MULTIPLE OUTLET SELECTIVE WITHDRAWAL TECHNIQUE FOR WATER QUALITY PREDICTION OF LAKE RELEASES

by

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INTRODUCTION

The demands on multipurpose reservoir planning, design and operation for quality releases have played a significant role in evaluating both existing and planned projects. The desire to meet downstream water quality criteria without diminishing the quantity has necessitated research aimed at the development of techniques useful to the project designer and operator in meeting these downstream goals.

One such technique resulting from research studies is selective withdrawal, whereby reservoir outlet ports are located at various levels enabling releases to be taken from one or more of several different strata.

Generally, downstream water quality goals center about the temperature of the water. However, thermal phenomena in terms of water quality may bring about differences in the concentration of dissolved oxygen, pH, suspended solids, etc; so much so that thermal stratification in reservoirs can be thought of as quality stratification.

BACKGROUND

Thermal stratification of lakes is brought about through the natural heat exchange processes of evaporation, radiation, and conduction as well as the amount and type of inflow and outflow. Hence, the effects of climatological, meteorological and hydrological factors must be combined to adequately describe the process of stratification. A detailed description of the interaction of these factors in bringing about stratification is available in the literature and is beyond the scope of this paper. Briefly, as air temperatures begin to increase in early Spring, the temperature of the water near the surface of a reservoir will also increase. Since the natural insulation properties of a reservoir increase with depth, warming at the surface will be confined to a relatively shallow layer. This warm upper layer is called the epilimnion. A region of rapidly changing temperature with depth called the thermocline is located just below the epilimnion. The remaining volume of the reservoir is occupied by the hypolimnion, a strata of colder, denser water. The extent and makeup of each layer is, as mentioned above, dependent upon numerous physical factors and may vary widely among reservoirs. The end result is a vertically layered or stratified pool containing distinct regions of water having particular chemical, physical and biological characteristics. The combined effects of temperature differences together with the other parameters result in a total stratification that can be analyzed in terms of density.

SELECTIVE WITHDRAWAL IN GENERAL

The mechanism of selective withdrawal for a given degree of density stratification has been accomplished at the Waterways Experiment Station through the use of physical model studies. These studies were performed in a step by step manner beginning with selective withdrawal through a single orifice. Both free and submerged weir flow were analyzed and finally, simultaneous multiple level releases were studied.

Since the detail analysis and results of single orifice and single weir operation has been described in earlier papers, only a summary of those studies will be presented here. The testing, analysis and results of the multiple level releases are presented in detail.

EXPERIMENTAL FACILITIES

The experimental facilities (fig. 1) contained four 1-in.-diameter outlet ports, each at a different elevation, at the end of a 3-ft-wide by 2-ft-deep channel. The channel was approximately 8 ft long with clear plastic sidewalls for ease of observation. The channel sidewalls were extended 16 ft into a 32-ft-long by 16-ft-wide by 4-ft-deep headbay, which was used to provide a relatively large reservoir supply of salt water and to allow the tests to be conducted with a falling head. Stratification was generated by means of differentials in both temperature and dissolved salts. 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, dense stratum was generated by filling the headbay and channel to a predetermined level with fresh water and then mixing in salt to

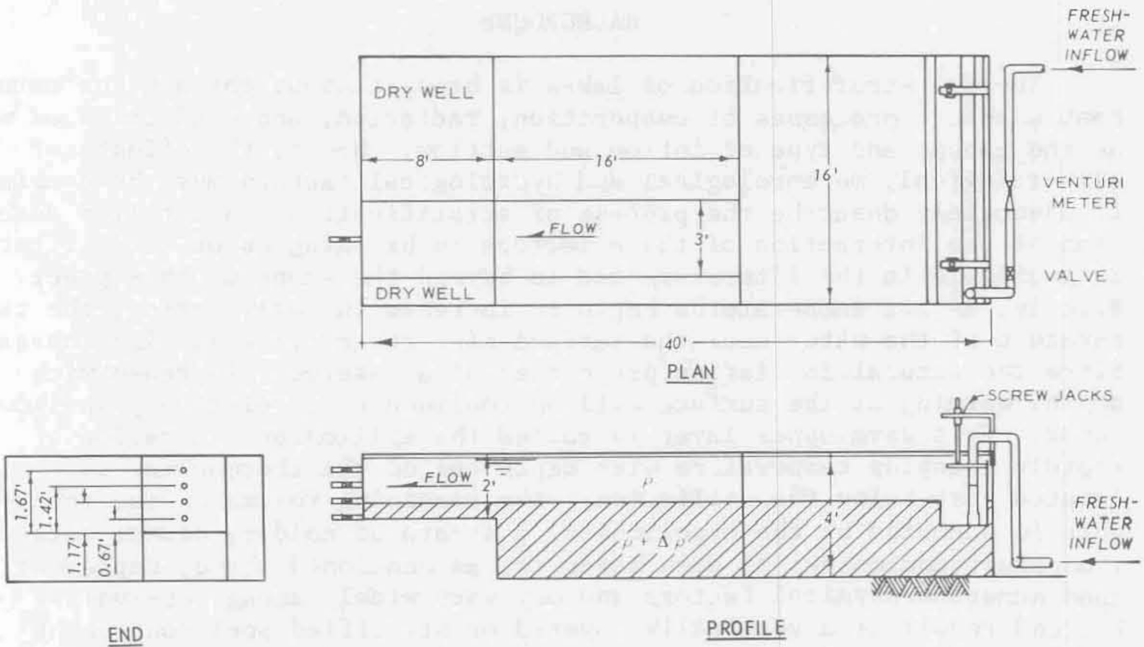


Fig. 1. Experimental facilities

give the desired density. 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 stratum. Valves were provided at each of the four outlets, and the flow rate from any one outlet was obtained by measuring the volume released with respect to time. All of the tests were conducted with no inflow. This condition was allowable because of the short duration of the test and the large volume of water available in the headbay.

The density distribution was determined in place from measurements of conductivity and temperature using a thermistor, a conductivity probe, and the appropriate indicators (fig. 2). The actual density of the fresh and saline waters used in the facilities for calibration purposes was determined using a hydrometer or gravimetric balance. Initially, a very distinct two-layer stratification existed; however, the variable temperature of the atomsphere generally heated or cooled the upper stratum during the day and night to the extent that it was necessary to monitor temperatures as well as salinity in order to determine an accurate measure of the densities 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.

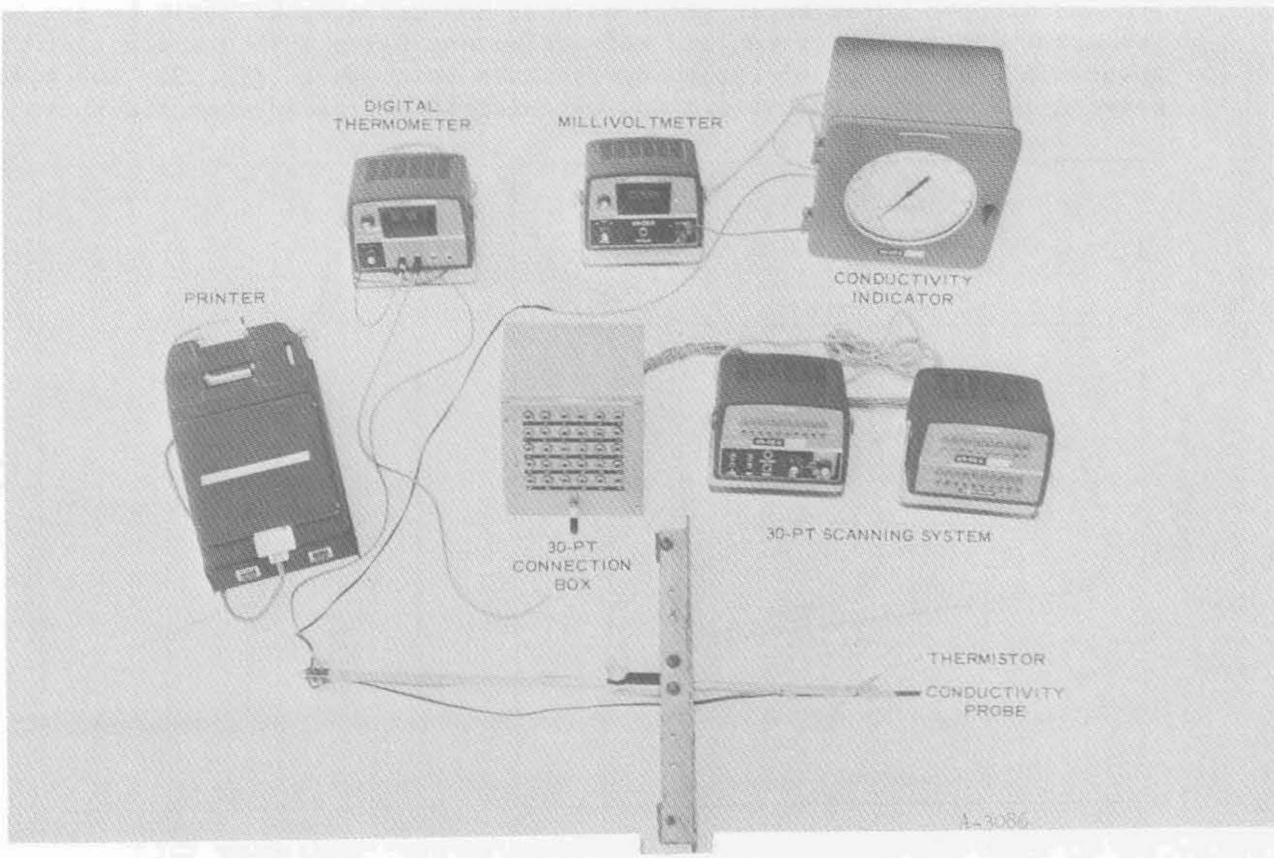


Fig. 2. Instrumentation used in experimental facilities

TESTS AND RESULTS

Test Procedure

After stratification had been generated, the test was initiated by withdrawing water through two preselected outlet ports. The currents created by initiating flow were allowed to stabilize prior to continuing the tests. The temperature and conductivity profiles were obtained in the test section, which was located approximately 6 ft upstream of the outlet ports. The flow rate from each port was then measured, and a dye streak was filmed. Prior tests indicated that there was very little difference in the withdrawal current at varying distances upstream of the outlet port and at various locations across the channel. For these reasons, one dye streak was filmed at a location 6 ft upstream of the outlet port in the center of the 3-ft-wide flume. This procedure was followed for different combinations of vertical spacing of the outlet ports and relative rate of discharge through the two outlet ports.

Basic Data

Movies of the dye streaks and grid system painted on the plastic side of the channel were run and then stopped at the frames in which the streaks reached the bottom of the channel; the streaks in these frames were traced and used as the reference time t = 0. The film was again run and stopped three other times so that the dye streaks could be traced. The error due to distortion and refraction was taken into account at this point. A typical set of traced dye streaks is shown in fig. 3. The time between the streaks was determined by calculations based upon the known

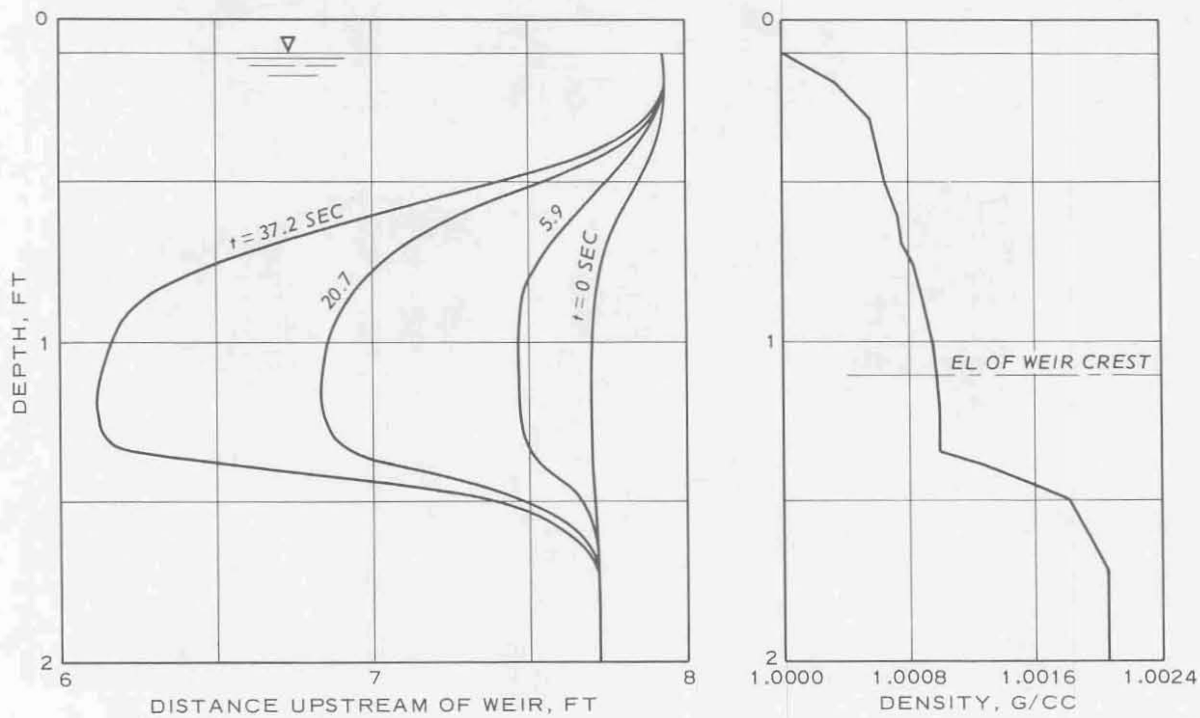


Fig 3. Typical traced dye streaks and density profile

speed of the camera and the number of frames between the traced streaks. The velocity at every 0.05 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, and these were averaged to yield one representative distribution.

Temperature and conductivity readings were converted to determine densities at various depths and were plotted to determine the density profile.

SUMMARY OF SINGLE ORIFICE STUDIES

The parameters considered in the single orifice selective withdrawal include the cross sectional area of the orifice, the discharge through the orifice and the degree of density stratification. These variables are combined in deminsionless form and related to the distance from the centerline elevation of the orifice to the top and bottom limit of the withdrawal zone. The shape of the velocity profile within these limits is a function of the density stratification.

The variables involved in the withdrawal current for single-orifice withdrawal are shown in fig. 4. Plate 1 shows the densimetric Froude

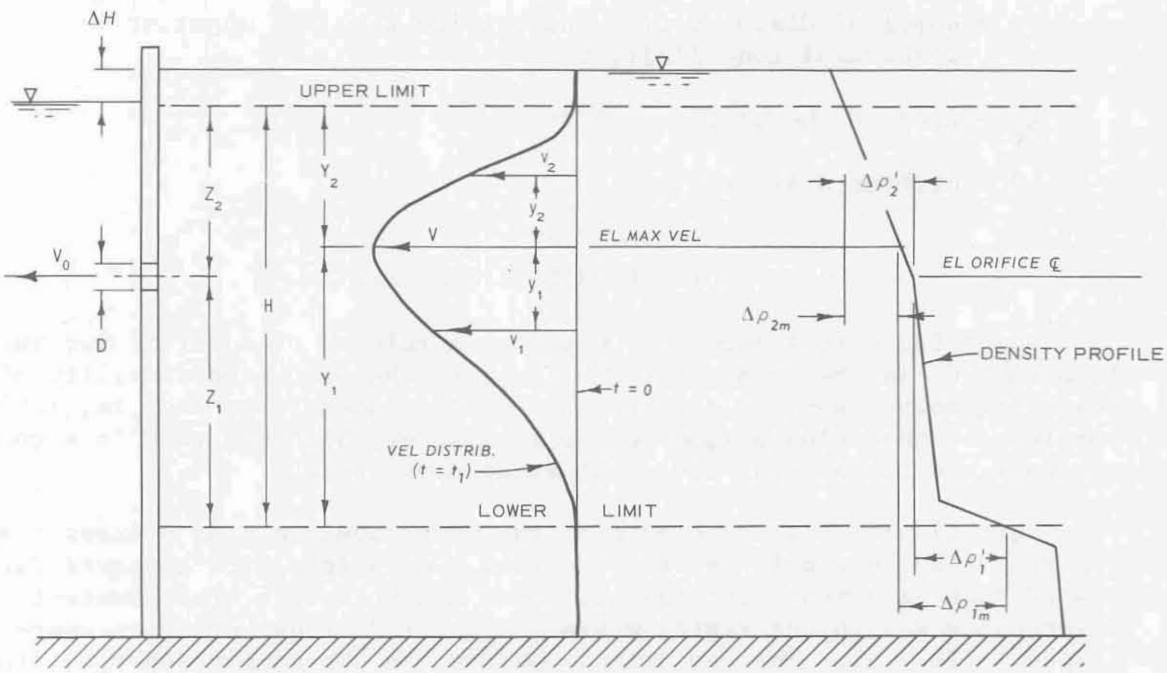


Fig. 4. Definition sketch of variables

number relationship used to determine the upper and lower withdrawal-zone limits. The equation of the line shown in plate 1 is

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

or

$$Q = Z^2 \sqrt{\left(\frac{\Delta\rho'}{\rho_o}\right) gZ} \tag{2}$$

where

V_o = average velocity through the orifice, fps

$\Delta\rho'$ = density difference of fluid between the elevation of the orifice center line (₵) and the upper or lower withdrawal zone limit, g/cc

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

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

Z = vertical distance from the orifice ₵ to the upper or lower withdrawal zone limit, ft

A_o = area of the orifice, sq ft

Q = orifice discharge, cfs

MULTIPLE ORIFICE RELEASES

The ability to selectively withdraw a release of a particular quality from various layers in a reservoir suggests the further possibility of achieving downstream goals through a blending operation; that is, taking portions of the release from two or more zones, blending them in a common wet well and discharging the combination downstream.

Initial attempts at describing the multilevel release process simply superimposed the single orifice results. Comparison with observed data showed poor agreement with that obtained analytically. The greatest discrepancy was in the region where the two individual profiles overlapped. (fig. 5). The deviations observed in the simple superposition were consistent for the range of conditions tested. Observed velocities were greater than computed values in the zone where the profiles overlapped, and the observed maximum velocities in each withdrawal zone were less than the corresponding computed value.

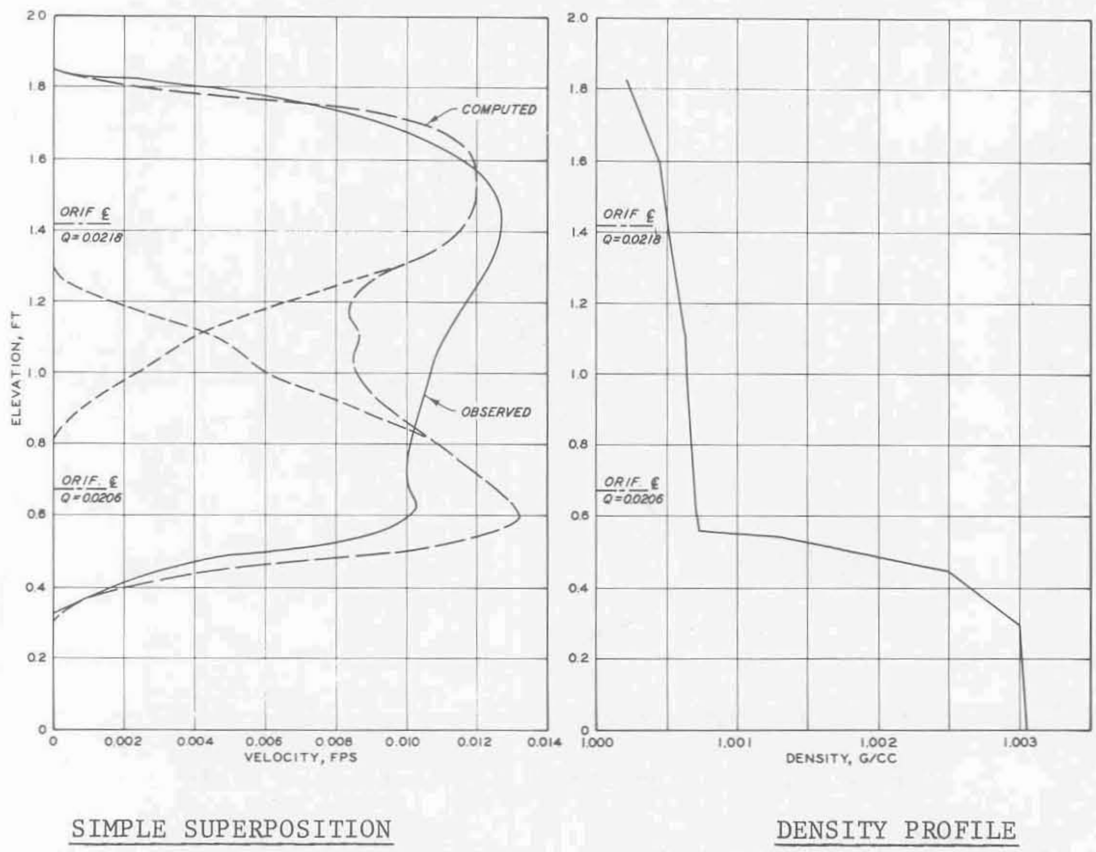


Fig. 5. Comparison of observed data with simple superposition

The inconsistencies resulting from simple superposition of the two profiles indicated that the velocities of one profile influence those of the other by reducing the shear force in any horizontal layer within the region of overlap. The net result of this mutual influence is an increase in velocities of both withdrawal profiles in the overlap zone. Based upon the single orifice data, a similar result can be brought about in the region of overlap by shifting the inner withdrawal limits of each profile to increase the total depth of each withdrawal zone. In order to maintain continuity, a decrease in the magnitude of the maximum velocity of each profile would necessarily accompany an expanding of the limits of the withdrawal zone. Therefore, shifting the bottom limit of the upper zone downwards and the top limit of the lower zone upwards brings about the required changes in the superimposed flow profile to account for the observed deviations.

Numerous trial and error attempts at locating the magnitude of shift needed in each test case led to the conclusion that the amount of shift of the inner withdrawal limits depends upon the amount of overlap of the single velocity profiles, the vertical spacing between the outlets, the discharge through the outlet, and the density gradient in the reservoir. Combining these parameters into dimensionless form yields a technique for controlling the shift of the inner limits. The relationships obtained are similar to the analysis of single orifice releases.

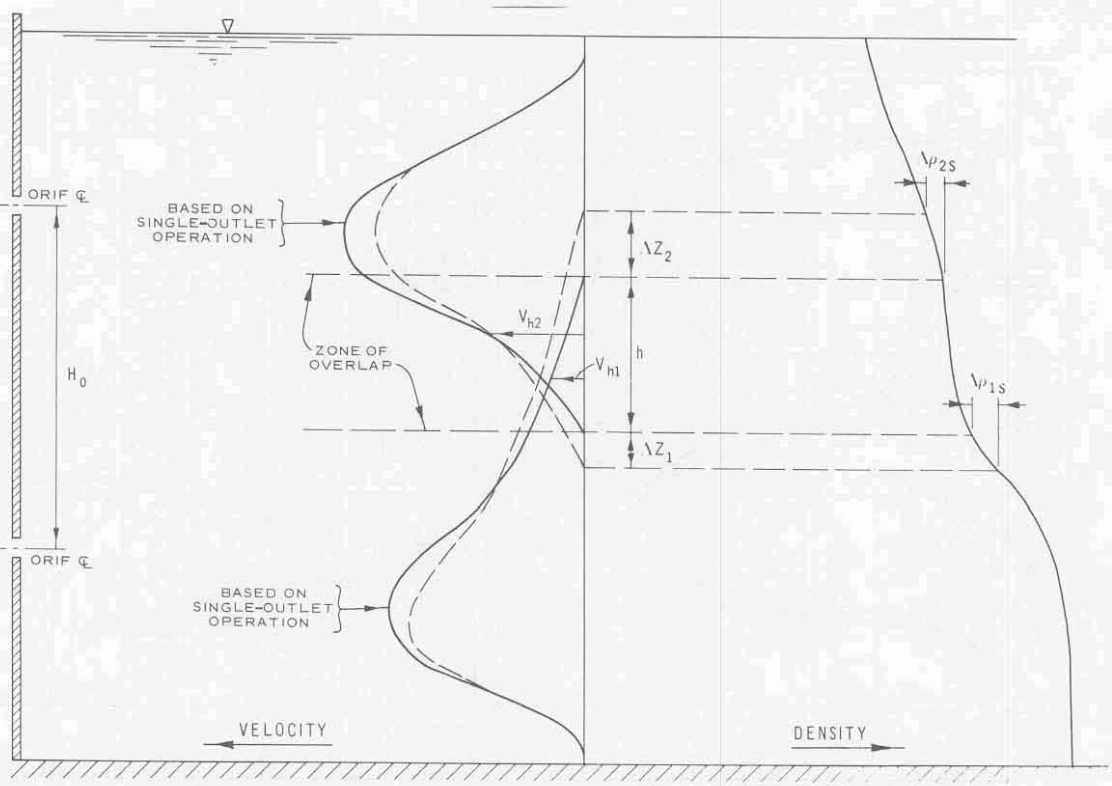


Fig. 6. Definition sketch for controlled shift

The controlled shift technique consists of a densimetric Froude number approach. Fig. 6 defines the variables involved in the relationship. For a given flow condition, some critical value of the densimetric Froude number is related to the ratio h/H_o, which is a measure of the degree of overlap of the two withdrawal zones obtained individually. Since h/H_o is constant for any given test, the value of the densimetric Froude number for the shift of both inner limits will be the same. The amount of shift of each will be the same only if the magnitude of the velocities of each in the region of overlap are the same and if the density gradient is constant. The relationship obtained is presented in Plate 5. The equation of the line shown is:

$$\frac{V_h}{\sqrt{\left(\frac{\Delta\rho_s}{\rho_\sigma}\right) g\Delta Z}} = 0.7 \left(\frac{h}{H_o}\right)^{1.25} \qquad (3)$$

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 withdrawal limit, ft

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

H_o = vertical distance between orifice ℄'s, ft

Fig. 7 compares the observed withdrawal profile obtained for the conditions shown with that resulting from the controlled shift technique. Comparison with Fig. 5 exemplifies the improvement over simple superposition.

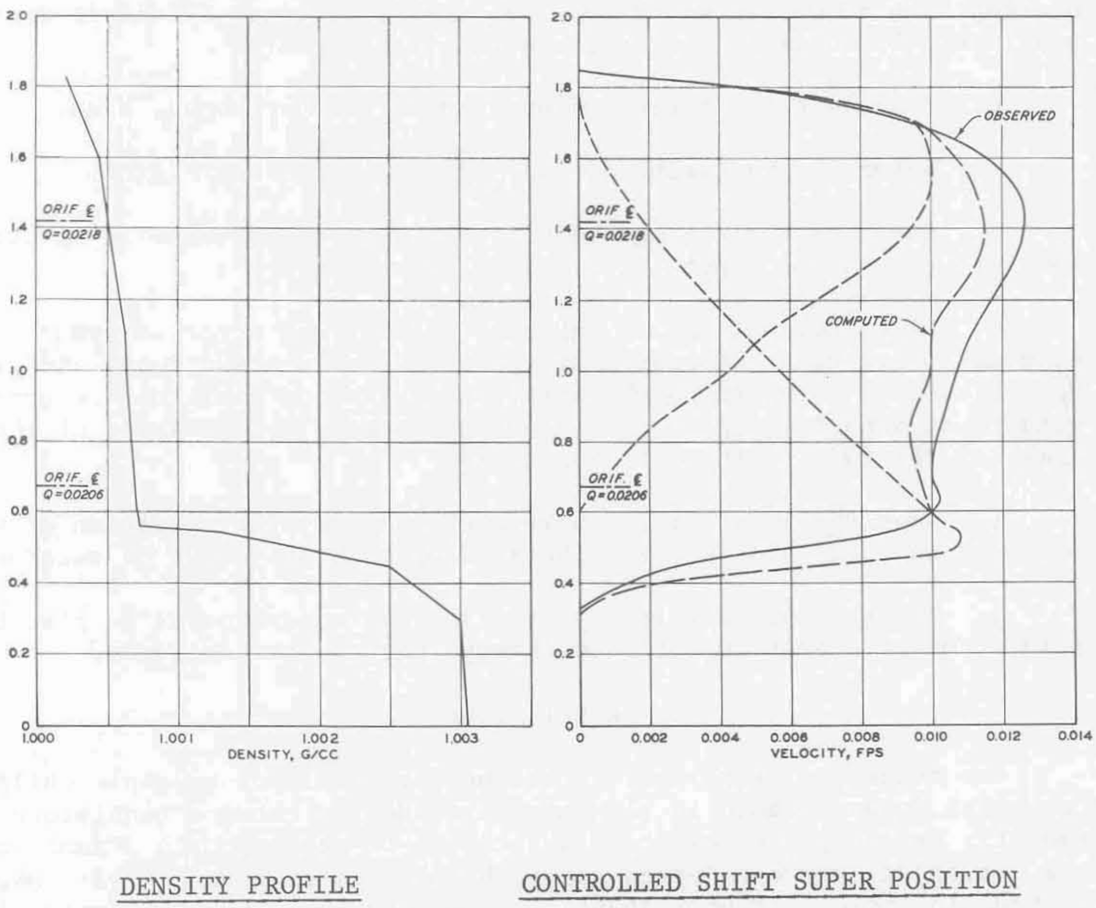


Fig. 7. Comparison of observed data with controlled shift technique

RECOMMENDED PROCEDURE

The procedure for obtaining the composite velocity, i.e., discharge profile will be explained under the assumption that two outlets located at different elevations are releasing flows at known rates and that the density profile is known. The following procedure should be used to obtain the discharge profile:

a. Calculate the upper and lower withdrawal zone limits of each individual profile using the equation shown in Fig. 4 or the curve shown in Plate 1.

b. Compute the elevation of maximum velocity within each zone according to Plate 2.

c. Determine the velocity distribution within each zone using the discharge, the width of the reservoir, and the normalized velocity profile based upon the results shown in Plates 3 or 4 depending upon boundary conditions.

d. Determine whether the withdrawal zones overlap. If there is no overlap, the composite withdrawal profile is obtained by simple superposition. If there is overlap, continue to step e.

e. Calculate the extent of overlap of the two zones, h/Ho.

f. Determine the value of $V_h / \sqrt{(\Delta\rho s/\rho_s) g\Delta Z}$ using Plate 5.

g. Evaluate the average velocity in the zone of overlap of the lower (V_{h1}) and the upper (V_{h2}) withdrawal zones.

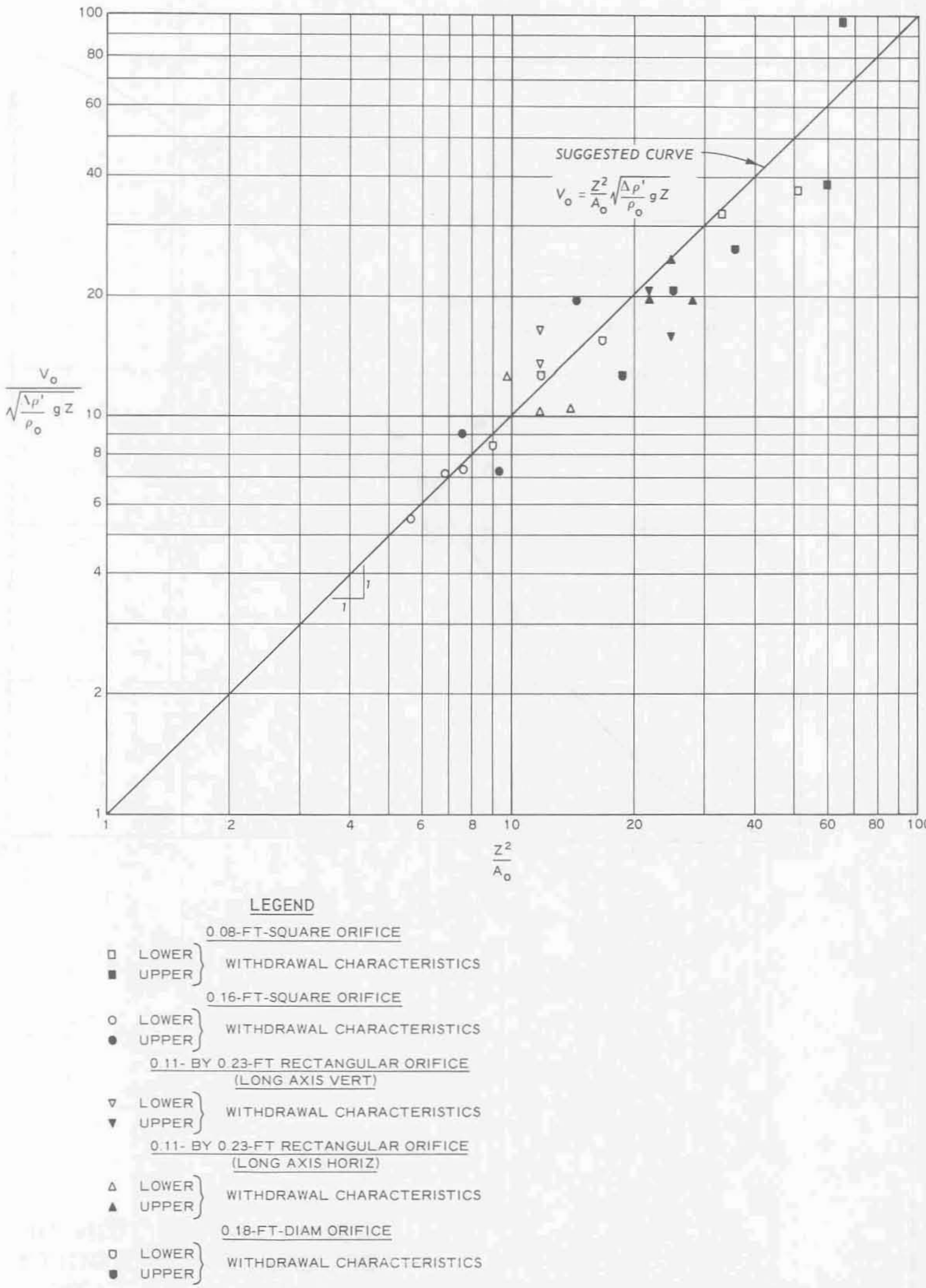
h. Since $\Delta\rho s$ and ΔZ are unknown, a trial and error procedure must be used to evaluate the amount of shift (ΔZ) of the two inner limits. V_{h1} is used in determining the shift of the bottom limit of the upper withdrawal zone ΔZ_1, and V_{h2} is used in determining the shift of the top limit of the lower withdrawal zone, ΔZ_2.

i. When the inner limits have been shifted, the elevation of maximum velocity and the velocity distributions of each zone must be recomputed.

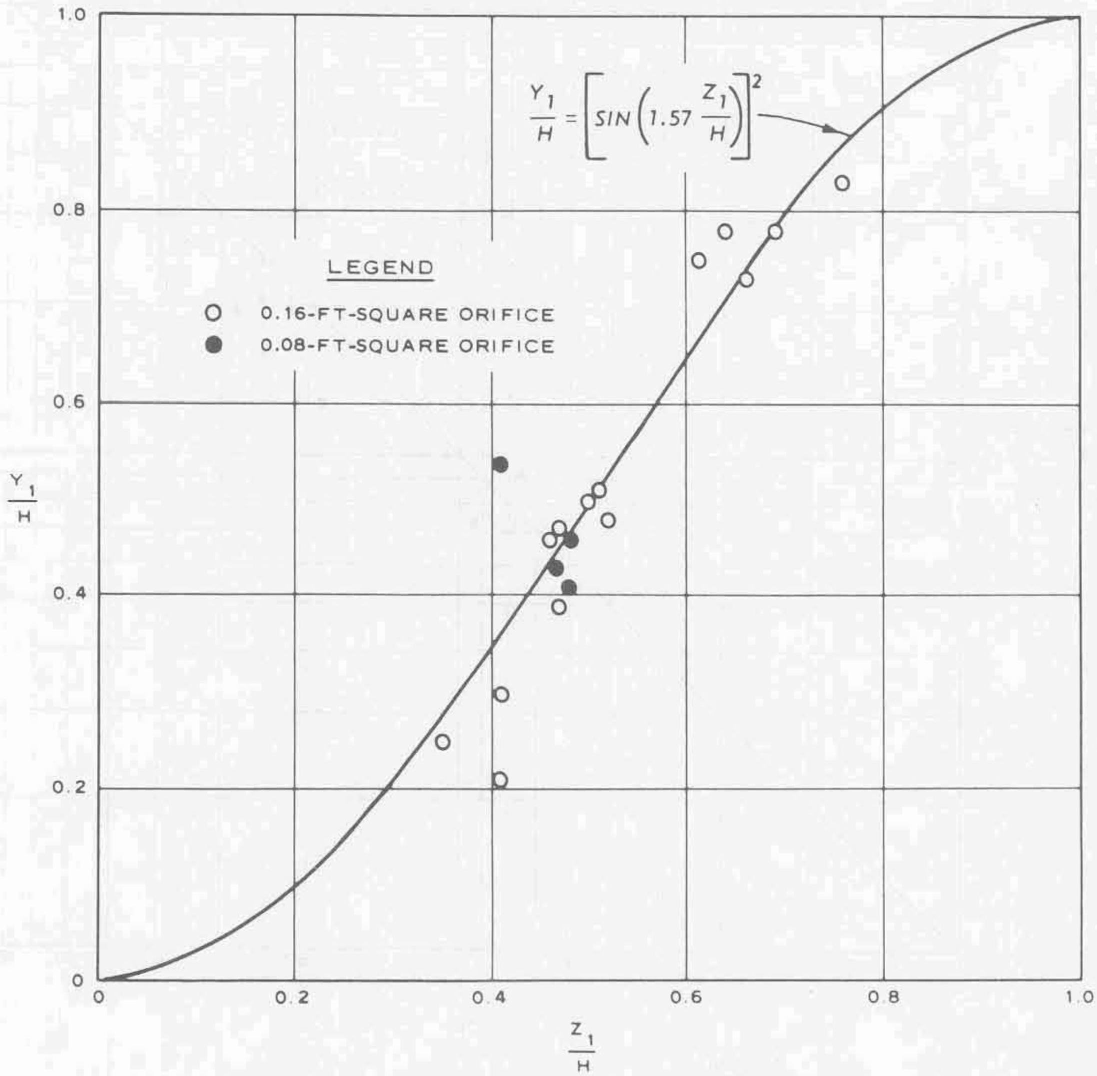
j. The recomputed velocity profiles are superimposed to give the final composite profile for flow through the two outlet ports.

APPLICATION

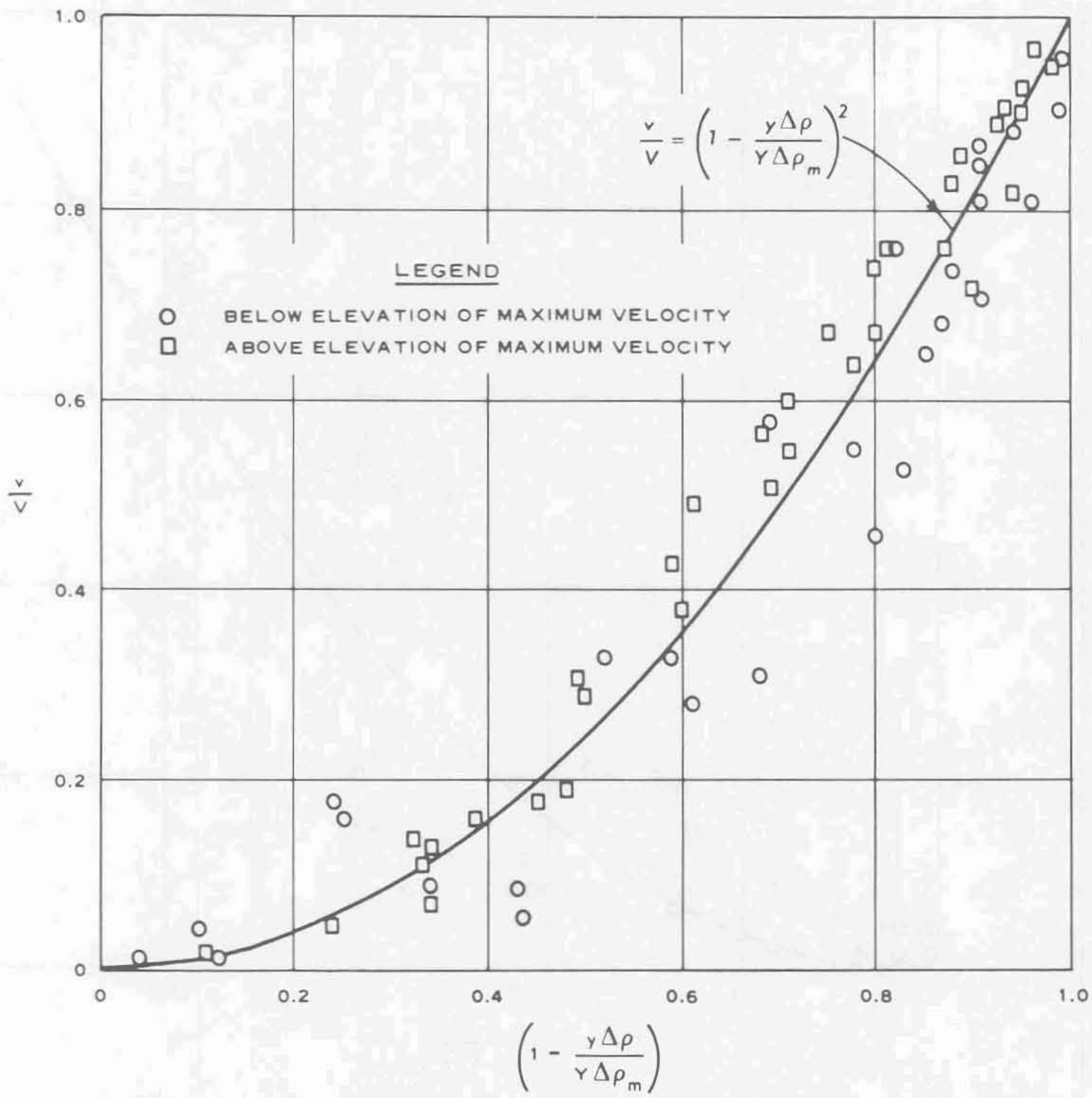
The selective withdrawal technique for single or multiple outlet operation is applicable in all cases provided no extreme conditions of geometry or topography exist in the region of the approach channel and the outlet structure. Curved approach channels or channels with abrupt changes in cross sectional shape have been shown to significantly alter the type of selective withdrawal that can be obtained. It is for these cases that physical model studies remain valuable in determining proper design and operational guides for the enhancement of water quality.



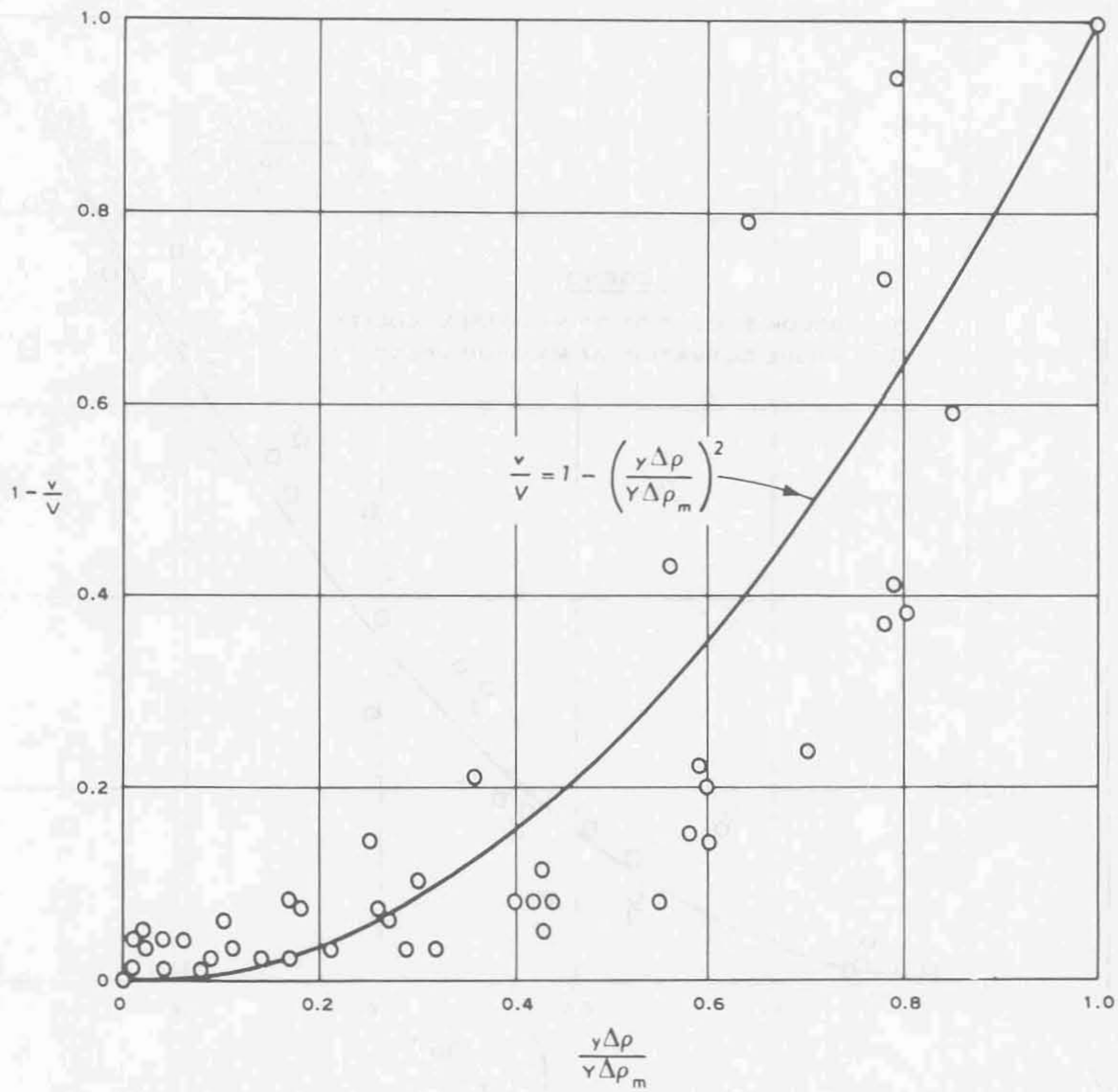
WITHDRAWAL CHARACTERISTICS OF ORIFICES



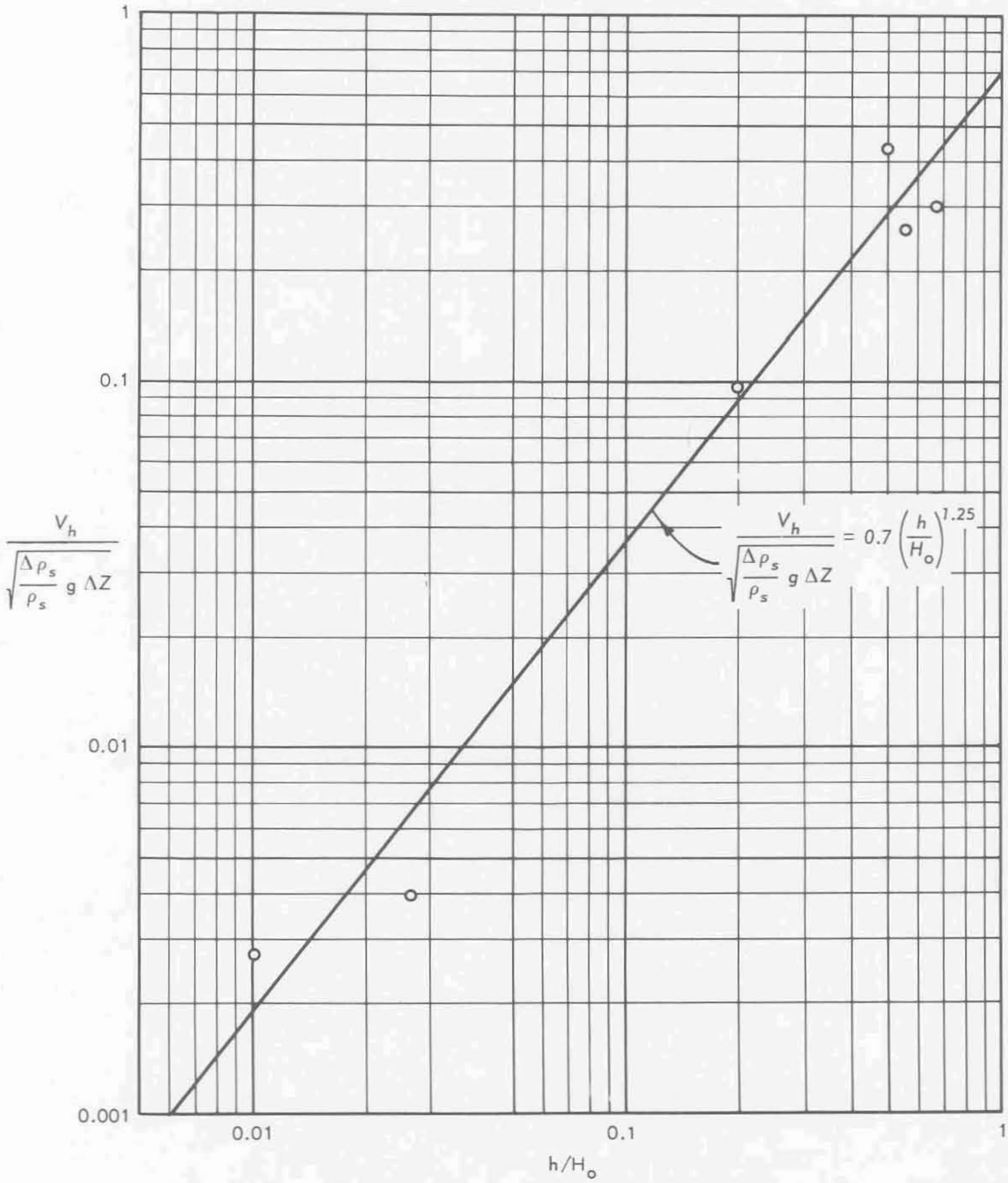
RELATIVE POSITION OF
OF MAXIMUM VELOCITY
IN STRATIFIED FLOW
THROUGH AN ORIFICE



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



CONTROLLED SHIFT FOR SIMULTANEOUS, MULTIPLE-LEVEL RELEASE