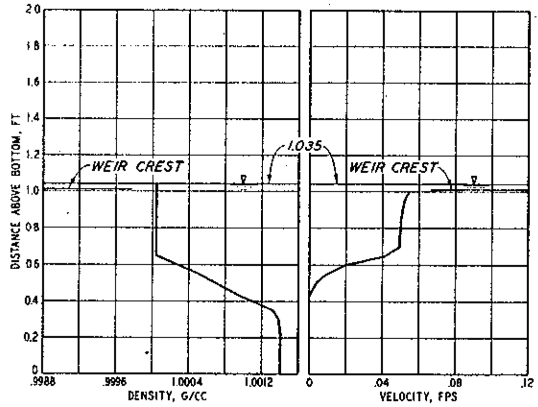


VERTICAL DISTRIBUTION OF DENSITY AND VELOCITY FOR SUBMERGED WEIR FLOW

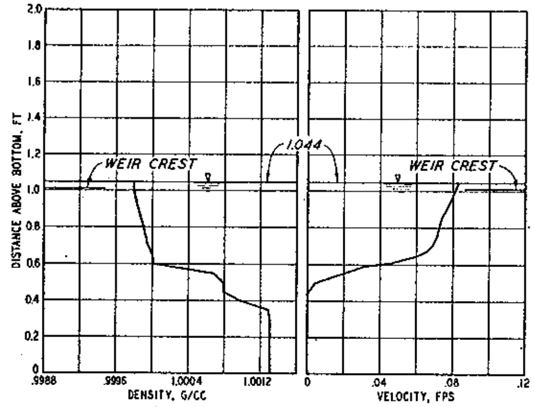
DISCHARGES 0.00897, 0.0243, 0.0581, AND 0.0716 CFS

WEIR CREST ELEVATION 1.000

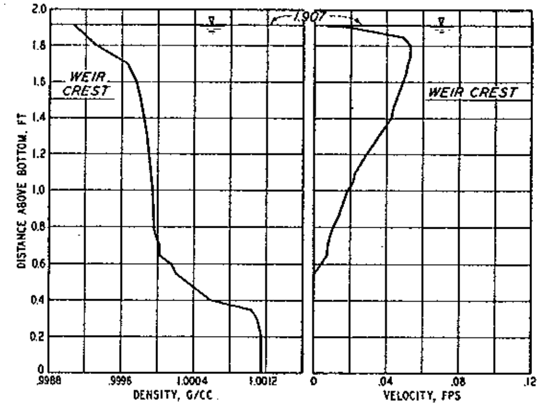
PLATE 6



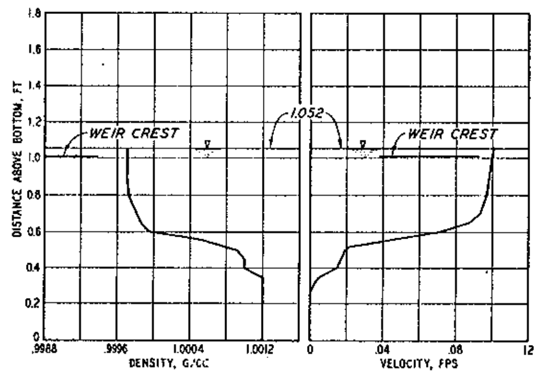
DISCHARGE 0.0169 CFS
WEIR CREST EL 1.005
FREE FLOW



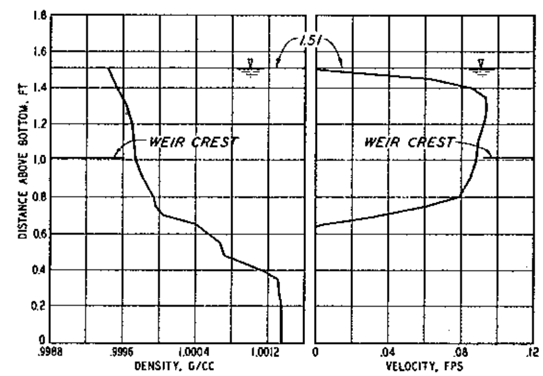
DISCHARGE 0.0256 CFS
WEIR CREST EL 1.005
FREE FLOW



DISCHARGE 0.0296 CFS
WEIR CREST EL 1.500
SUBMERGED FLOW



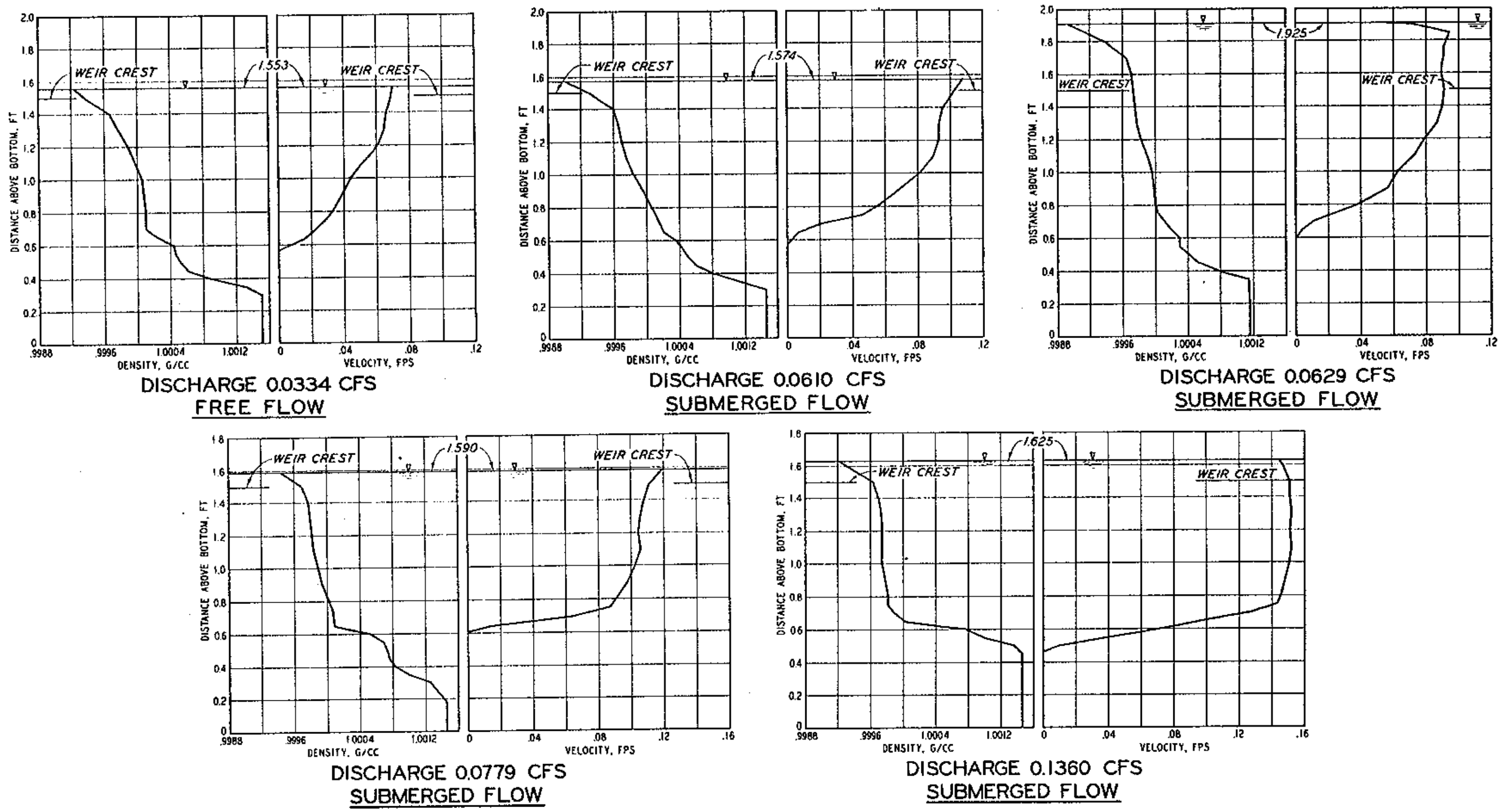
DISCHARGE 0.0422 CFS
WEIR CREST EL 1.005
FREE FLOW



DISCHARGE 0.0577 CFS
WEIR CREST EL 1.005
SUBMERGED FLOW

VERTICAL DISTRIBUTION OF DENSITY AND VELOCITY FOR FREE AND SUBMERGED WEIR FLOW

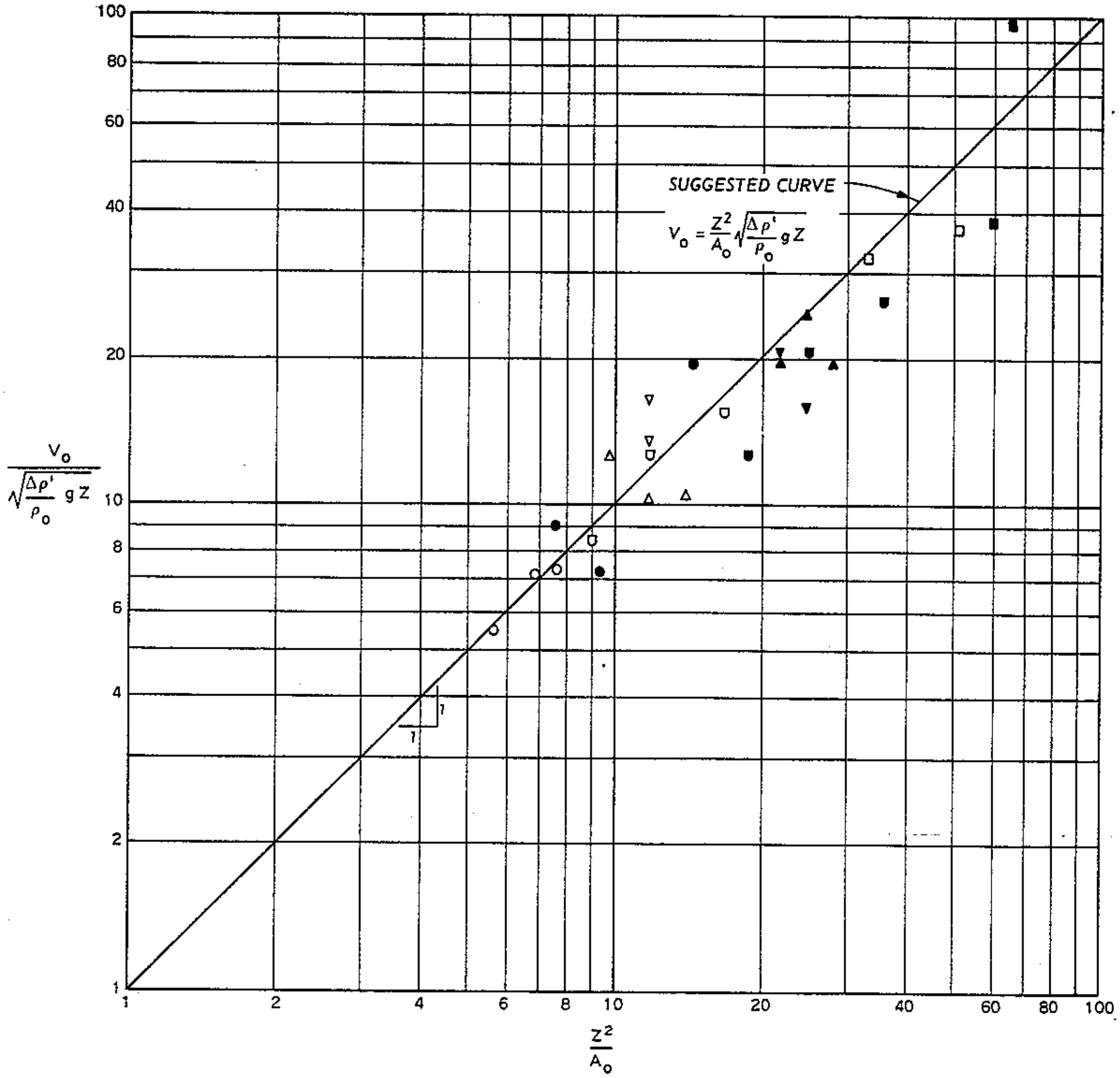
DISCHARGES 0.0169, 0.0256, 0.0296, 0.0422, AND 0.0577 CFS



VERTICAL DISTRIBUTION OF DENSITY AND VELOCITY FOR FREE AND SUBMERGED WEIR FLOW

DISCHARGES 0.0334, 0.0610, 0.0629, 0.0779, AND 0.1360 CFS

WEIR CREST ELEVATION 1.500



LEGEND

0.08-FT-SQUARE ORIFICE

□ LOWER, ■ UPPER — WITHDRAWAL CHARACTERISTICS

0.16-FT-SQUARE ORIFICE

○ LOWER, ● UPPER — WITHDRAWAL CHARACTERISTICS

0.11- BY 0.23-FT RECTANGULAR ORIFICE (LONG AXIS VERT)

▽ LOWER, ▼ UPPER — WITHDRAWAL CHARACTERISTICS

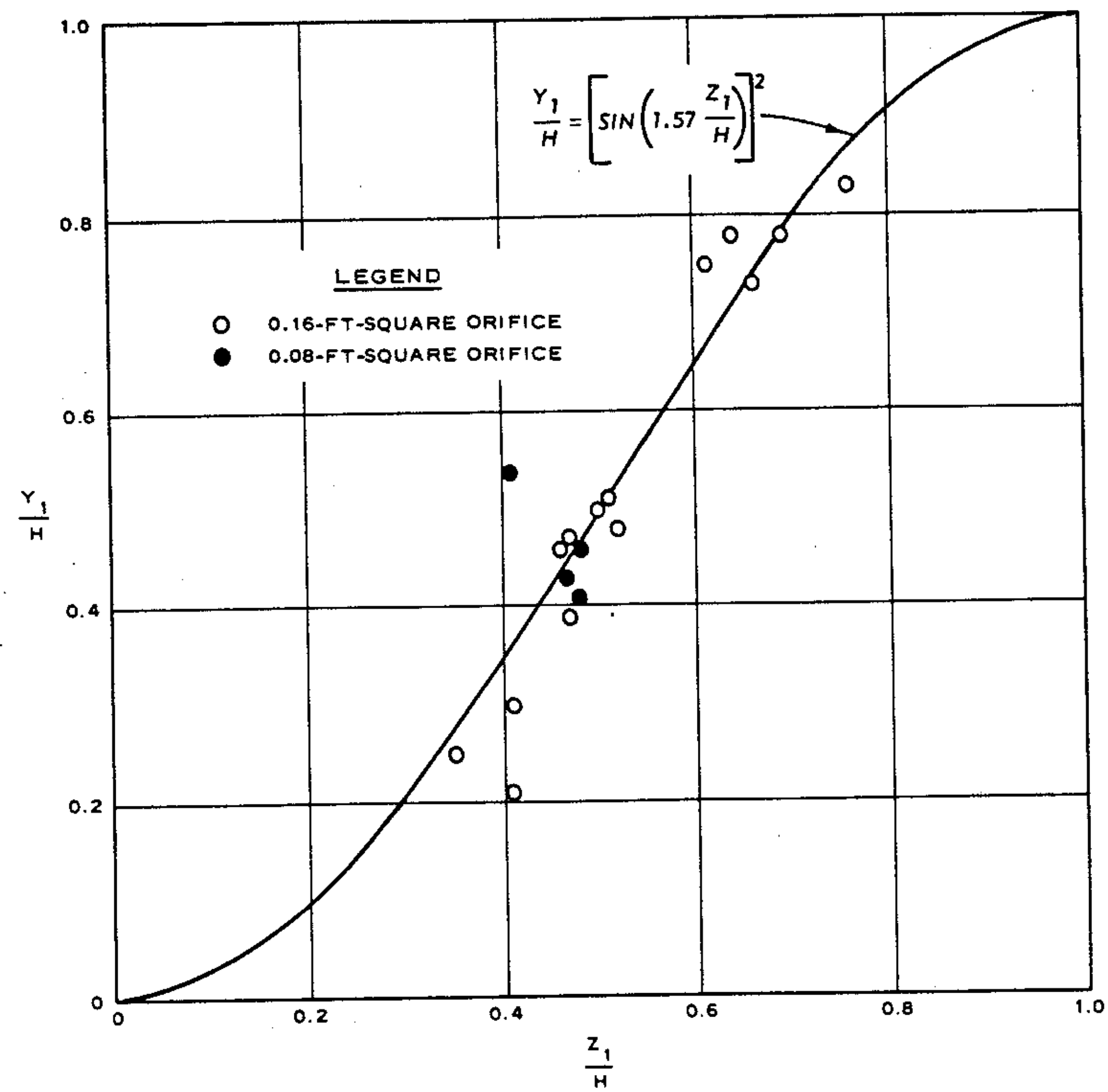
0.11- BY 0.23-FT RECTANGULAR ORIFICE (LONG AXIS HORIZ)

△ LOWER, ▲ UPPER — WITHDRAWAL CHARACTERISTICS

0.18-FT-DIAM ORIFICE

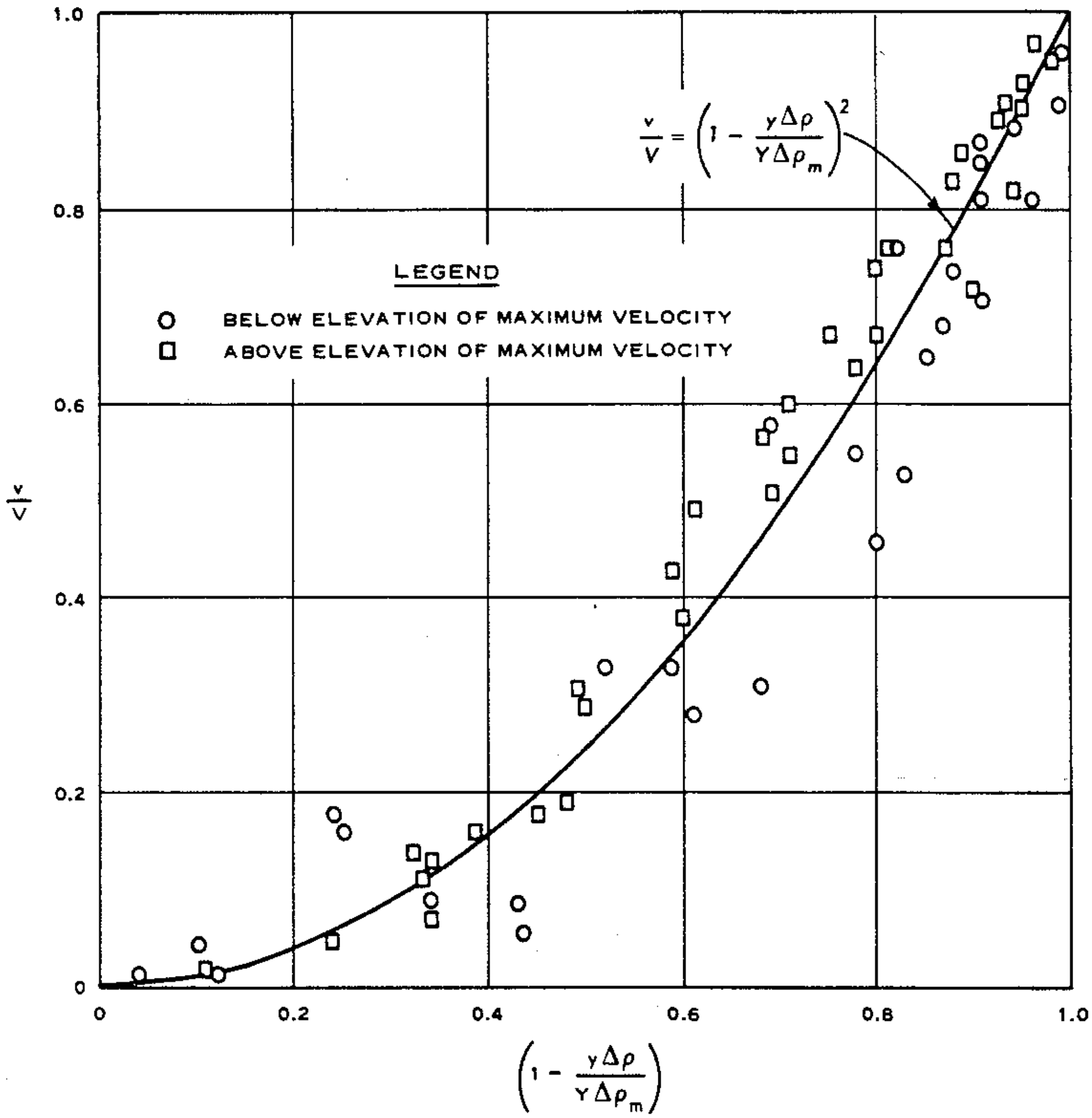
◡ LOWER, ● UPPER — WITHDRAWAL CHARACTERISTICS

WITHDRAWAL CHARACTERISTICS OF ORIFICES

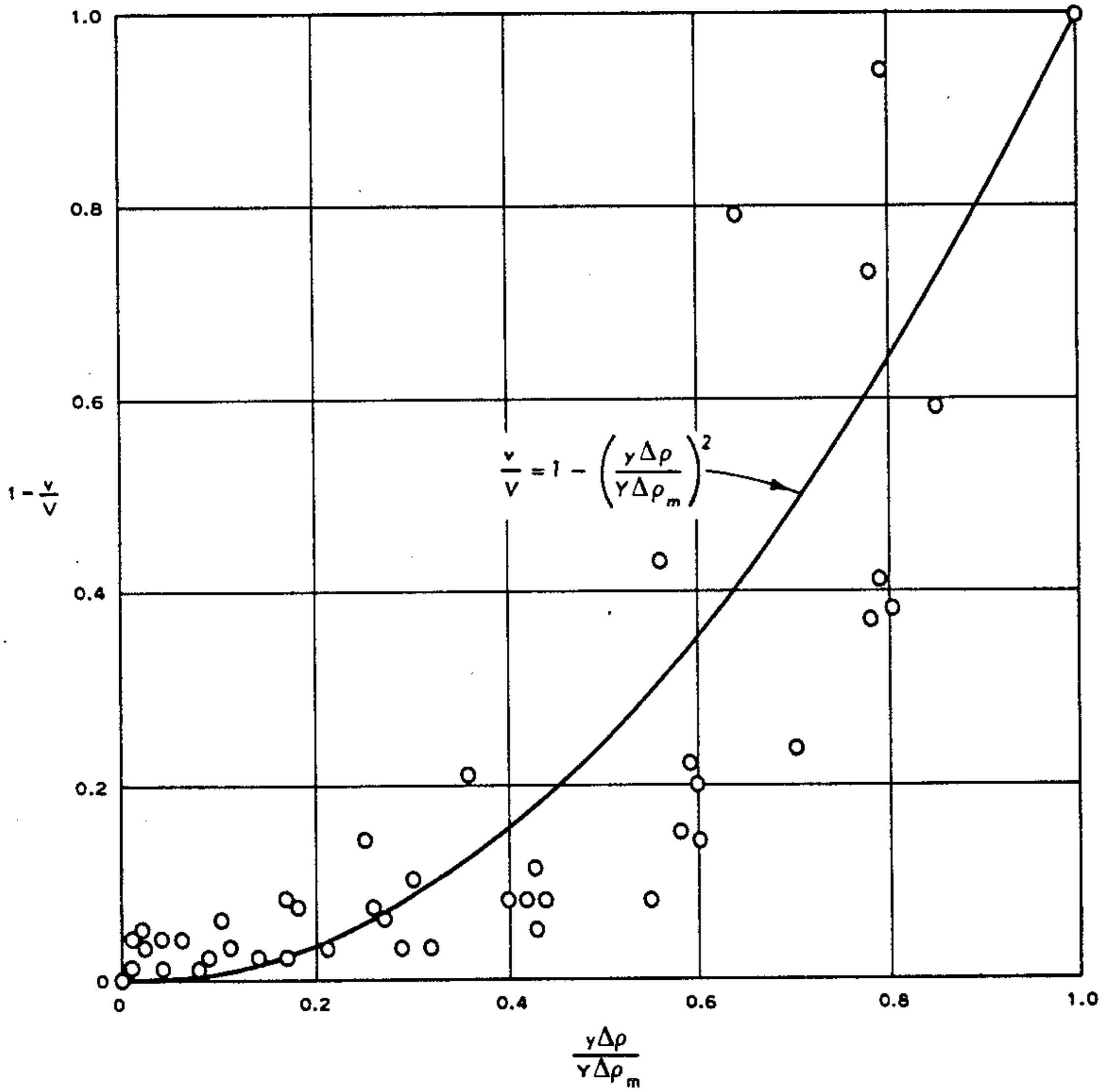


RELATIVE POSITION OF
OF MAXIMUM VELOCITY
IN STRATIFIED FLOW
THROUGH AN ORIFICE

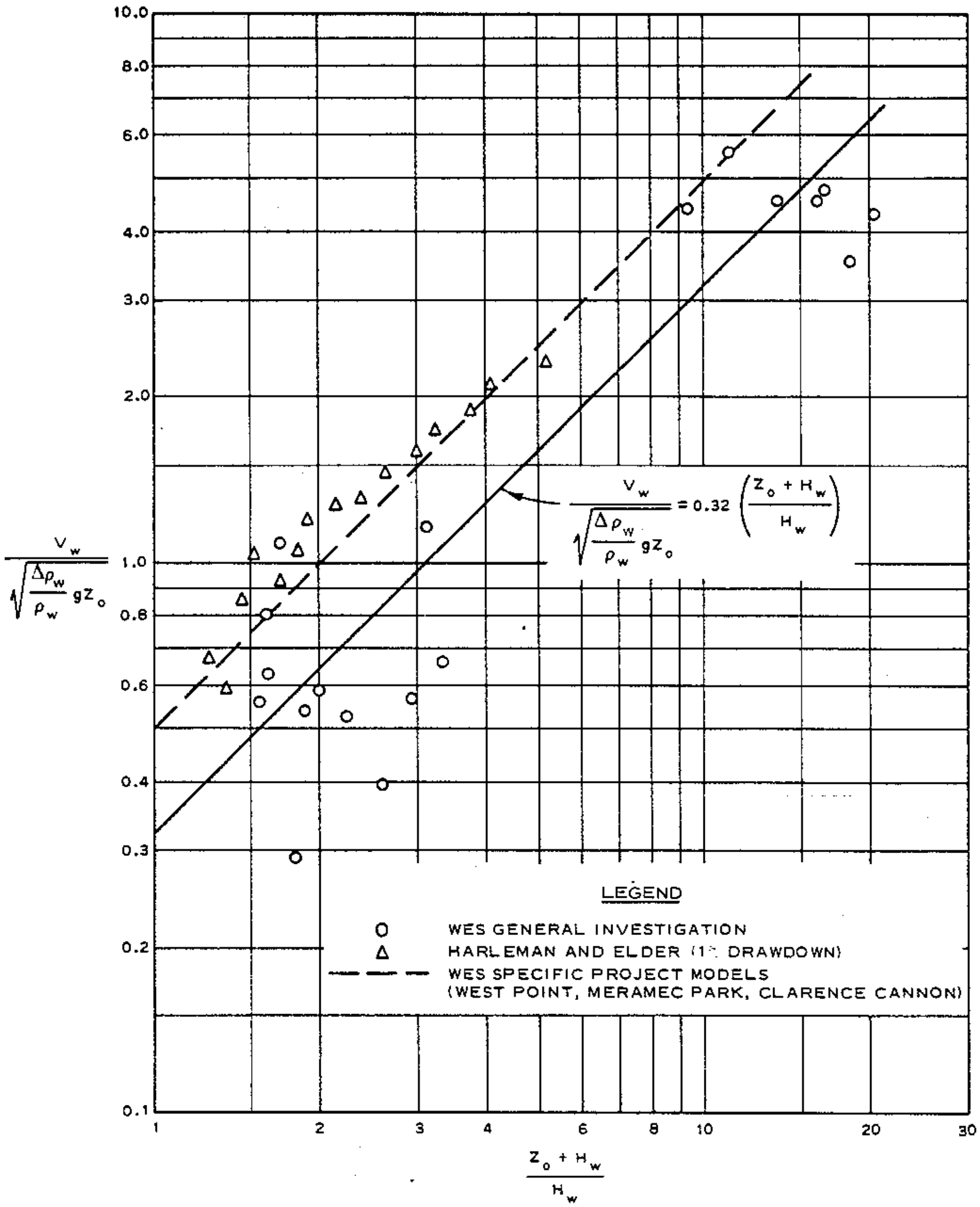
PLATE 10



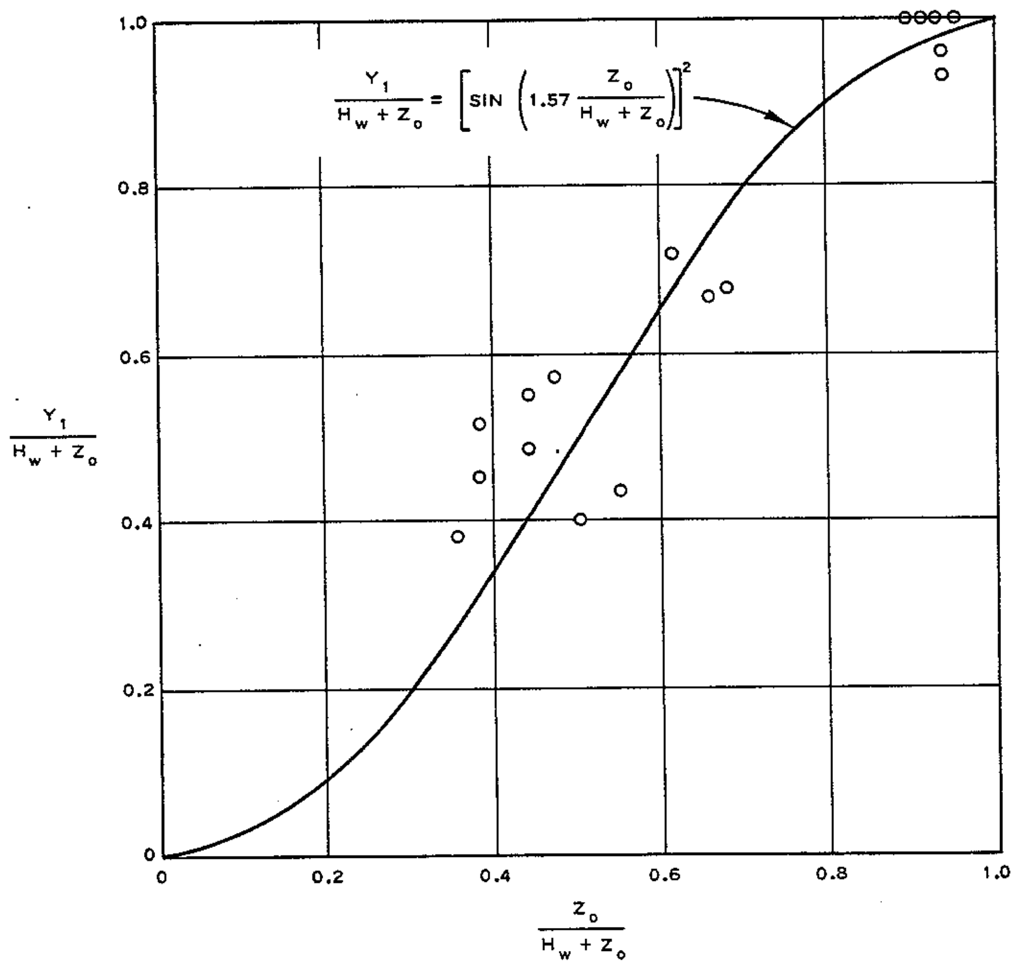
DIMENSIONLESS VELOCITY DISTRIBUTION FOR STRATIFIED FLOW THROUGH AN ORIFICE (BOUNDARY EFFECTS NEGLIGIBLE)



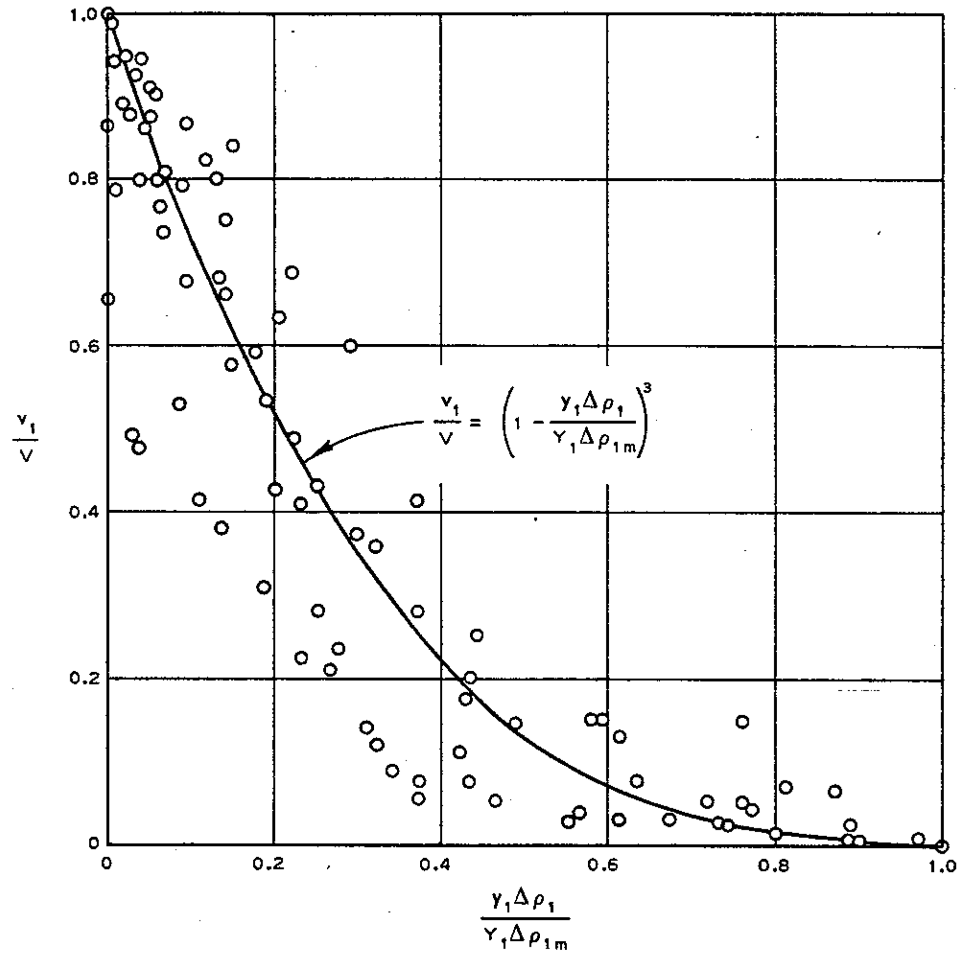
DIMENSIONLESS VELOCITY
DISTRIBUTION FOR STRATIFIED
FLOW THROUGH AN ORIFICE
FOR CONDITIONS IN WHICH
A BOUNDARY LIMITS
THE WITHDRAWAL ZONE



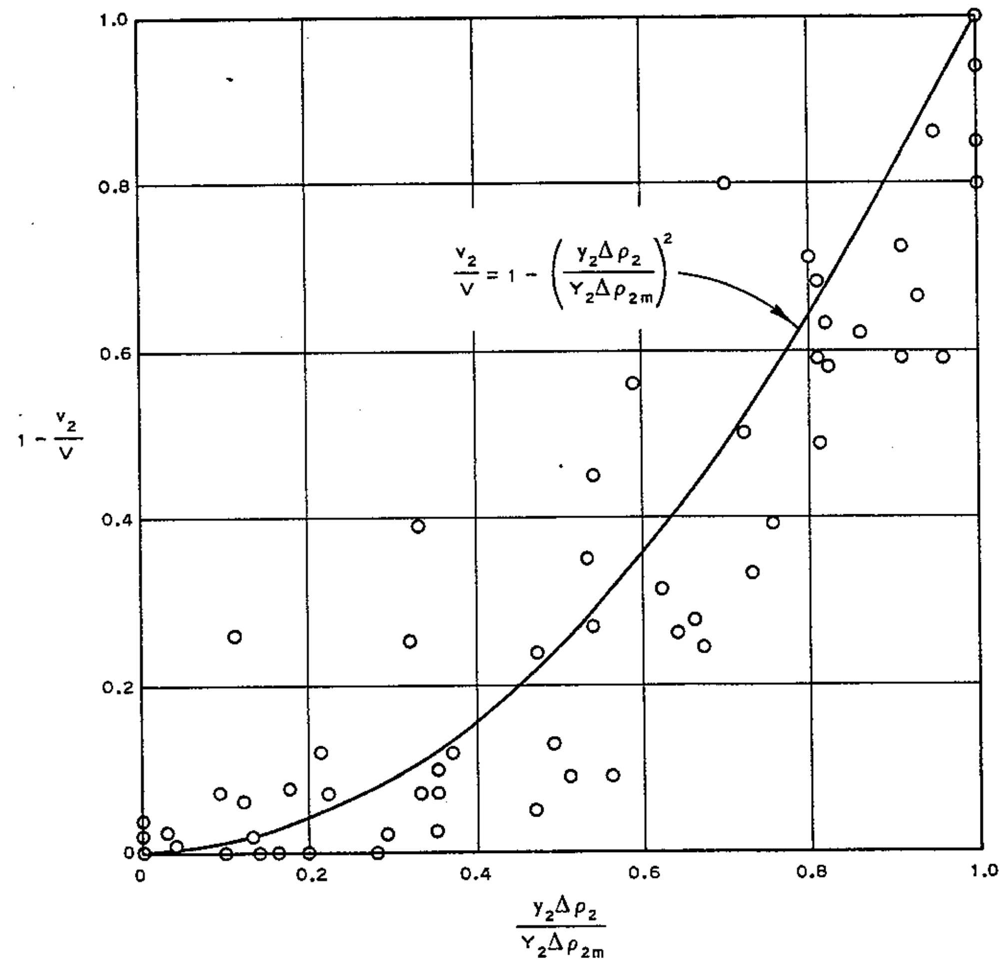
WITHDRAWAL CHARACTERISTICS
OF WEIR



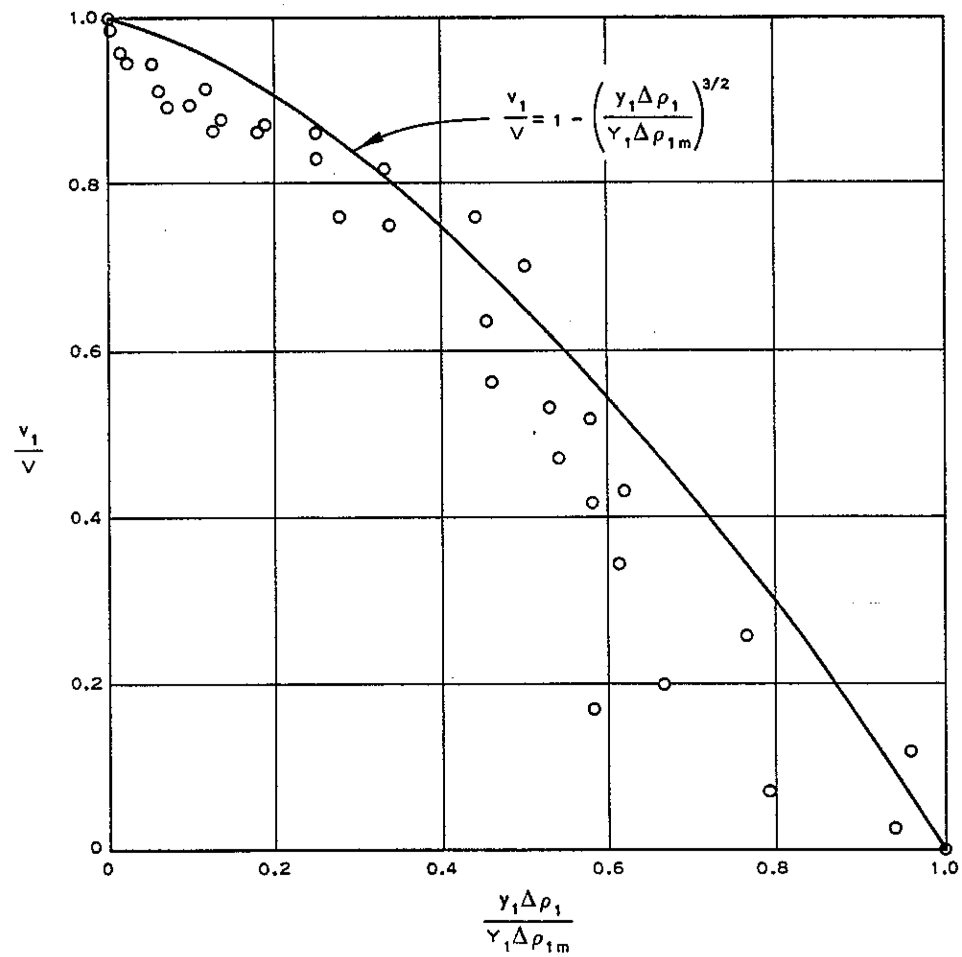
RELATIVE POSITION OF THE MAXIMUM VELOCITY TO THE WEIR CREST AND THE LOWER LIMIT OF WITHDRAWAL



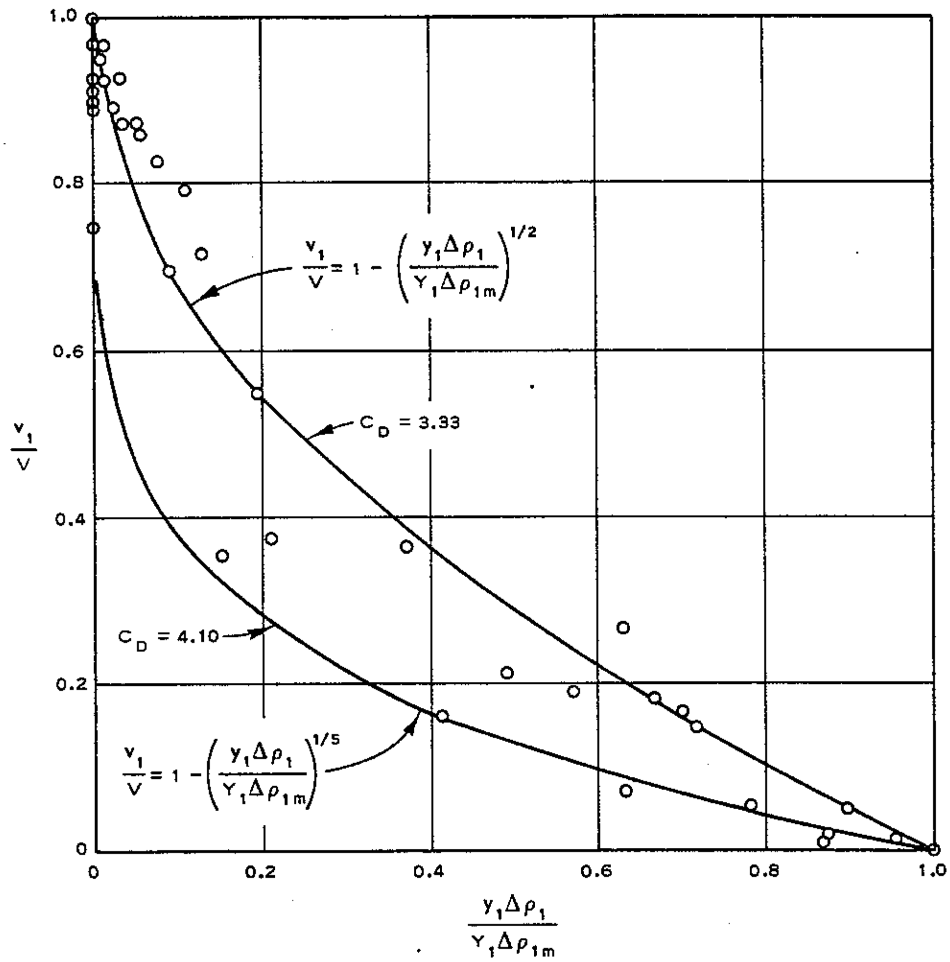
DIMENSIONLESS VELOCITY DISTRIBUTION
FOR PORTION BELOW MAXIMUM VELOCITY
WITH SUBMERGED WEIR FLOW
(BOUNDARY EFFECTS NEGLIGIBLE)



DIMENSIONLESS VELOCITY DISTRIBUTION FOR PORTION ABOVE MAXIMUM VELOCITY WITH SUBMERGED WEIR FLOW (FREE SURFACE BOUNDARY EFFECT)



DIMENSIONLESS VELOCITY DISTRIBUTION FOR FREE WEIR FLOW (FREE SURFACE BOUNDARY EFFECT), $C_D = 3.00$



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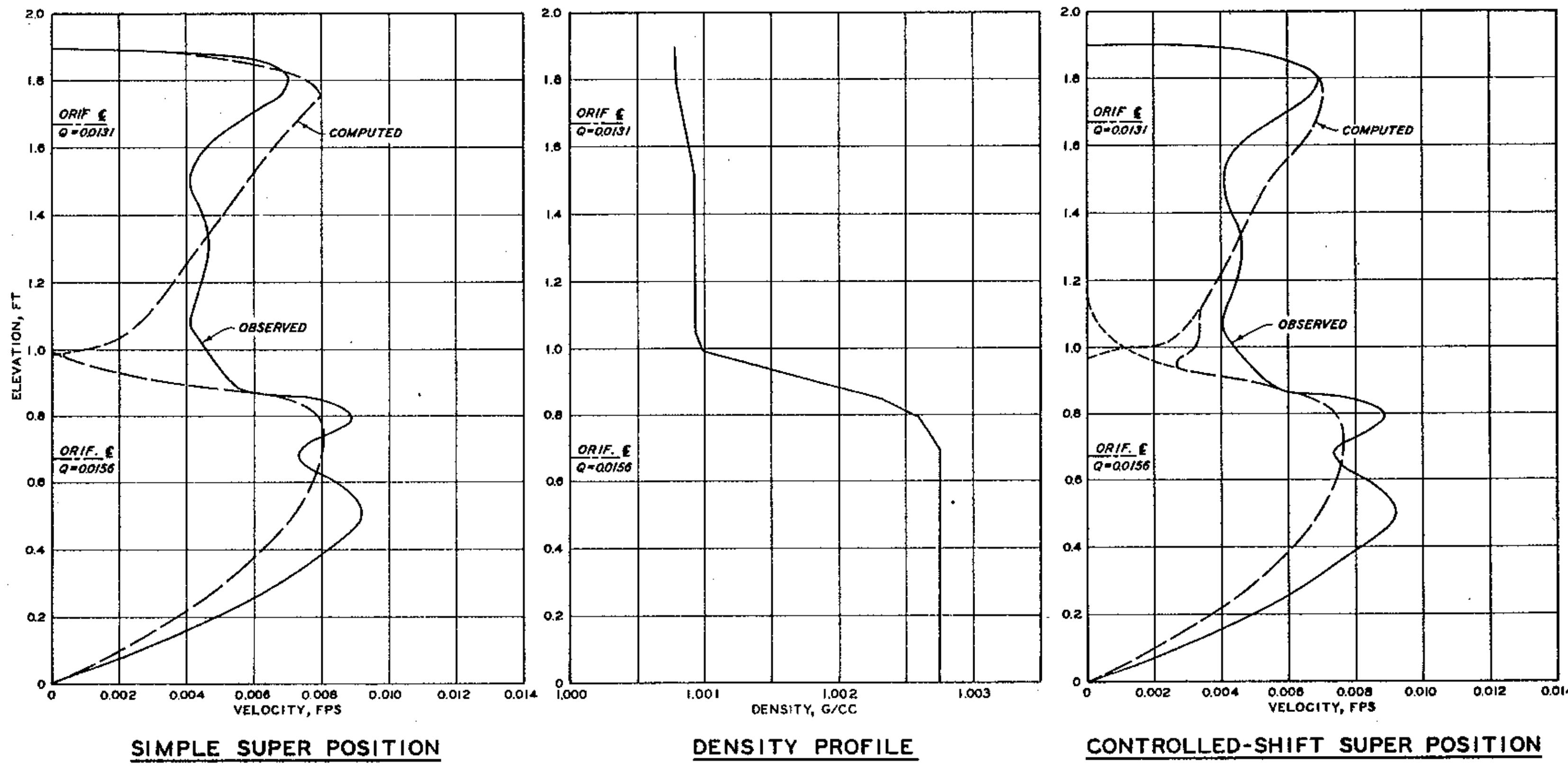

VERTICAL DISTRIBUTIONS OF
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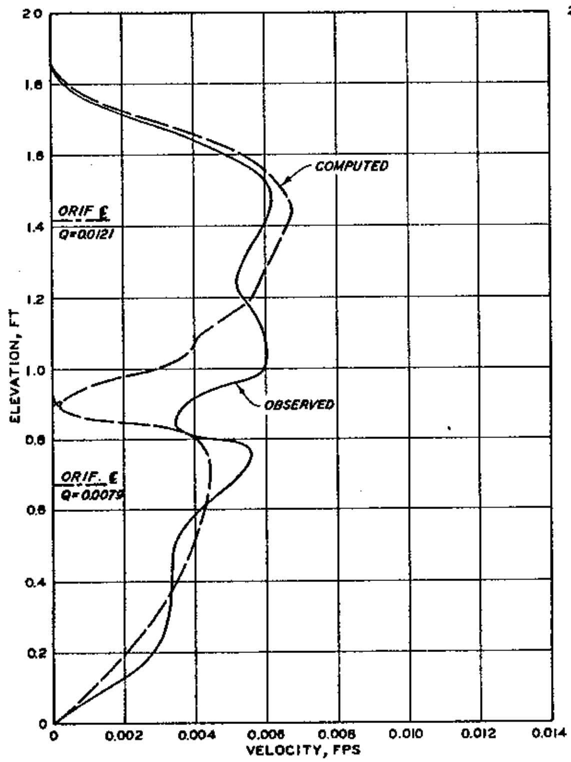
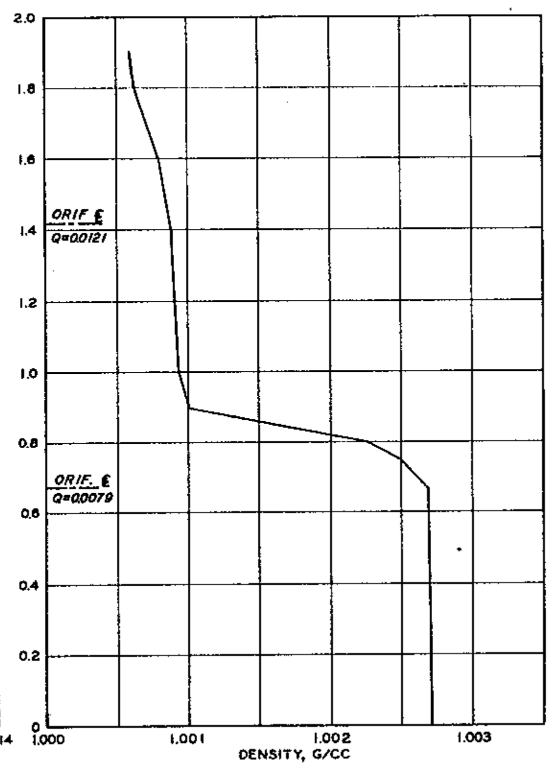
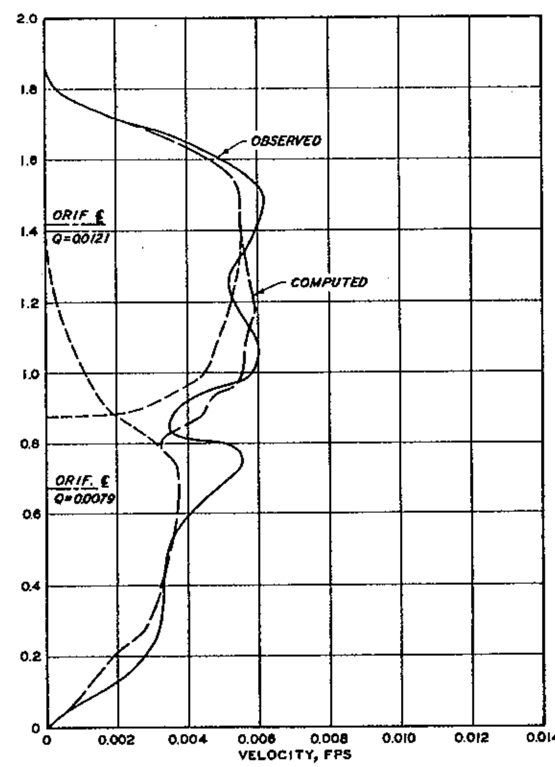
DISCHARGES 0.0131 AND 0.0156 CFS



SIMPLE SUPER POSITION

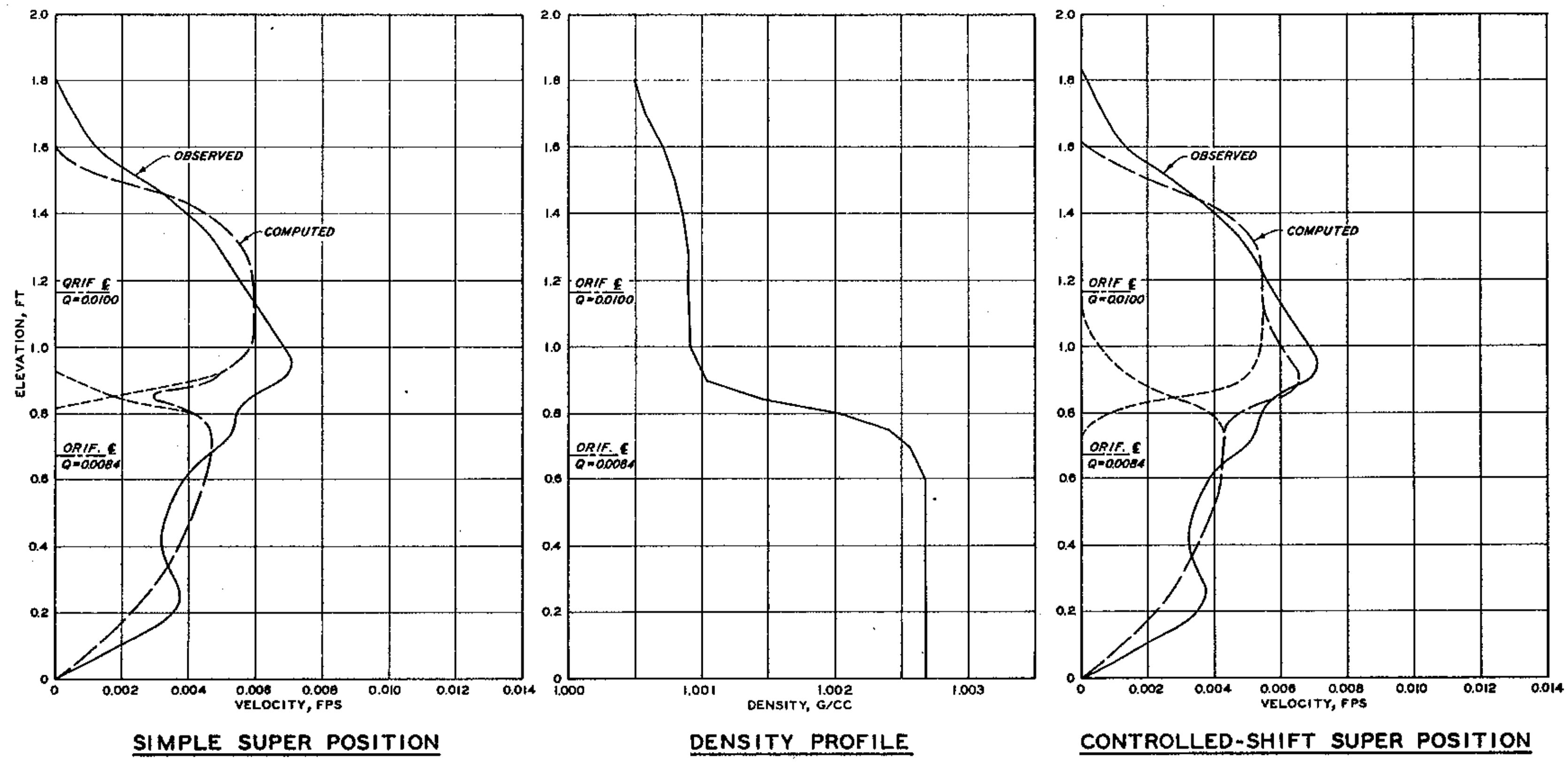


DENSITY PROFILE



CONTROLLED-SHIFT SUPER POSITION

VERTICAL DISTRIBUTIONS OF
VELOCITY AND DENSITY
DISCHARGES 0.0121 AND 0.0079 CFS



VERTICAL DISTRIBUTIONS OF
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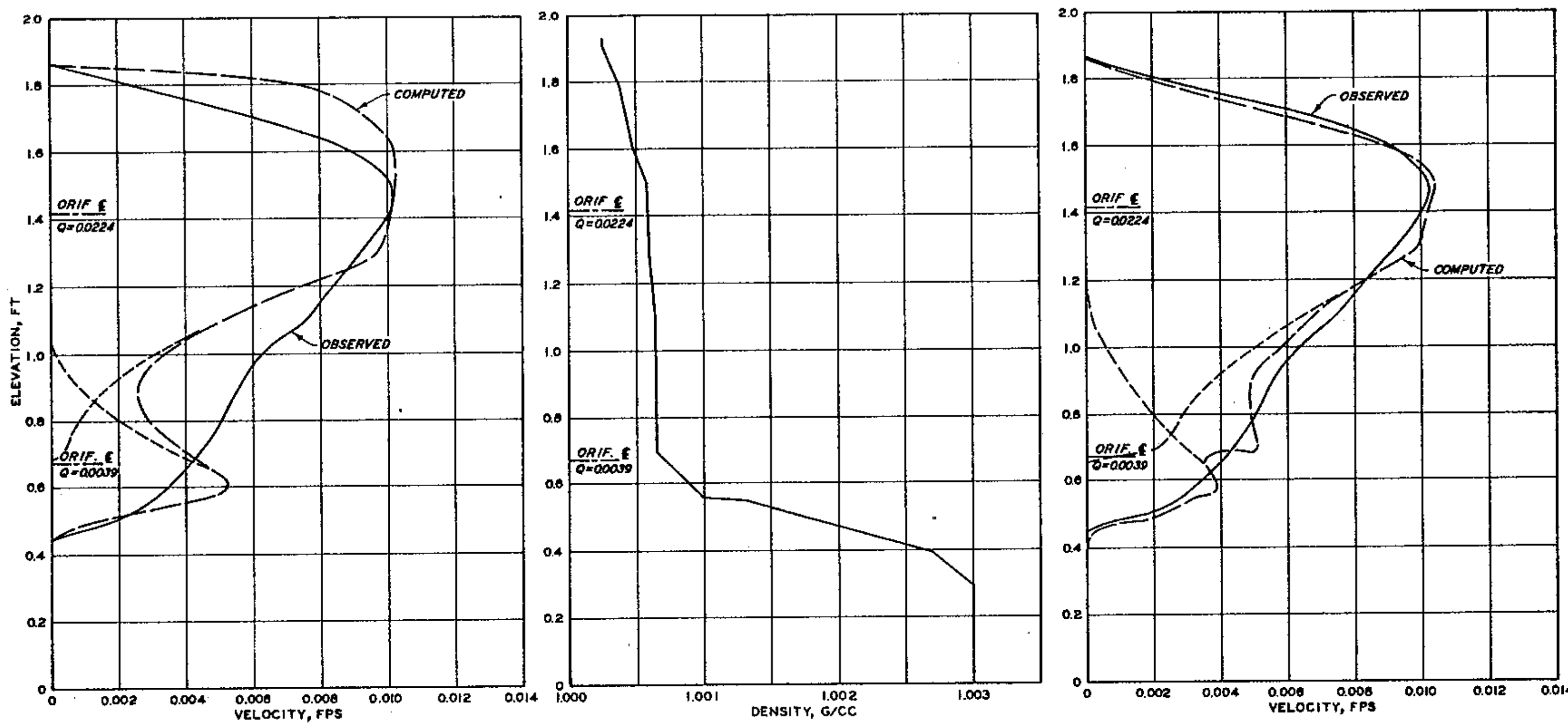
DISCHARGES 0.0100 AND 0.0084 CFS



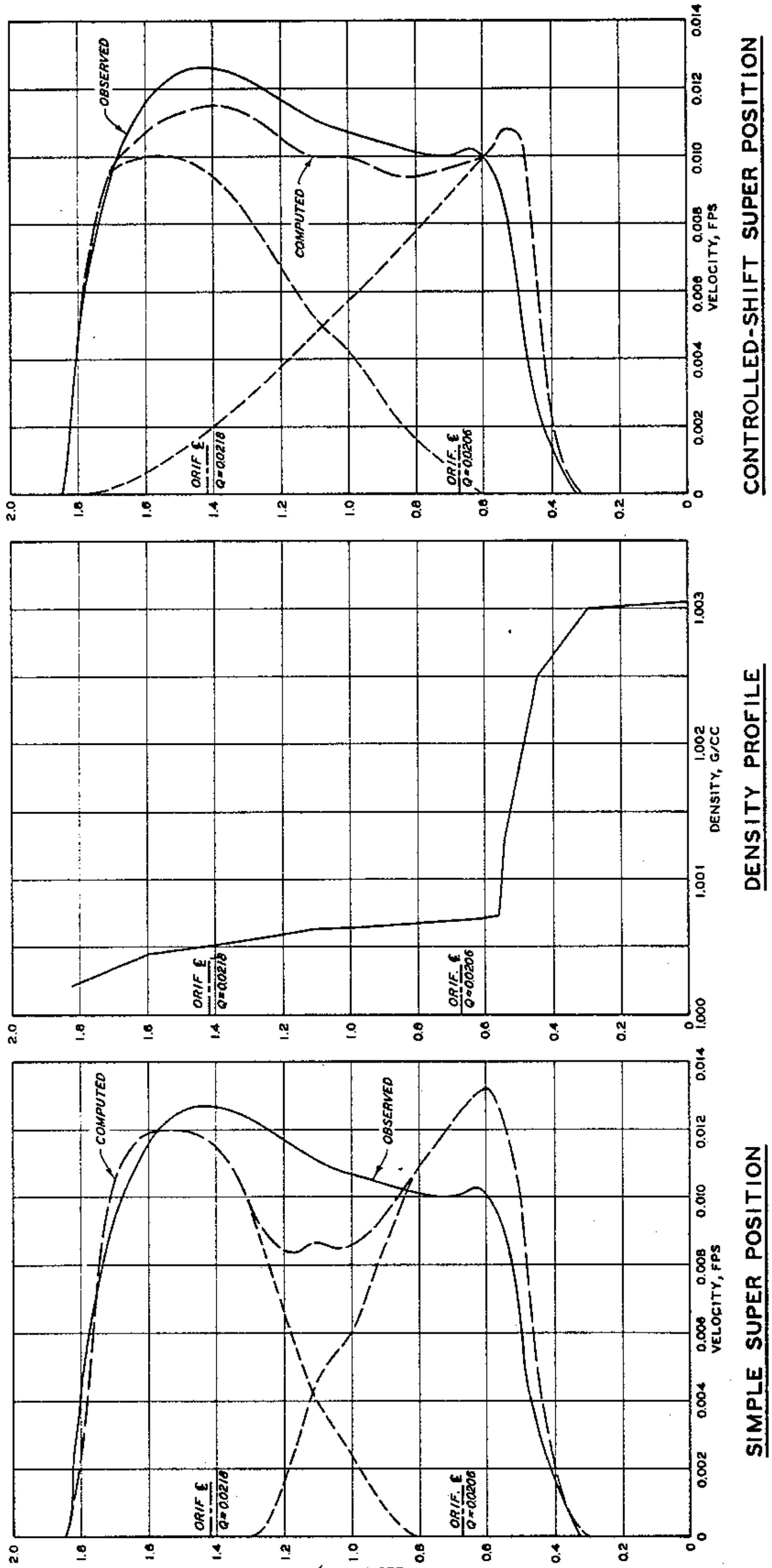
SIMPLE SUPER POSITION

DENSITY PROFILE

CONTROLLED-SHIFT SUPER POSITION

VERTICAL DISTRIBUTIONS OF
VELOCITY AND DENSITY
DISCHARGES 0.0224 AND 0.0039 CFS

PLATE 22



VERTICAL DISTRIBUTIONS OF
VELOCITY AND DENSITY
DISCHARGES 0.0218 AND 0.0206 CFS

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* U. S. Army Engineer Waterways Experiment Station Vicksburg, Miss.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

SELECTIVE WITHDRAWAL FROM MAN-MADE LAKES; Hydraulic Laboratory Investigation

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final report

5. AUTHOR(S) *(First name, middle initial, last name)*

Joseph P. Bohan
John L. Grace, Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1973	60	12

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	Technical Report H-73-4
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Office, Chief of Engineers, U. S. Army U. S. Army Engineer Districts, Philadelphia, Savannah, Huntington, St. Louis, and Louisville

13. ABSTRACT

Laboratory investigations were conducted at the U. S. Army Engineer Waterways Experiment Station to determine the withdrawal-zone characteristics created in a randomly density-stratified impoundment by releasing flow through a submerged orifice, over a free and submerged weir, or through a combination of the above. Density stratification was generated in the experimental facilities by creating differentials in both temperature and salinity. Velocity profiles were obtained from movies of dye streak displacements. Through the investigations, generalized relationships for describing the vertical limits of the withdrawal zone and the vertical velocity distribution within the zone have been developed. Techniques for handling conditions in which the water surface or bottom boundary controlled the limits of the withdrawal zone and for describing the composite velocity profile resulting from withdrawal zones which overlapped have also been developed. If the velocity profile and the reservoir width with respect to depth are known, a vertical flow rate distribution can be determined. This flow rate distribution can then be applied as a weighting function to the reservoir profile of any water-quality parameter to determine its value in the reservoir release.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hydraulic models						
Lakes						
Reservoirs						
Selective withdrawal						
Stratified flow						

Unclassified

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