RESEARCH REPORT H-72-3

SIMULTANEOUS, MULTIPLE-LEVEL RELEASE FROM STRATIFIED RESERVOIRS

Hydraulic Laboratory Investigation

by

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December 1972

Sponsored by U. S. Army Engineer Districts, Huntington and Louisville
U. S. Army Engineer Division, Ohio River

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

ARMY-MRC VICKSBURG, MISS.

FOREWORD

The experimental investigation reported herein was jointly sponsored by the U. S. Army Engineer District, Huntington; the U. S. Army Engineer District, Louisville (LD); and the U. S. Army Engineer Division, Ohio River (ORD). The studies were conducted in the Hydraulics Laboratory of the Waterways Experiment Station (WES), Vicksburg, Mississippi, during the period December 1971 to April 1972, under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and T. E. Murphy, Chief of the Structures Branch. The investigation was conducted by Mr. J. P. Bohan and PFC T. L. Gloriod, under the supervision of Mr. J. L. Grace, Jr., Chief of the Spillways and Channels Section. This report was prepared by Mr. Bohan.

Mr. G. R. Drummond of the ORD and Mr. Summerville of the LD visited the WES during the investigative phase of the study to observe the testing and discuss preliminary results.

COL Ernest D. Peixotto, CE, and Mr. F. R. Brown were the Director and Technical Director, respectively, of the WES during the conduct of the investigation and the preparation and publication of this report.

CONTENTS

NOTATION

A_o	Area of the orifice opening, sq 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 orifice ℄'s, ft
Q	Discharge, cfs
t	Time, sec
v_1	Local velocity in the zone of withdrawal at a distance y_1 below the elevation of maximum velocity V, fps
v_2	Local velocity in the zone of withdrawal at a distance y_2 above the elevation of maximum velocity V, fps
V	Maximum 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
y_1	Vertical distance from the elevation of the maximum velocity V to the corresponding local velocity v_1, ft
y_2	Vertical distance from the elevation of the maximum velocity V to 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_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 withdrawal limit, 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

$\Delta\rho_1'$ 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

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

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
inches	2.54	centimeters
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 research was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) to determine the characteristics of the withdrawal zone resulting from the simultaneous release of flows from a randomly stratified impoundment through outlets located at different elevations. Stratification was generated in experimental facilities by creating differentials in both temperature and dissolved salt. The density profile was determined by measuring the temperature and conductivity profiles and combining the effects on density of these two factors. The velocity distributions were obtained by filming the displacement of a dye streak in the flow.

Superimposing the separate and distinct velocity profiles for each of the outlets based on single-outlet operation (as used in a previous WES investigation) to obtain the composite velocity profile, due to simultaneous release through two outlets, did not yield completely satisfactory comparisons between predicted and observed results. Further analyses were made to develop a generalized technique, which involved a controlled shift of the withdrawal limits in the zone of overlap prior to superimposing the two separate and distinct velocity profiles. This technique yielded good agreement between observed and predicted, selective withdrawal characteristics.

When the composite velocity profile in the reservoir has been determined by the recommended method, a weighted-average technique can be applied to determine the value of any water-quality parameter in the outflow for which a vertical distribution within the reservoir is known.

SIMULTANEOUS, MULTIPLE-LEVEL RELEASE FROM STRATIFIED RESERVOIRS

Hydraulic Laboratory Investigation

PART I: INTRODUCTION

Background

1. The recent attacks on pollution and the desire to enhance the quality of our water resources have greatly increased the demands on multipurpose reservoir planning, design, and operation. The desire to meet the objectives with regard to downstream quality, as well as quantity, has made it necessary to develop techniques to improve the quality of reservoir releases. One of the techniques which has been developed to attain a higher release quality is selective withdrawal, whereby outlet ports are placed at various levels in a reservoir in order to withdraw water of a desired quality. The problem then becomes one of determining the vertical extent of the withdrawal layer created in the reservoir and the velocity distribution therein. Research regarding this problem began in 1966 at the U. S. Army Engineer Waterways Experiment Station and resulted in a technique for predicting the extent of the withdrawal zone and the velocity distribution for flow through a single orifice and over a submerged weir. The results of these investigations are reported in references 1 and 2.

Purpose and Scope of Study

2. The study reported herein was conducted to determine whether superimposing the predicted velocity profiles for individual outlet ports at different elevations, based on results reported in reference 1, would be an adequate description of the velocities in the withdrawal current created in a stratified reservoir for the simultaneous release of flows through multiple-level outlet ports. A limited number of tests were conducted using two outlet ports to obtain results for

different vertical spacings and various flow distributions between outlets. When it was decided that the simple superpositioning principle mentioned above would not be adequate, further analysis of the data was conducted in order to develop a predictive technique that would give better agreement between the observed and predicted velocity profiles.

PART II: EXPERIMENTAL FACILITIES

3. The experimental facilities (fig. 1) contained four 1-in.*-diam. 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

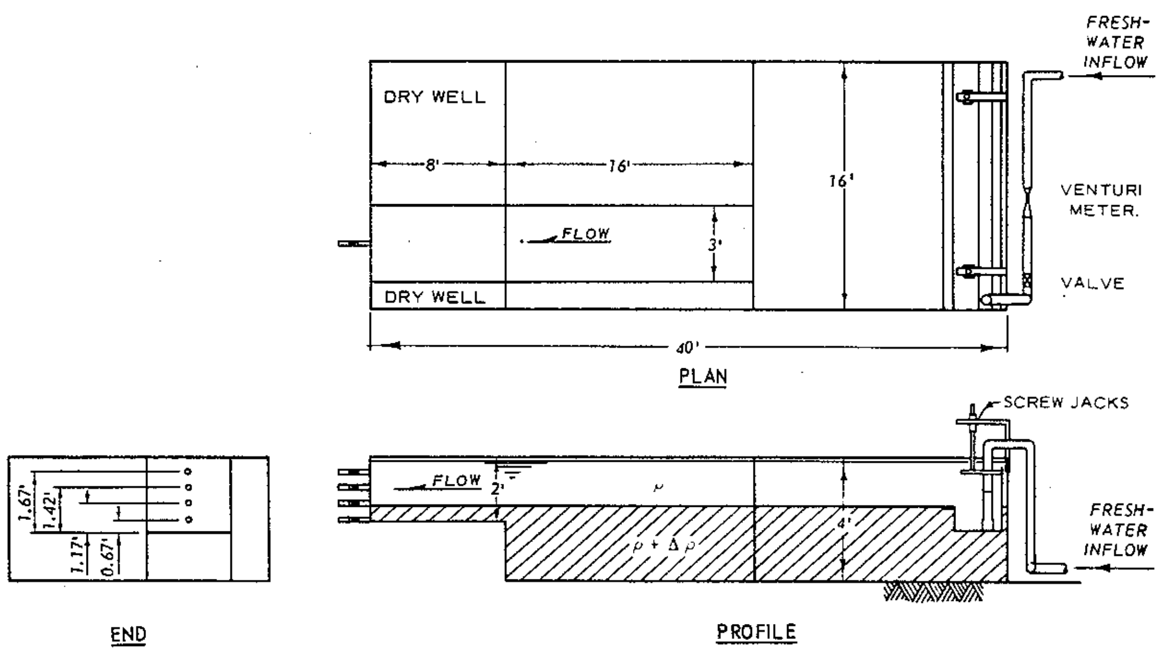

Fig. 1. Experimental facilities

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

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.

4. 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

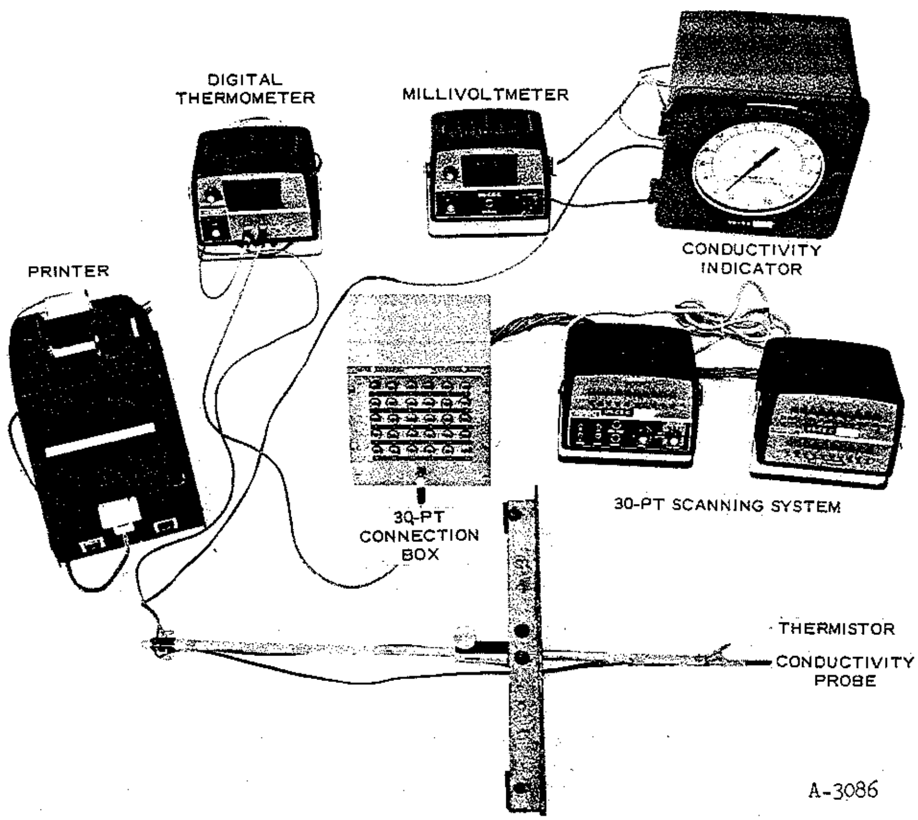

Fig. 2. Instrumentation used in experimental facilities

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 atmosphere 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.

PART III: TESTS AND RESULTS

Test Procedure

5. 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

6. 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 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

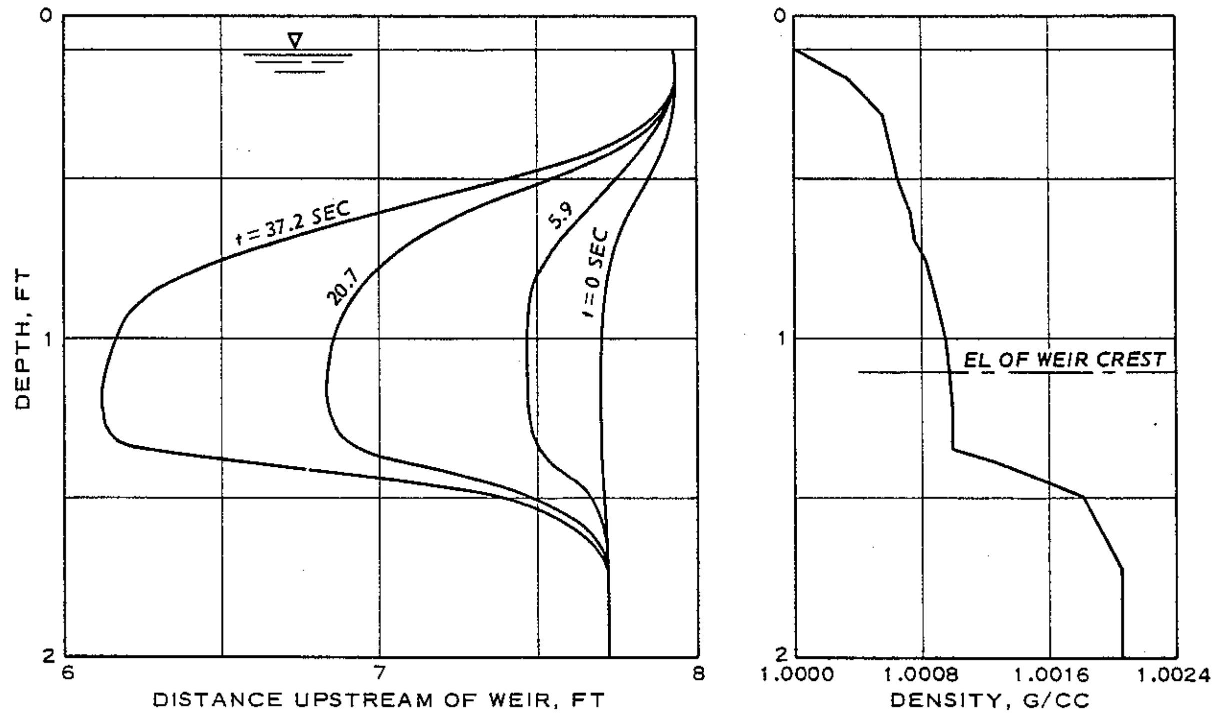

Fig. 3. Typical traced dye streaks and density profile

distributions were obtained, and these were averaged to yield one representative distribution.

7. Temperature and conductivity readings were converted to determine densities at various depths and were plotted to determine the density profile. The velocity and density profiles are presented in plates 1-6.

Data Analysis

8. The test results were used to predict the extent of and the velocity distribution within the withdrawal current created in the reservoir by flow through each individual outlet port, using the procedure presented in reference 1. These computed withdrawal currents were then superimposed to create a composite velocity profile for each test. These computed profiles were then compared with the observed velocity profiles (see plates 1-6).

9. The variables involved in the withdrawal current for single-orifice withdrawal are shown in fig. 4. Plate 7 shows the densimetric

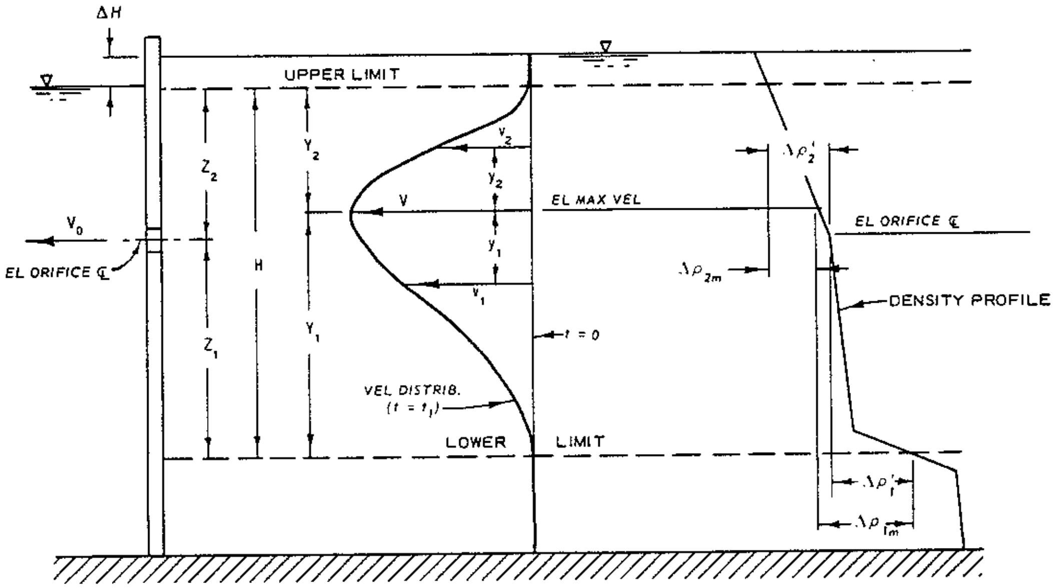

Fig. 4. Definition sketch of variables

Froude number relationship used to determine the upper and lower withdrawal-zone limits. The equation of the line shown in plate 7 is

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

or

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

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

The elevation of the maximum velocity within the withdrawal zone can then be determined from the equation

$$\frac{Y_1}{H} = \left[\sin\left(1.57\,\frac{Z_1}{H}\right)\right]^2 \qquad (3)$$

where

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

H = total thickness of the withdrawal zone, ft

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

Plate 8 can also be used to determine the elevation of maximum velocity. When the withdrawal-zone limits and the elevation of maximum velocity have been determined, the velocity distribution can be obtained from the relationships shown in plate 9 (if the withdrawal zone has not been influenced by the water surface or bottom boundary) or from those shown in plate 10 (if the boundaries have affected the withdrawal limits).

10. Comparison of the observed and predicted velocity profiles, based on simple superpositioning, indicated a consistent deviation in all of the tests. The observed velocities appeared greater than the predicted in the zone where the profiles overlapped, and, in most cases, the predicted maximum velocities in each of the withdrawal zones were greater than the observed. For this reason, the data were further analyzed in order to develop a technique for predicting a composite velocity profile that would result in better agreement between the observed and predicted profiles.

11. In the zone where the velocity profiles overlapped, based on simple superpositioning, it was reasonable to assume that the velocities of one of the profiles would influence those of the other by reducing the shear force in any horizontal layer. The result of this influence was an increase in velocities of both withdrawal layers within this zone. Shifting the inner withdrawal limits to increase the depths of both zones caused the velocities in the zone of overlap to increase. In order to maintain continuity, a decrease in the maximum velocity of each withdrawal zone would have to occur. Shifting the inner withdrawal

limits would therefore provide both adjustments necessary to reduce the discrepancy in the simple superpositioning technique.

12. Good agreement between the observed and predicted velocity profiles, based on simple superpositioning, occurred in the region between the elevation of maximum velocity and the upper withdrawal limit, for the upper withdrawal zone, and in the region between the elevation of maximum velocity and the lower withdrawal limit, for the lower withdrawal zone. For this reason, it was assumed that the area between the orifice ℄'s was the zone of influence, and so the inner withdrawal limits were extended to the opposite orifice ℄. This extension did not result in good agreement for all of the profiles. An attempt was then made to shift the inner withdrawal limits to the elevation of maximum velocity of the opposite withdrawal zone. But this shift was not satisfactory for all of the tests.

13. Further reasoning indicated that the amount of shift of the inner withdrawal limits should be a function of the amount of overlap of the velocity profiles, based on single-outlet operation, the vertical spacing between the outlets, and the density profile in the reservoir. A large density gradient would tend to inhibit a shift of a withdrawal limit while a small gradient would allow a greater shift. This tendency led to the development of a technique for shifting the inner withdrawal limits by an amount determined from the above variables. This reasoning is similar to that used to develop the techniques for predicting the withdrawal limits for flow through an orifice and over a submerged weir.

14. The controlled-shift technique consists of a densimetric Froude number approach. Figure 5 is a definition sketch showing the terms used in the analysis. The first approach taken to develop this technique was to determine some common critical value of a densimetric Froude number for the withdrawal limit shifts in all of the tests. It was evident from the results that a common densimetric Froude number could not be obtained. The final approach taken was to relate the critical value of a densimetric Froude number for each test to the value of h/H_o, which is a measure of the amount of overlap of the two withdrawal

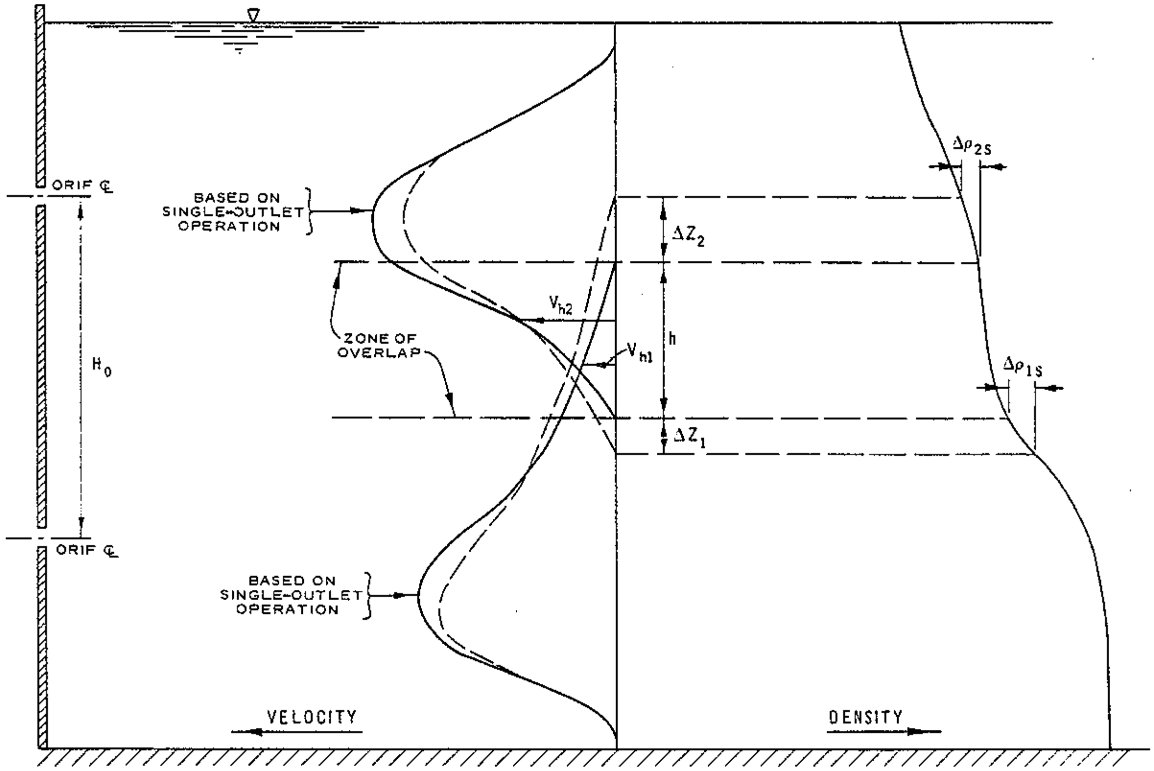

Fig. 5. Definition sketch for controlled shift

zones. This relationship, as shown in plate 11, is expressed as

$$\frac{V_h}{\sqrt{\left(\frac{\Delta\rho_s}{\rho_s}\right) g\Delta Z}} = 0.7 \left(\frac{h}{H_o}\right)^{1.25} \qquad (4)$$

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

Since h/H_o is constant for any one test, the value of the densimetric Froude number for the shift of both of the inner withdrawal limits for any one test will be the same. The value of the densimetric Froude number for each test was arrived at by adjusting the inner withdrawal limits until good agreement was obtained between the observed and predicted velocity profiles and until 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 this controlled-shift technique is shown in plates 1-6.

Recommended Procedure

15. The recommended procedure for obtaining the composite velocity profiles will be explained under the assumption that two outlets are discharging at different elevations and that the density profile in the reservoir and the outlet-port elevations and discharges are known. The following procedures should be followed for obtaining the profiles:

- a. Calculate the upper and lower withdrawal limits for both withdrawal zones, using equation 2 or plate 7.
- b. Calculate the elevation of maximum velocity within the two withdrawal zones, using equation 3 or plate 8.
- c. Calculate the velocity distribution within the two withdrawal zones using the discharge, the width of the reservoir, and the normalized velocity profile, based on the results shown in plate 9 (if the withdrawal limit does not extend to either the water surface or the bottom boundary) or those shown in plate 10 (if the withdrawal limit does extend to one or both of the boundaries).
- d. Determine whether the withdrawal zones overlap.
- e. If the withdrawal zones do not overlap, the analysis is complete. If they do overlap, continue to step f.
- f. Determine a measure of the extent of overlap of the two withdrawal zones, h/H_o .

g. Using the value of h/H_o, calculate the value of $V_h/\sqrt{(\Delta\rho_s/\rho_s)g\Delta Z}$ using equation 4 or plate 11.

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

i. 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 withdrawal limits. V_{h1} is used in determining the shift of the lower limit of the upper withdrawal zone ΔZ_1, and V_{h2} is used in determining the shift of the upper limit of the lower withdrawal zone ΔZ_2.

j. When the inner withdrawal limits have been shifted, a new elevation of maximum velocity is evaluated for the two withdrawal zones, and the velocity distributions are recomputed.

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

PART IV: DISCUSSION OF RESULTS

16. The results reported herein offer a technique for evaluating the composite, vertical velocity profile created in a randomly stratified reservoir by the simultaneous release of flow through any number of outlets located at different elevations. This evaluation may include orifice withdrawal as well as free or submerged weir withdrawal, using the results reported in reference 2, to obtain the velocity profiles for the weir flow. From the composite velocity profile and the elevation-width relationship in the reservoir just upstream of the outlet, the relative contribution from any horizontal layer to the total outflow can be determined. A weighted-average technique can then be applied to determine the value of any water-quality parameter in the outflow for which a profile in the reservoir is known. This technique can be used in conjunction with a reservoir water-quality monitoring program to determine operating procedures at a reservoir with an existing multi-level intake structure or to evaluate the effectiveness of a proposed multi-level intake structure at an existing or proposed water resources project. The technique recommended for single-orifice withdrawal has been used on several prototype impoundments and has provided excellent agreement between observed and predicted outflow quality.[3,4]

17. This investigation and those reported in references 1 and 2 were conducted in flumes with rectangular cross sections. The effect of geometry in the vicinity of an intake structure has 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 New Hope Reservoir, the model indicated that an inlet located on the upstream face would permit releases approximately double those permitted through a side inlet, without initiating withdrawal below the interface of the thermocline. Stratified flow patterns observed in the 1:40-scale, three-dimensional model of the outlet works proposed for Meramec Park Reservoir, which reproduced approximately 400 to 500 ft of the reservoir topography and a curved, narrow approach channel upstream of a fixed-level intake, also indicated local geometry

to be of importance. The narrow approach channel and shallow depth of the reservoir created shear along the interface, which, during high flows, caused considerable mixing and turbulence along the interface.

18. Considerably greater mixing and/or blending of the warm and cold waters should be anticipated with an intake structure located in a relatively shallow, narrow section of a reservoir. The interface tends to be elevated and lowered, respectively, along the inner and outer portions of a curved approach channel. These observations indicate that the geometry of multiple- and/or fixed-level intakes and the geometry adjacent to the intakes may have a significant effect upon the withdrawal characteristics.

19. It is believed that the use of hydraulic models to evaluate the effectiveness of specific proposed structures should be encouraged to ensure reasonably adequate and accurate performance of proposed water resources projects as well as to gain additional knowledge concerning the mechanics of stratified flow.

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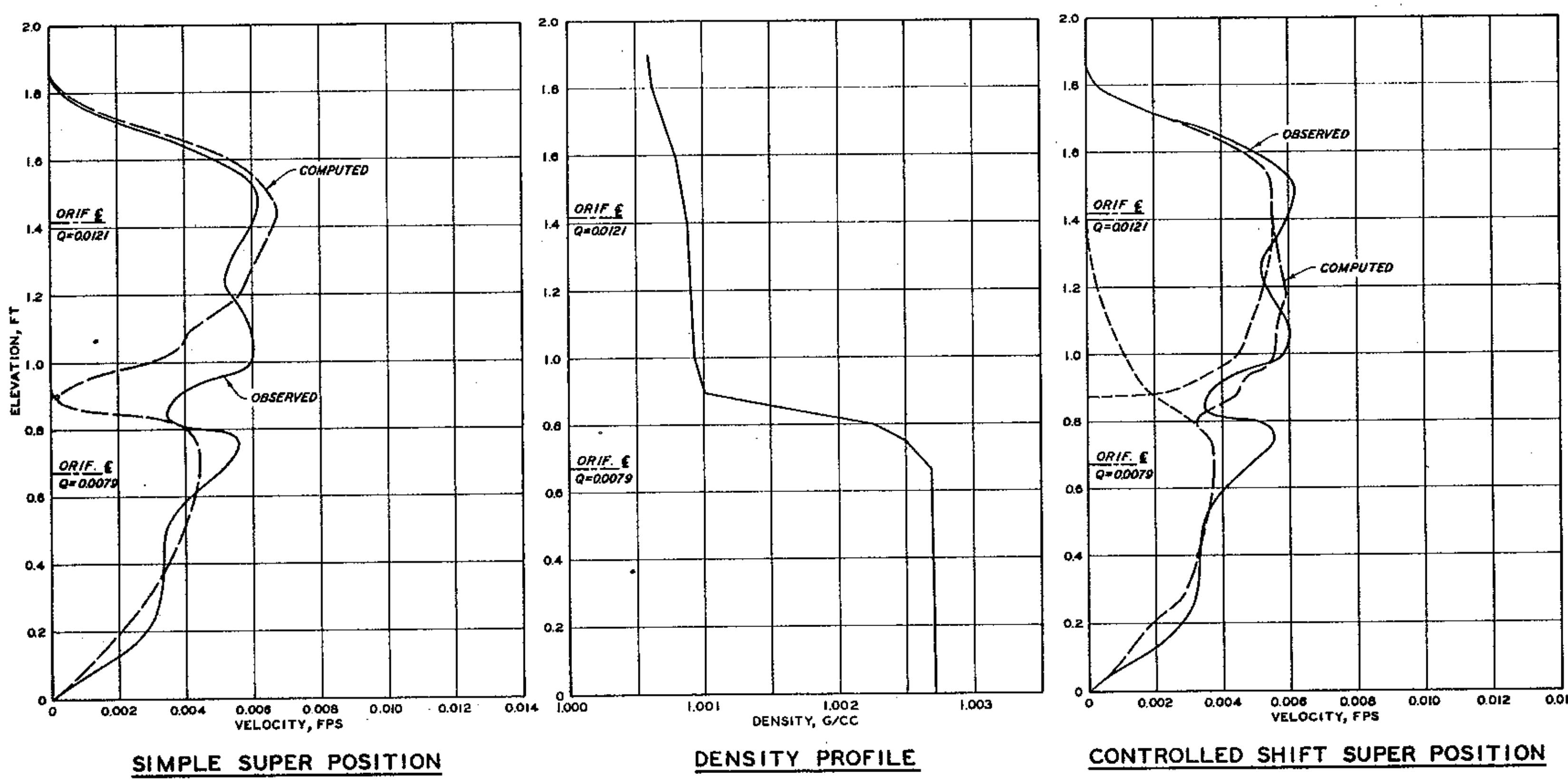
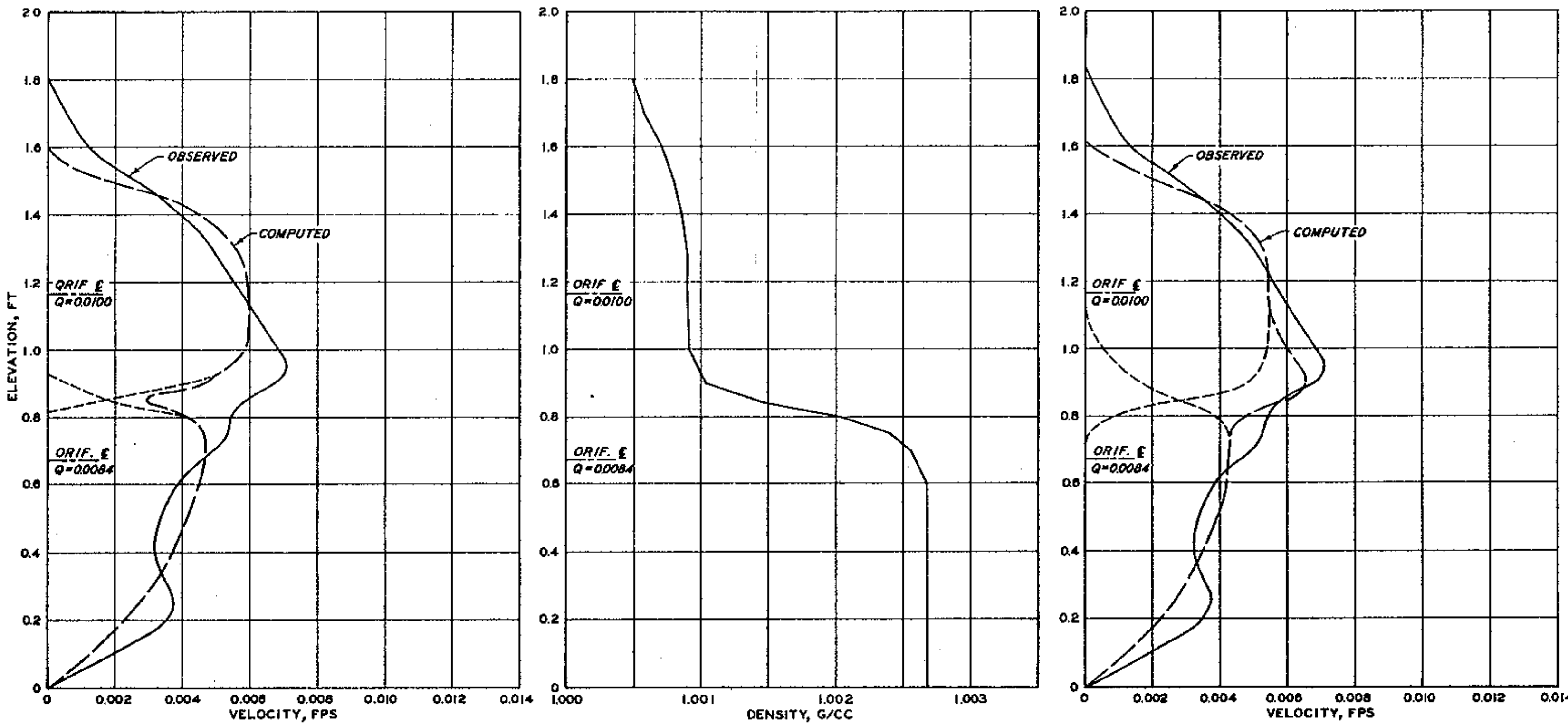
PLATE 2



VERTICAL DISTRIBUTIONS OF
VELOCITY AND DENSITY
DISCHARGES 0.0121 AND 0.0079 CFS

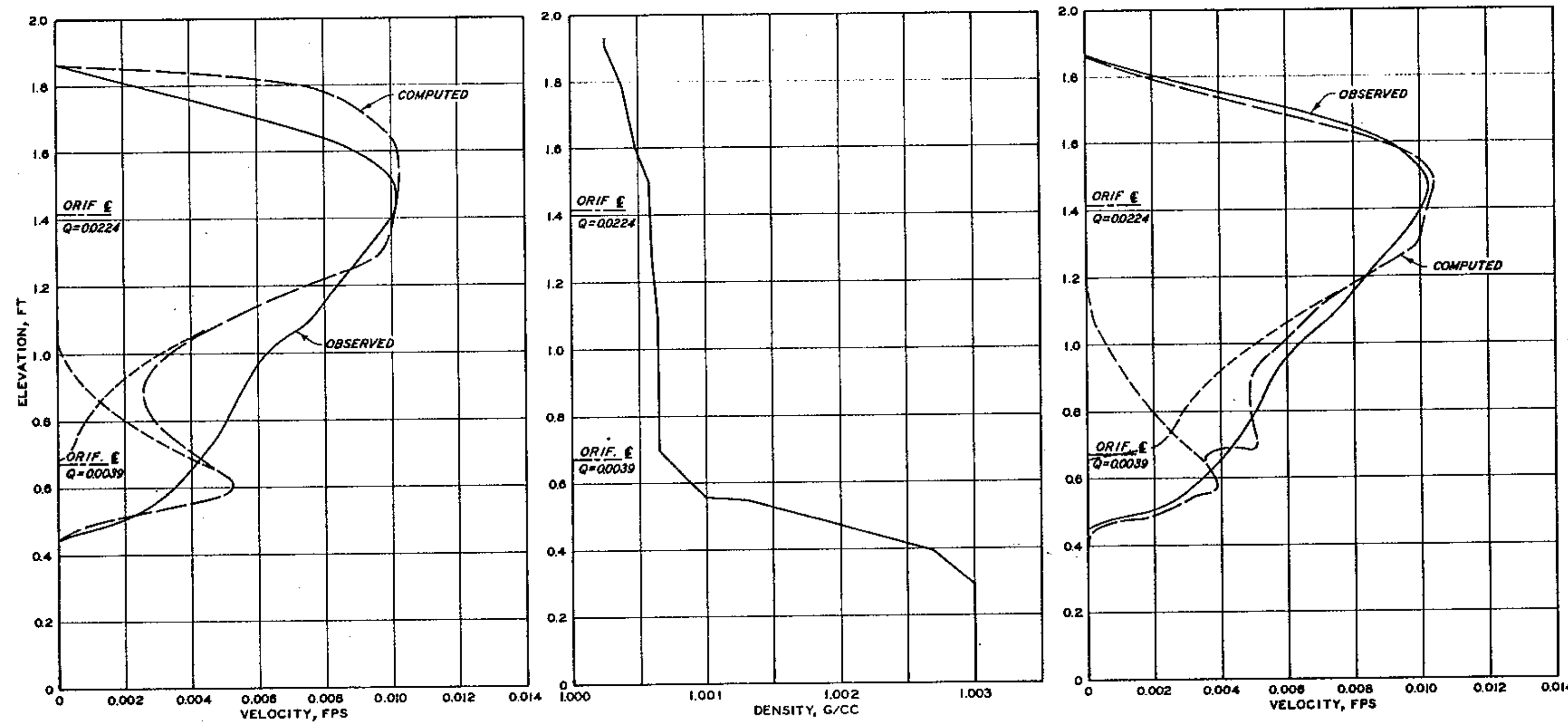


SIMPLE SUPER POSITION

DENSITY PROFILE

CONTROLLED SHIFT SUPER POSITION

VERTICAL DISTRIBUTIONS OF
VELOCITY AND DENSITY
DISCHARGES 0.0100 AND 0.0084 CFS



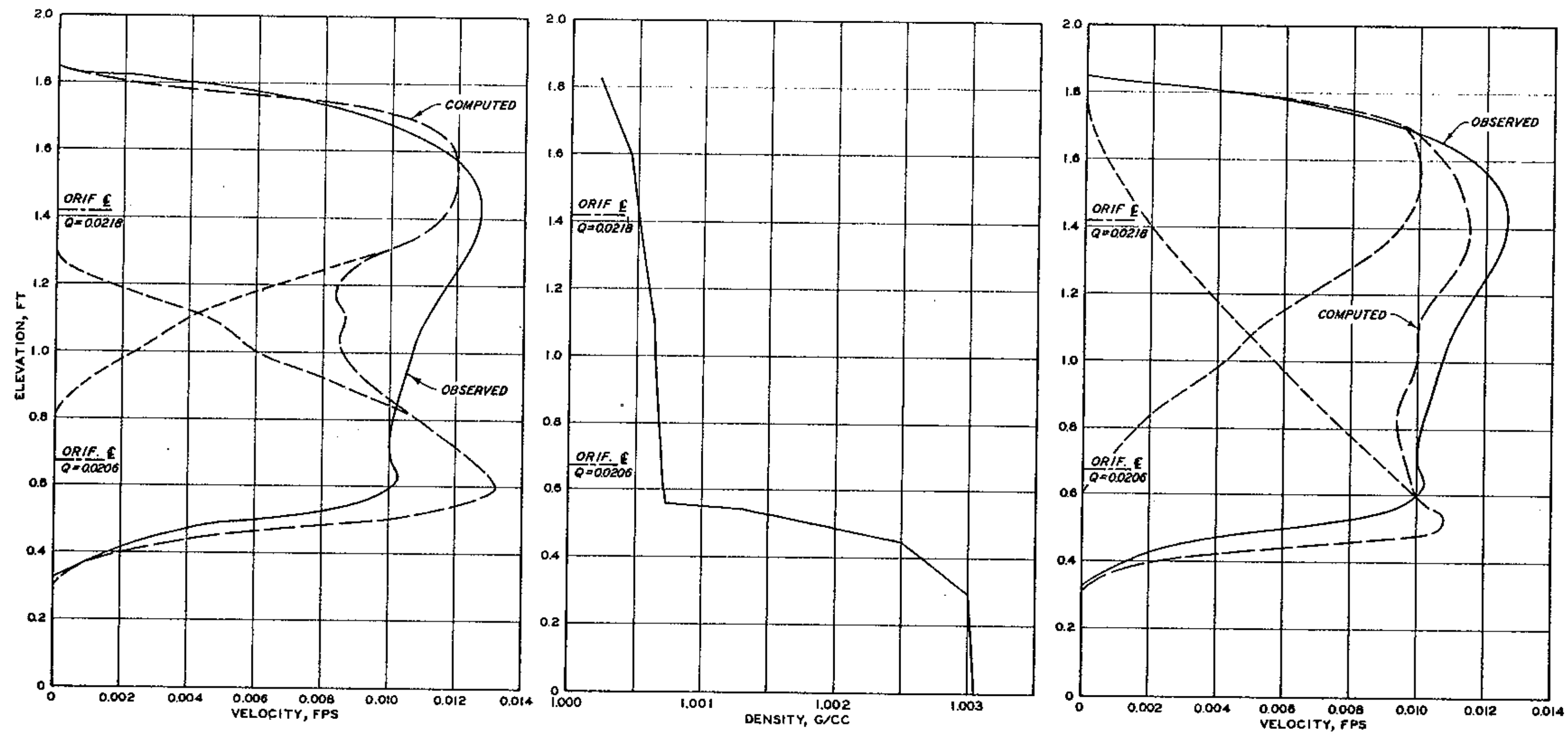
SIMPLE SUPER POSITION

DENSITY PROFILE

CONTROLLED SHIFT SUPER POSITION

VERTICAL DISTRIBUTIONS OF VELOCITY AND DENSITY
DISCHARGES 0.0224 AND 0.0039 CFS

PLATE 4

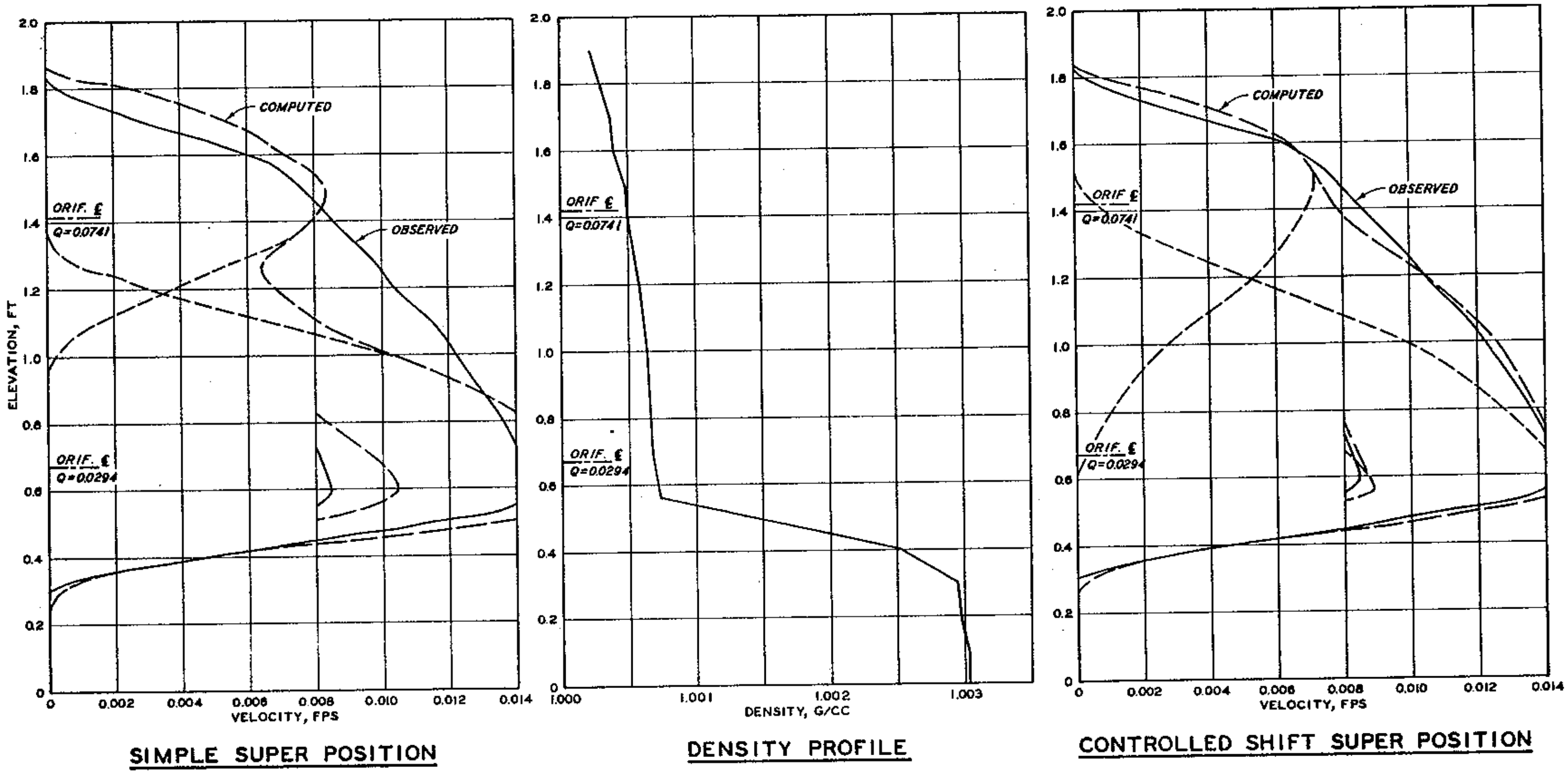


SIMPLE SUPER POSITION

DENSITY PROFILE

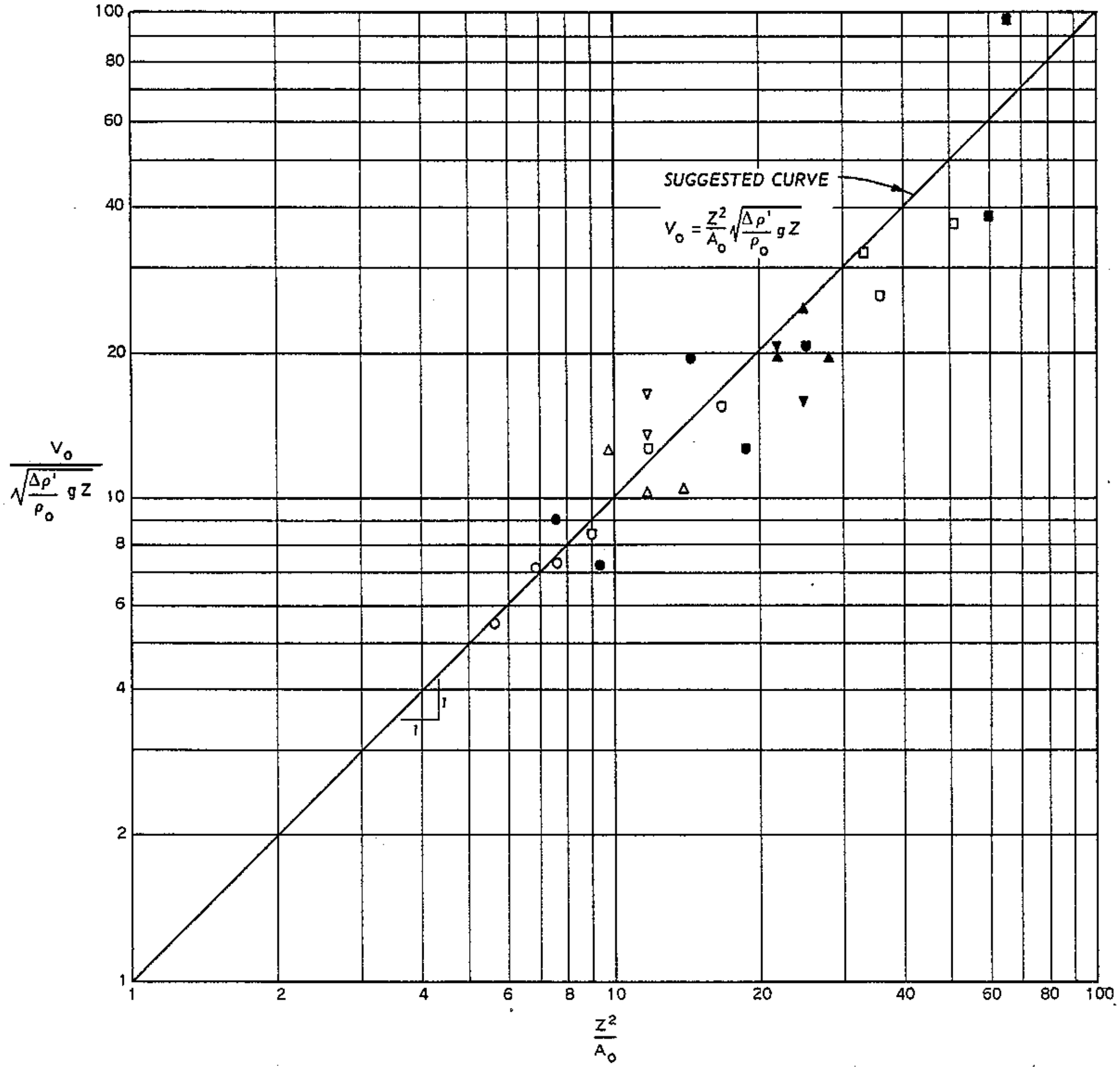
CONTROLLED SHIFT SUPER POSITION

VERTICAL DISTRIBUTIONS OF
VELOCITY AND DENSITY
DISCHARGES 0.0218 AND 0.0206 CFS



VERTICAL DISTRIBUTIONS OF
VELOCITY AND DENSITY
DISCHARGES 0.0741 AND 0.0294 CFS

PLATE 6



LEGEND

0.08-FT-SQUARE ORIFICE

□ LOWER } WITHDRAWAL CHARACTERISTICS
■ UPPER }

0.16-FT-SQUARE ORIFICE

○ LOWER } WITHDRAWAL CHARACTERISTICS
● UPPER }

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

▽ LOWER } WITHDRAWAL CHARACTERISTICS
▼ UPPER }

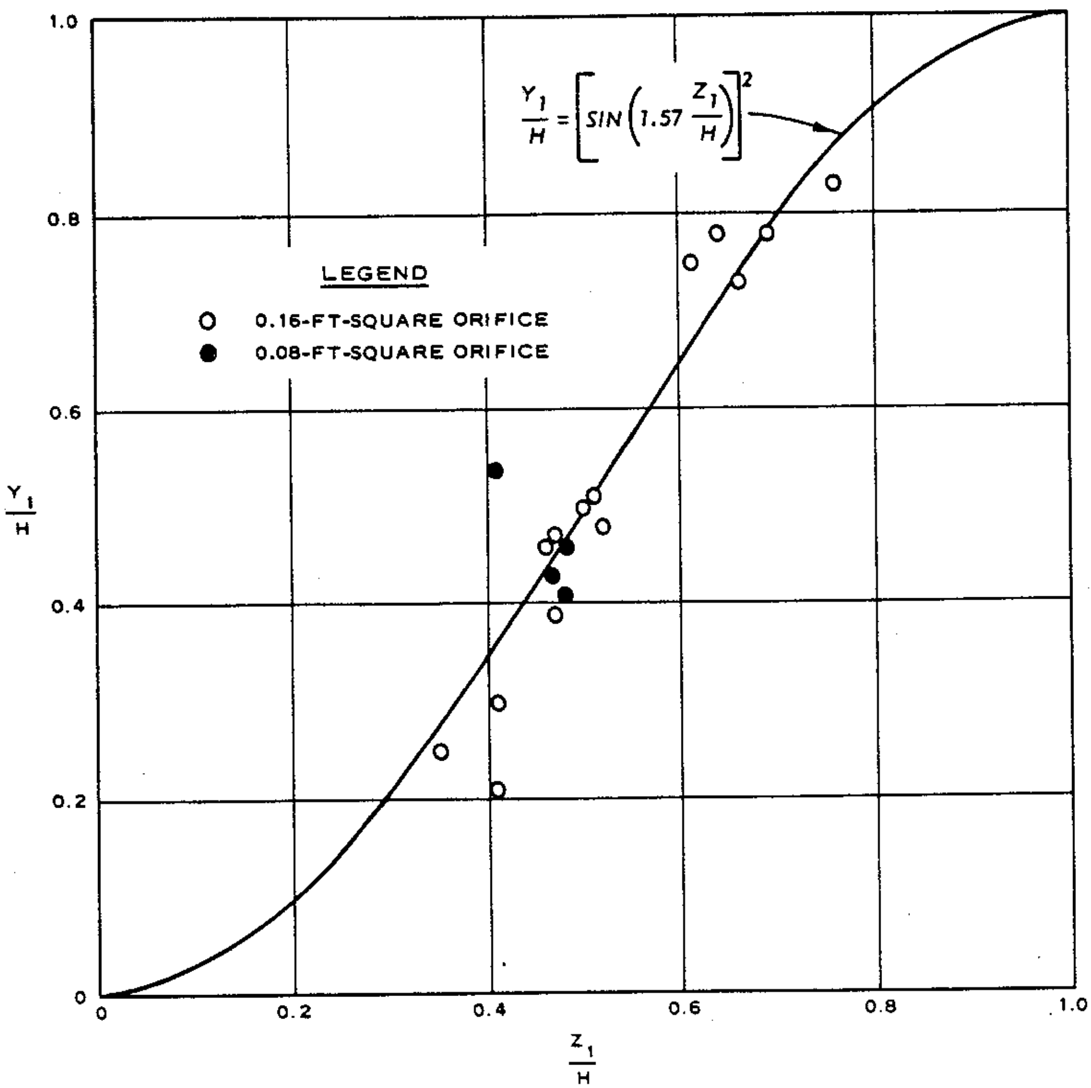
0.11- BY 0.23-FT RECTANGULAR ORIFICE (LONG AXIS HORIZ)

△ LOWER } WITHDRAWAL CHARACTERISTICS
▲ UPPER }

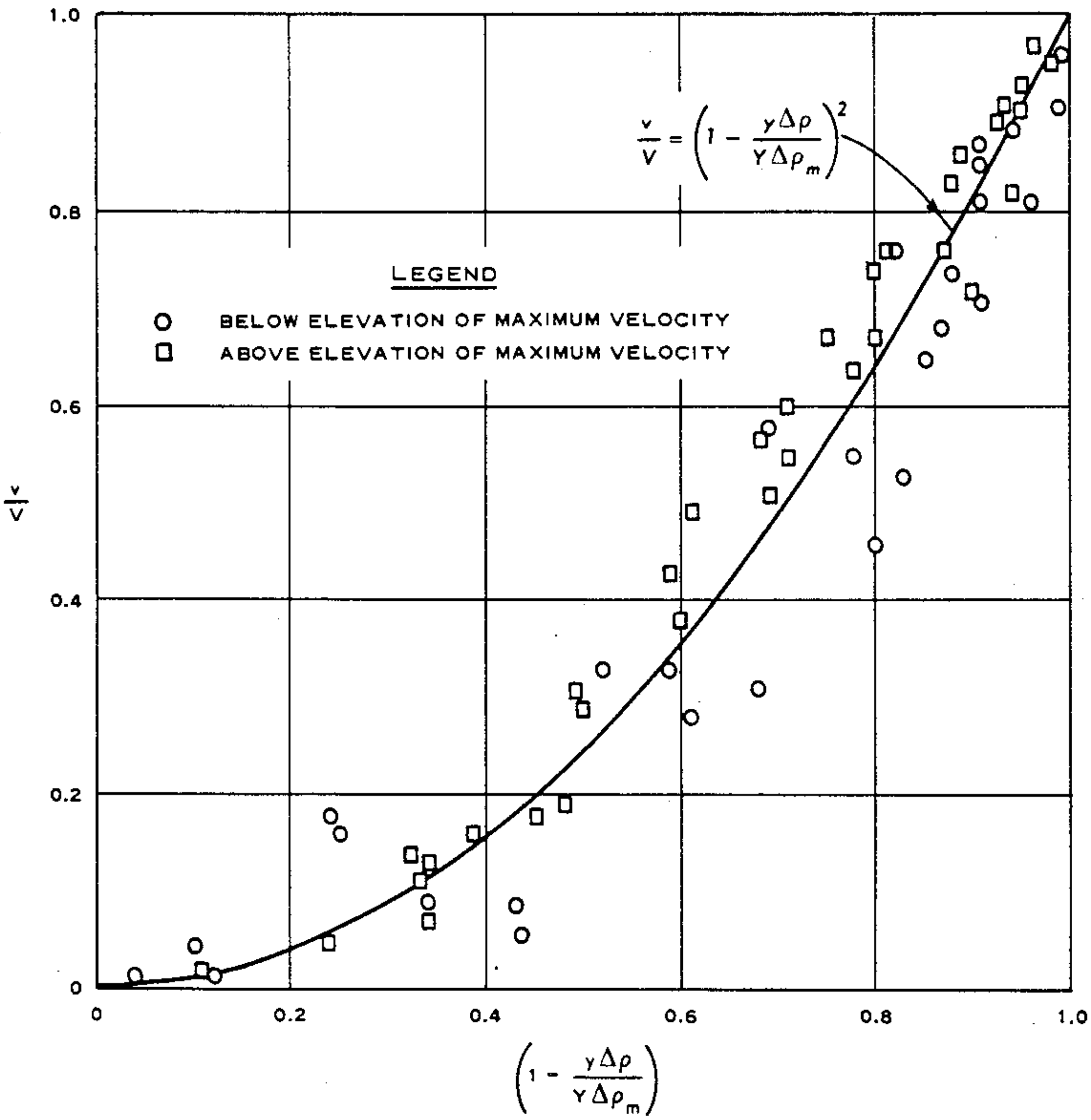
0.18-FT-DIAM ORIFICE

◌ LOWER } WITHDRAWAL CHARACTERISTICS
⬮ UPPER }

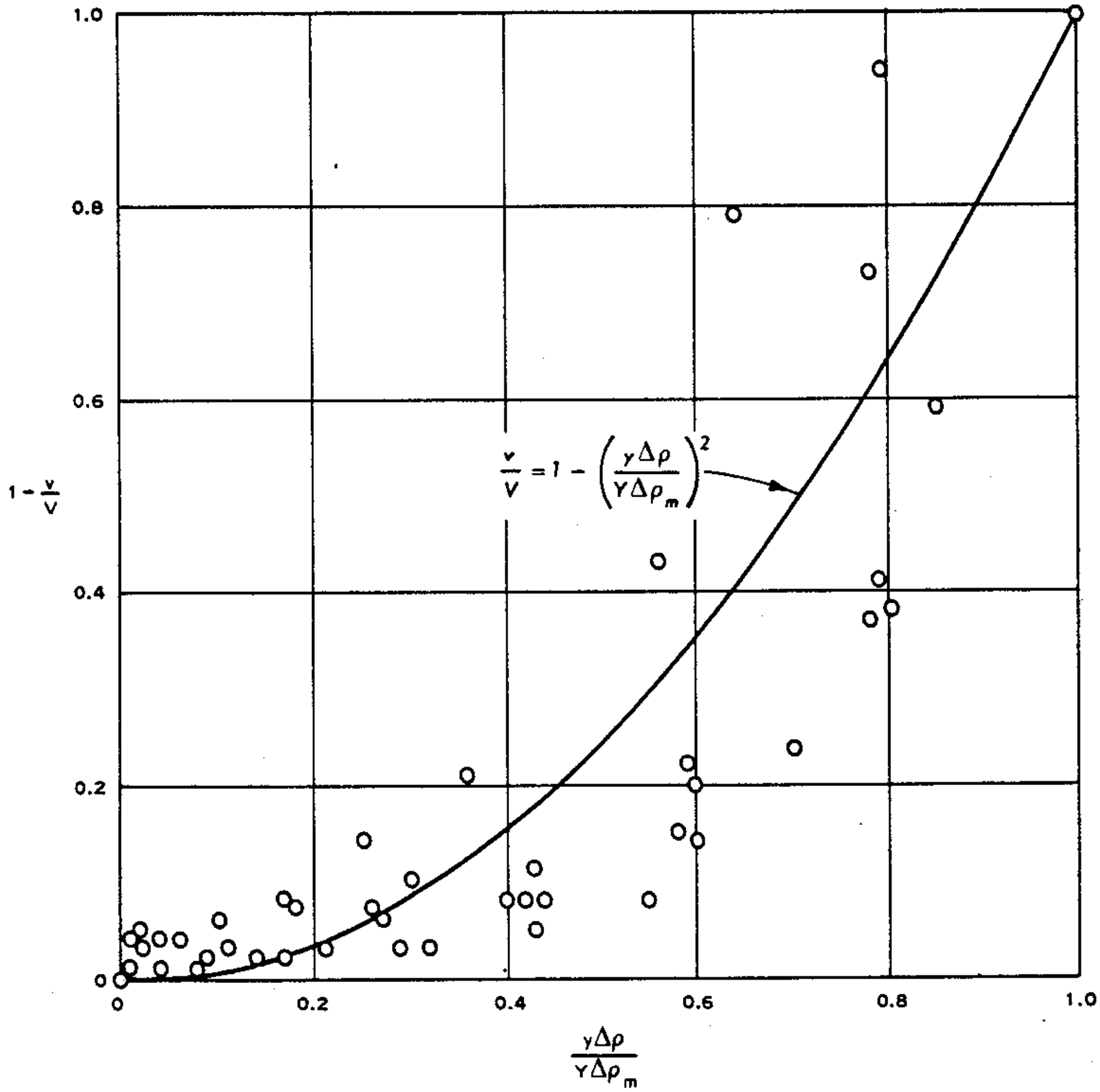
WITHDRAWAL CHARACTERISTICS OF ORIFICES



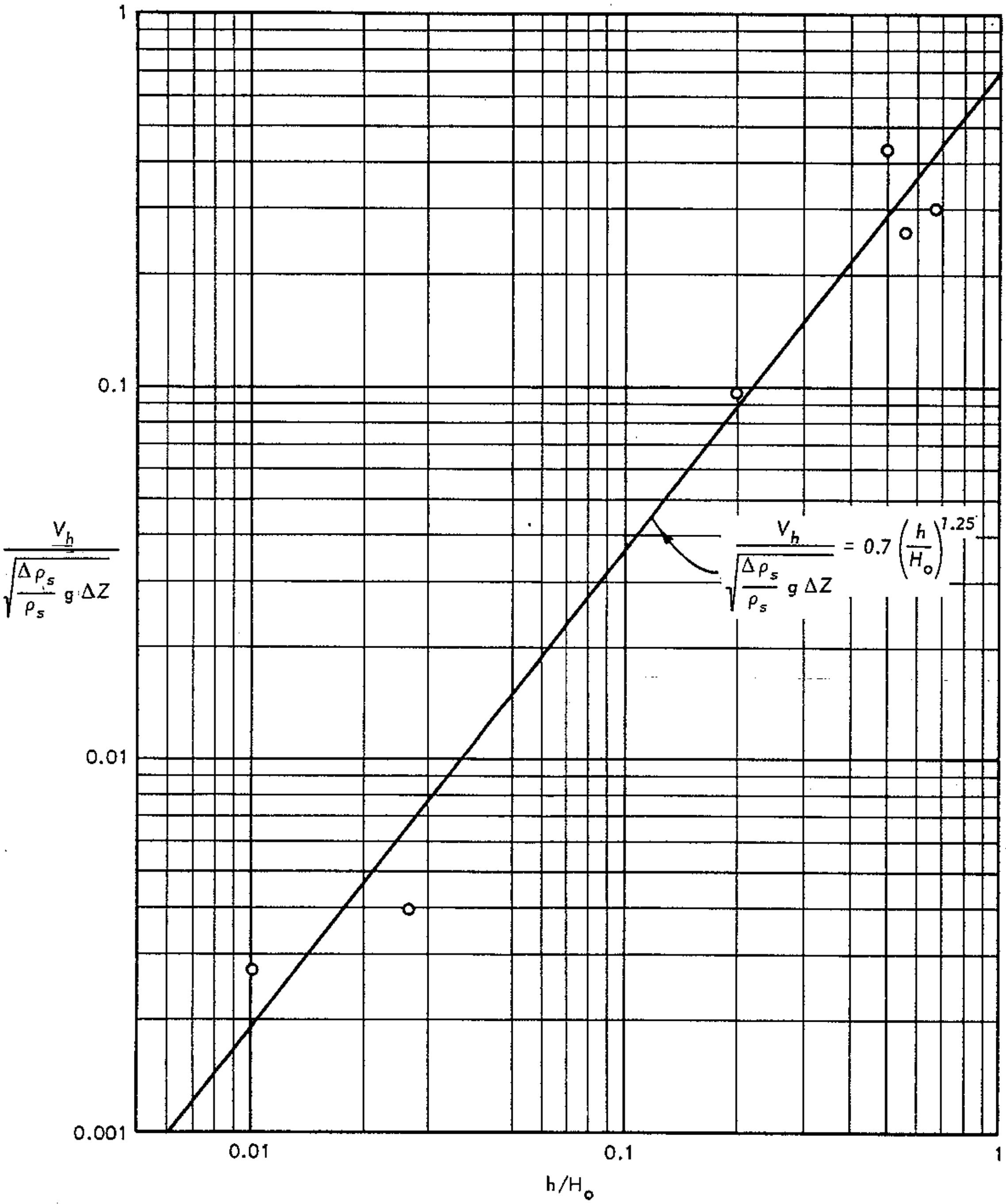
RELATIVE POSITION
OF MAXIMUM VELOCITY
FOR ORIFICE WITHDRAWAL



VELOCITY DISTRIBUTION
IN STRATIFIED FLOW
FOR ORIFICE WITHDRAWAL
BOUNDARY EFFECTS NEGLIGIBLE



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



CONTROLLED SHIFT FOR SIMULTANEOUS, MULTIPLE LEVEL RELEASE

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

SIMULTANEOUS, MULTIPLE-LEVEL RELEASE FROM STRATIFIED RESERVOIRS
Hydraulic Laboratory Investigation

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

Final report

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6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1972	34	4

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	Research Report H-72-3
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 U. S. Army Engineer Districts, Huntington and Louisville U. S. Army Engineer Division, Ohio River

13. ABSTRACT

Laboratory research was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) to determine the characteristics of the withdrawal zone resulting from the simultaneous release of flows from a randomly stratified impoundment through outlets located at different elevations. Stratification was generated in experimental facilities by creating differentials in both temperature and dissolved salt. The density profile was determined by measuring the temperature and conductivity profiles and combining the effects on density of these two factors. The velocity distributions were obtained by filming the displacement of a dye streak in the flow. Superimposing the separate and distinct velocity profiles for each of the outlets based on single-outlet operation (as used in a previous WES investigation) to obtain the composite velocity profile, due to simultaneous release through two outlets, did not yield completely satisfactory comparisons between predicted and observed results. Further analyses were made to develop a generalized technique, which involved a controlled shift of the withdrawal limits in the zone of overlap prior to superimposing the two separate and distinct velocity profiles. This technique yielded good agreement between observed and predicted, selective withdrawal characteristics. When the composite velocity profile in the reservior has been determined by the recommended method, a weighted-average technique can be applied to determine the value of any water-quality parameter in the outflow for which a vertical distribution within the reservoir is known.

DD FORM 1473 1 NOV 65 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hydraulic models Reservoirs Stratified flow Velocity measurement Water quality						

Unclassified

Security Classification