

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

by

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ABSTRACT

This investigation is a study of the characteristics of sluice gate discharge of flows which are stratified due to density differences. Specifically, it was desired to determine the conditions for which simultaneous discharge, under the sluice gate, of both the dense and lighter layers of fluid would occur. The investigation was divided into two phases:

A. Experiments in which the lower dense current possessed relatively high velocities of approach with resulting entrance turbulence.

B. Experiments in which the lower dense current was drawn from an essentially infinite source reservoir with little or no initial turbulence.

In A above, mixing of the two layers occurred due to the entrance disturbances before any drawdown under the gate of the supernatant fluid occurred.

In B above, drawdown will occur under certain conditions. These conditions can be approximately defined in terms of a Froude number in the dense layer at the gate and the ratio of gate opening to depth of dense layer. Density differences between the upper and lower layers ranging from .2 to .4 percent were investigated.

Thesis supervisor: Professor Donald R. F. Harleman
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eng. C. C. Jacobson, Jr. Aug. 31, 1954

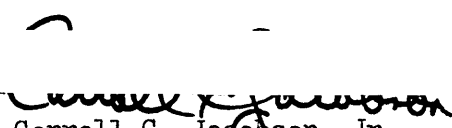
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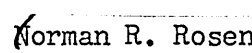
To The Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of
Master of Science in Civil Engineering from the Massachusetts
Institute of Technology, we submit this thesis entitled, "SLUICE
GATE DISCHARGE OF STRATIFIED FLOW."

Respectfully submitted,


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ACKNOWLEDGEMENTS

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DEFINITION OF NOTATION

a	height of gate opening in inches
c	Gariel's parameter
c	celerity of interfacial waves
F_g	A Froude number in the dense layer at the gate
F_h	Froude number in the dense layer at a distance 60 inches upstream of the gate
g	acceleration of gravity
g'	reduced effect of gravity in dense layer equals $g \frac{\Delta \rho}{\rho}$
h	depth of dense layer in inches at a point 60 inches upstream of the gate
h_r	depth of dense layer in the reservoir above the level of the flume bottom
h_u	depth of supernatant fluid in inches
H'	depth of light and dense fluid upstream of the gate
H	depth of dense fluid downstream of the gate
N	Reynolds number
q	rate of flow per unit width, in^2/sec
Q	rate of flow, in^3/sec
ΔR	Venturi manometer deflection in feet
T	temperature
V	velocity of dense fluid
w	depth of wedge in inches
x	horizontal coordinate axis, $x = 0$ at gate and positive upstream
z	vertical coordinate axis, $z = 0$ at lip of gate and positive upward

$\gamma = \gamma_2$	unit weight of dense fluid
γ_1	unit weight of light fluid
$\Delta\gamma$	difference of unit weights of denser and lighter fluid
ρ_1	density of lighter fluid
$\rho = \rho_2$	density of denser
$\Delta\rho$	differences in density of denser and lighter fluid

I SUMMARY

A. Object

The object of this thesis was the investigation of the flow under a sluice gate or curtain wall from a reservoir in which the liquid stored consists of two fluids of slightly different densities. Specifically, it was desired to determine the conditions under which steady state discharge of both the lighter and heavier liquids would occur through the gate simultaneously.

B. Method

At the beginning of the experiment the two fluids, fresh water above the salt water, are stored behind a gate in a flume and reservoir. The flume is filled with the denser liquid on the downstream side of the gate. As the gate is opened, a pump draws the dense liquid through the gate and recirculates it through the system. Measurements are taken of the profile of the interface between the liquids on the upstream side, the depths of the layers involved, the discharge through the gate, the gate opening, and the density difference between the liquids. The results were analyzed to determine the relationship between relative gate opening, discharge, density difference and certain dimensionless flow characteristics.

C. Scope

The first phase of the work consisted of the modification and fabrication of equipment which satisfactorily reproduced the desired phenomena. The second phase included the conduct of experiments at different values of density difference, relative gate opening and discharge to obtain critical values of these parameters at which the discharge of both layers through the gate began, or to indicate the values

at which the flow of the denser current was limited by excessive turbulence and mixing at the interface.

The first phase, that is the equipment modification and fabrication, dominated the investigation timewise, so that the experimental data obtained, while it presents a good picture of the phenomena occurring and is an indication of trends towards critical values of discharge characteristics, is not in itself complete, and recommendations are given for future study in this field.

D. Conclusions

With an essentially constant head source of the density current, drawdown of the lighter fluid, i.e., essentially steady flow of two layers under the gate, will occur under certain conditions. These conditions are a function of the relative gate opening, the density difference and a Froude number in the dense layer, and can be approximately defined for the range of experimental data herein.

II INTRODUCTION AND THEORETICAL CONSIDERATIONS

A. Introduction

"A density current may be described as a gravity flow of a liquid or a gas through, under, or over a fluid of approximately equal density." (1)

An introduction to the complexity and importance of density current phenomena is best provided by a direct quotation from reference (2).

"Water stored in large reservoirs on tributary streams thermally stratifies during the period from spring to fall. Inflow moves through these reservoirs in the form of density currents due primarily to temperature differentials and secondarily to dissolved minerals and suspended sediment. Cold water released from tributary storage reservoirs

into downstream reservoirs on the main stream causes induced density currents in those reservoirs.

In practical system operation, TVA found that density current flows were important to industrial water use, stream pollution, recreation, municipal water supply, and steam plant condensing water.

Water temperatures for use of industry are affected by density flows through reservoirs. Sources of water supply may be polluted by flow patterns set up through density currents. Portions of main reservoir bodies may or may not be safe for swimming, depending upon density current flows. Reservoir embayments may be unfit for swimming because of pollution being carried upstream in the embayments by subsurface flows. Of particular significance is the part played by density currents in serving as the means for providing condenser water of suitable temperature at TVA's large Kingston steam plant."

If in addition to temperature and sediment density currents in fresh water reservoirs, the salt wedge intrusion into coastal rivers and estuaries is considered, the density current problem assumes tremendous economic and social implications.

Actually, as the above quotation indicates, density currents are relatively common phenomena when recognized. More observable density currents in nature will also include warm and cool air masses and dust storms.

B. Theoretical considerations

A quantitative discussion of density currents is beyond the scope of this investigation. However, a qualitative analysis is possible and advantageous. The following will discuss the general factors affecting a single dense current flow under a sluice gate or curtain wall, a simplification of the Kingston steam plant problem. (2, 3)

A discharge equation for the sluice gate shown in Figure 1 may be obtained by application of the modified continuity and energy equations and by assumption of the head loss downstream of the gate. Let section 1 refer to the flow conditions at some distance upstream of the gate, section 2 to the sluice gate itself, and section 3 to some location downstream of the gate. In accordance with the notation of Figure 1 and for a unit width:

$$\text{from continuity: } q = hV_1 = aV_2 = HV_3 \quad (1)$$

from the energy equation written between section 1 and 3:

$$\frac{(Y - \Delta Y)H'}{\gamma} + \frac{\Delta Y h}{\gamma} + \frac{V_1^2}{2g} = H + \frac{V_3^2}{2g} + h_{\text{loss}} \quad (2)$$

assuming uniform velocity and hydrostatic pressure distribution at the two sections.

The head loss may be evaluated as the difference of the velocity heads for sections 2 and 3:

$$h_{\text{loss}} = \frac{V_2^2}{2g} - \frac{V_3^2}{2g} = \left(\frac{h}{a}\right)^2 \frac{V_1^2}{2g} - \frac{V_3^2}{2g} \quad (3)$$

From equation (2) then, the discharge equation may be established as follows, introducing c_d as a coefficient:

$$q = c_d a \sqrt{\frac{2g}{1 - \left(\frac{a}{h}\right)^2}} \sqrt{(H' - H) - (H' - h) \frac{\Delta Y}{\gamma}} \quad (4)$$

It is seen that $(H' - H)$ must at all times exceed the term $(H' - h) \frac{\Delta Y}{\gamma}$ in magnitude to give flow in the assumed direction. It is also established that for increasing values of $\frac{a}{h}$ the difference in these two heads will decrease for a given discharge. With increasing density differences, H' must be raised to maintain a given flow. This equation shows that $(H' - H)$ is the dominant term. However, it cannot be

determined accurately by experiment except by a special precision manometer, which was not available for this investigation.

Assuming $c_d = 0.6$, which appears to be a reasonable value from considerations of a submerged sluice gate in free surface flow, and applying equation (4) to some of the experimental data obtained in this investigation, the order of magnitude of $(H' - H)$ is 0.005 - 0.0015 feet.

Ignoring viscous effects, it is reasonable to assume that in the situation shown in Figure 1 it is possible to increase the head differential $(H' - H)$ across the gate until the supernatant fluid is drawn through the gate.

Gariel (4) describes a limiting condition for the depth h at which there will be no appreciable flow of the supernatant fluid through the gate as $c = \frac{g'h^3}{q^2} = .43$, where h is defined as "the vertical distance from the horizontal plane of the slit to the interface sufficiently far upstream at the moment when not more than one percent of salt water is withdrawn in the mixture," q is the discharge per unit width for conditions which limit h , and g' is the reduced effect of gravity and equals $g \frac{\rho_2 - \rho_1}{\rho_2}$ where ρ_1 is the density of the upper fluid and ρ_2 the density of the lower fluid. Gariel verified this experimentally within appropriate limits of experimental error. Because of different experimental conditions, h has no identical counterpart in the present investigation. The salient feature about $c = \frac{g'h^3}{q^2}$ is that it is in the form of $1/F^2$, where F is a Froude number. Therefore ignoring viscosity, drawdown may be defined by some value of a parameter in the form of a Froude number.

The stability of the interface becomes important when considering the drawdown of the lighter fluid, for mixing could conceivably

occur before drawdown. If the velocity of the dense current, V , equals or exceeds the interfacial wave celerity, c , the interfacial waves will break and mixing of the two layers will occur. Thus mixing may be defined by a form of the Froude number, $V/c = 1$. (5)

The viscosity of the two fluids, brine and fresh water, does not vary appreciably, the kinematic viscosity, ν , for 3.5% saline sea water = 1.182×10^{-5} ft²/sec and $\nu = 1.134 \times 10^{-5}$ ft²/sec for fresh water, both at 65°F. (6) Viscous shear will retard the flow and modify the velocity gradient. From a consideration of the two forces involved, gravity and viscosity, a stability relationship may be determined, $\theta = \frac{1}{NF^2}$ where N and F are appropriate forms of the Reynolds and Froude numbers respectively. (5)

III PROCEDURE

A. Outline of method of attack and reasons for its selection

The method of attack in this investigation was based primarily on considerations of conditions in the field at the Kingston plant of the TVA. (2)

The elements to be considered were the existence and source of a density current, the sluice gate for control of the discharge of the stratified flow, and the physical character of the flow.

The density current in the field is due to a temperature differential, but because of the inherent difficulty in controlling the temperature in the laboratory it was decided to use a brine.

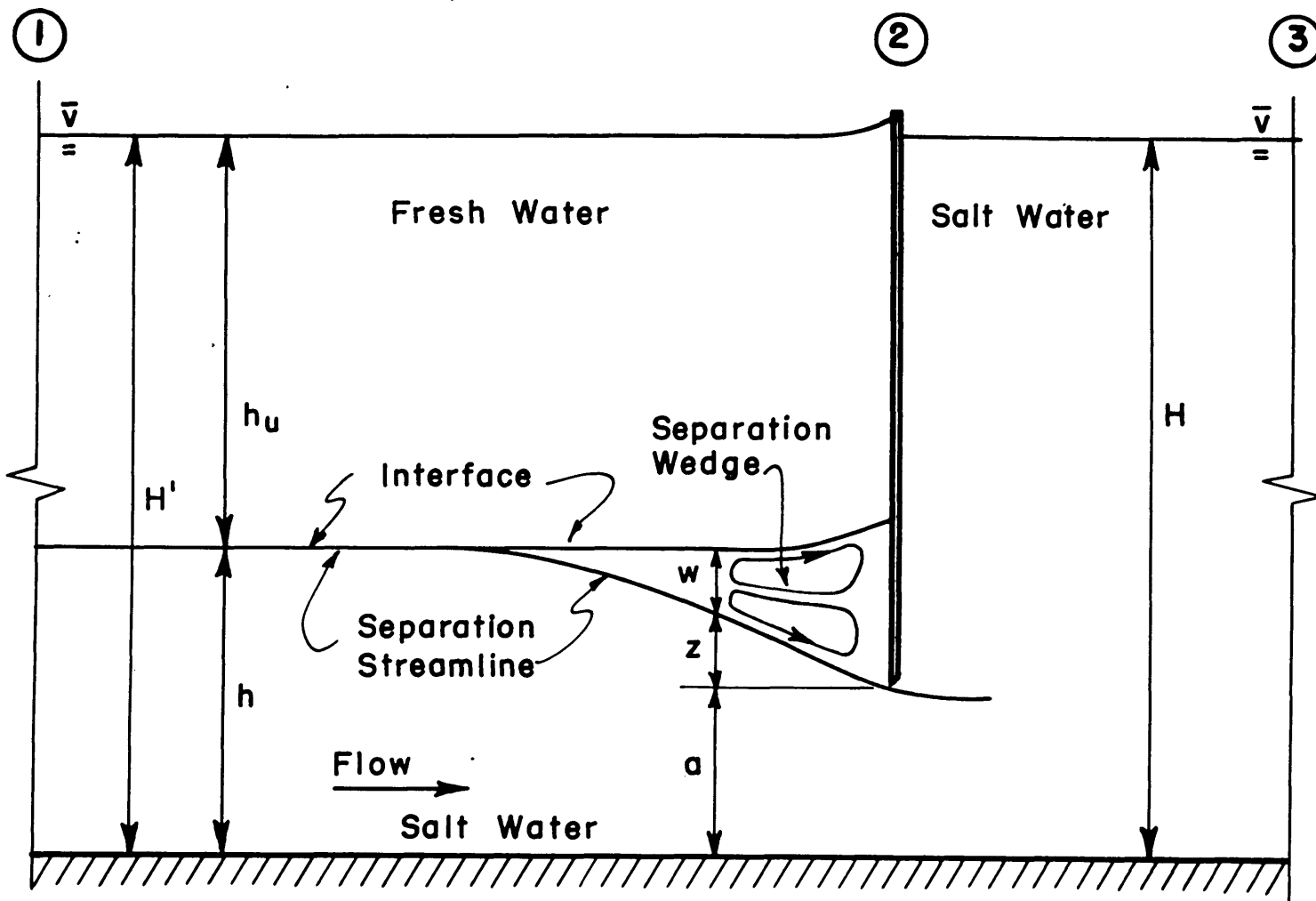


FIGURE 1 DEFINITION SKETCH

The density gradient at Kingston varies somewhat gradually with the depth, but in order to exercise control and to make observations in the laboratory, two definite layers with a sharp line of demarcation were used.

The variables involved in the experiments are primarily the relative gate opening, $\frac{a}{h}$, the density difference and the Froude number in the density current. The relative gate openings used were in the range of about 0.5 to 0.8, the lower limit selected to give more stable conditions for observation, and the upper limit selected to approach that to be used in the field.

The range of density differences in the field is from about 0.1% to 0.2%. However, these small differences are extremely sensitive to transient conditions in the laboratory, therefore a range of about 0.2% to 0.4% was used.

The Froude number range was to be determined for critical conditions for various combinations of the other variables involved.

As a result of these considerations, the equipment was set up in the laboratory to include a reservoir with stratified flow, an adjustable gate, and a circulating system to resupply the density current. By using fresh water in the upper layer, the density difference could be controlled by varying the density of the lower layer. The discharge was controlled by means of a variable speed pump and valves in the circulating system.

B. Description of equipment

The experiments in this investigation were run in two groups: first, on the equipment as initially modified by addition of a

new circulating system, and second, as finally modified by the addition of a reservoir.

Figure 2 is a schematic diagram of the original equipment, and Figure 3 is a schematic diagram of the equipment after modifications.

1. Flume and Reservoir

The flume is a glass-walled channel eight feet long, four and a half inches wide and eighteen inches deep, equipped with a lucite bottom and fluorescent lights under the bottom for illumination. An adjustable gate with rubber seals was located two feet, eleven inches from the downstream end of the channel. Three-quarter inch drain and fill valves were provided at the downstream and upstream ends of the flume respectively.

A reservoir was attached to the upstream end of the flume and consists of a steel tank eighteen inches square and three feet deep with lucite front and back walls to enable observation of the density interface. The supply pipe discharges into the side of the reservoir near the bottom. The reservoir is joined to the flume by means of a lucite transition section, the reservoir end of which is eighteen inches wide by twenty-one inches deep, while the flume end is four and a half inches wide by eighteen inches deep. The section is twelve inches long and is made of three cylindrical quadrants of five inch radii joined at right angles. The shape of the transition section was chosen arbitrarily to give a smooth transition and still be as simple as possible to fabricate.

2. Circulating system

The circulating system on the flume initially consisted

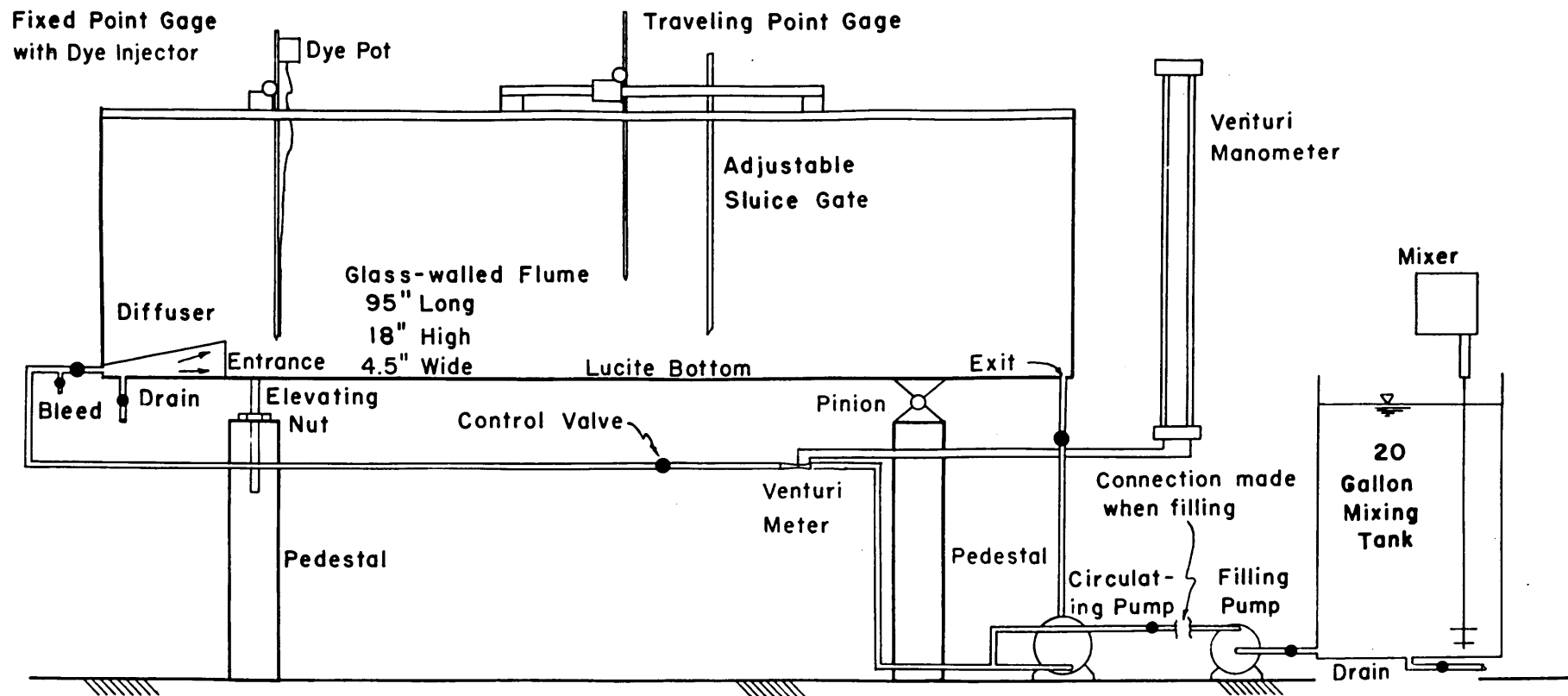
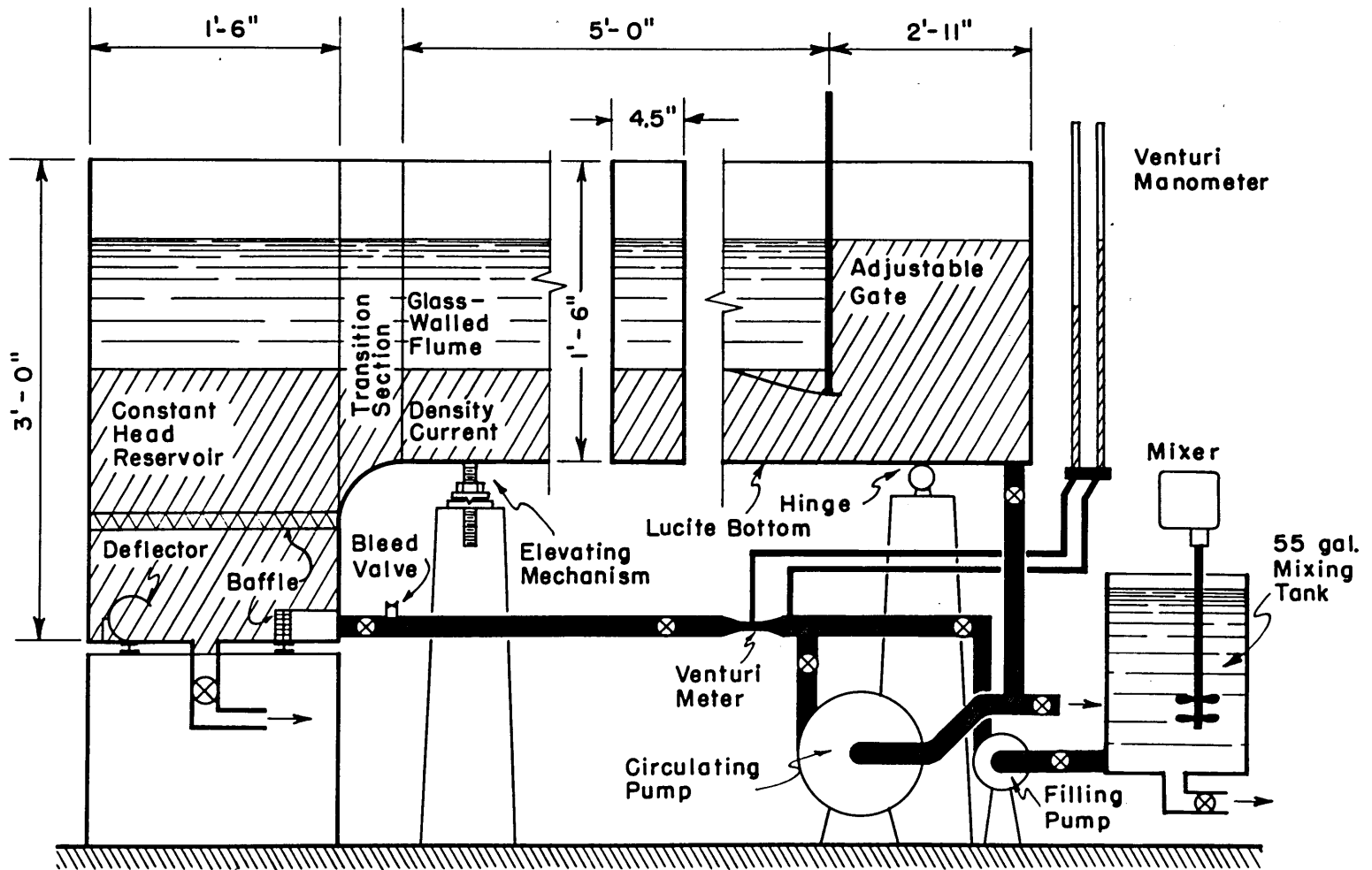


Figure 2 SCHEMATIC DIAGRAM OF DENSITY CURRENT FLUME BEFORE MODIFICATION



NOTES: Reservoir is Square. Sides of Transition Section are Cylindrical Quadrants

FIGURE 3 SCHEMATIC DIAGRAM OF DENSITY CURRENT FLUME AND RESERVOIR AFTER FINAL MODIFICATION.

of half-inch pipe and an Eastern Industrial (Model F) centrifugal pump rated at seventeen gallons per minute. The pump and its driving motor are manufactured as a close coupled unit; this required throttling of the discharge through a needle valve which heated the liquid sufficiently to change the density difference. This system was modified by installing three-quarter inch piping to allow for larger discharges at lower velocities and by remounting the pump motor. The pump and motor were connected by V-belt pulleys through a Toledo Timer split-pulley reducer. The ratio of pump pulley to motor pulley was 3.5:1. The split-pulley reducer gave an additional variation of 3:1, and with the combination it was possible to use the 3450 rpm A. C. motor at speeds from approximately 950 to 2600 rpm. This in turn gave a range of discharges from about 3 to 26 cubic inches per second.

3. Filling system

The filling system consists of a mixing tank for mixing the salt solution, mixer, pump and half-inch pipe leading into the circulating line through a tee. Initially a 20-gallon mixing tank was used but this was replaced by a 55-gallon tank after the reservoir was added. The mixer consisted of a pair of four and a half inch counter pitch propellers mounted on a detachable shaft, driven by a one-quarter horsepower electric motor.

4. Instrumentation

The instruments used included those for measuring specific gravities, metering the flow, and measuring water surface and interface elevations.

a. Specific gravity - Specific gravity determinations were made by means of a Westphal balance. The action of this balance is essentially that of determining by means of a sensitive beam balance

the weight required to overcome the buoyant effect of a fluid on a suspended glass plummet. With this instrument specific gravities can be estimated to the nearest one ten-thousandth.

b. Discharge - Discharges were measured by means of a $3/4$ " x $19/32$ " Venturi meter in the circulating pipe. It was connected to a water-air manometer graduated in hundredths of a foot. The meter was calibrated by means of a volumetric tank and the discharge calibration curve is shown in Appendix 3.

c. Depth measurements - Depth measurements were made by means of two fixed point gages, on the reservoir and at a point five feet upstream of the gate on the flume, by a traveling point gage on a rail carriage running the length of the flume, and by means of a grid on the side of the flume.

d. Liquids and dyes - The light liquid used in all cases was fresh water. The dense layer used was a brine made by mixing salt, NaCl, to the desired specific gravity. To distinguish between the layers in the flume, the dense layer was dyed with fluorescein, $C_{20}H_{12}O_5$, a yellowish-red crystalline compound which imparted to the dense layer a brilliant yellow-green color when subjected to transmitted light, but did not destroy the transparency.

In addition, a marker fluid was used to intensify the streamline appearance and occasionally to color the wedge. This was a solution of potassium permanganate, $KMnO_4$, in the brine. It was injected into the flow either by a long hypodermic syringe with a bent needle, or from a dye pot and tube mounted on a traveling point gage.

5. Diffusers and baffles

The use of diffusers and baffles was a constant source

of difficulty in these experiments. Before addition of the reservoir, the flume was equipped with a gradually enlarging diffuser to help dissipate the jet of dense liquid as it entered the flume. At the downstream end of the diffuser a baffle made of radiator core was provided to further dissipate velocities in the dense current before it entered the main stream. At high discharges, the diffuser was not effective and the resultant mixing which occurred disturbed the density current, often to the point of precluding further data being obtained.

Various shapes and depths of diffuser and dense layer were tried but none proved satisfactory at high discharges.

Similar problems were encountered in the reservoir. At high discharges the jet went through the baffle, struck the wall on the far side of the reservoir and was deflected upward with resulting boiling and mixing at the interface. A curved deflector made of a partial circular lucite section was installed to deflect the jet downward but this merely moved the boiling across the reservoir. Finally, a horizontal baffle was installed across the reservoir at a depth of about 6 inches from the bottom. This baffle consisted of a wire basket filled with a two-inch layer of one-inch size stone. This baffle successfully eliminated the boiling at the interface except at extreme discharges.

6. Modifications

The major modification to the equipment after the new circulating system was installed was the addition of the inlet reservoir. Without the reservoir, the density current entered the flume with relatively high velocities. This was undesirable for two reasons: first, it did not represent conditions in the field where the contrary was the case; second, it caused excessive turbulence and mixing at the

exit from the baffle which precluded carrying the experiments far enough to approach critical conditions at the gate.

Addition of the reservoir and its negligible velocities of approach proved very satisfactory and enabled the experiments to be carried to the point where drawdown of the upper layer was obtained.

C. Description of test procedure

The basic procedure in the experimental runs was the same before and after modification of the equipment.

Initially the flume was filled with fresh water upstream of the gate to the depth desired for the run, and the salt solution was added to the same depth downstream. The levels on both sides of the gate were kept equal at all times during filling and prior to operation to prevent leakage around the gate. After the reservoir was added, only sufficient fresh water was used initially to give the required depth after filling. This was found to be approximately 17 inches in the reservoir initially for a 6-inch final layer in the flume. The dense liquid was then introduced on the upstream side of the gate through the filling system, the lines first being bled to remove leftover liquids and air. Filling was controlled by a half-inch steel needle valve in the entrance line from the filling pump. It was essential to start filling very slowly to avoid mixing at the entrance to the flume or reservoir. In the reservoir it was found that the flow could be gradually increased by watching the action inside the diffuser and at the exit of the baffle. At both places mixing would occur if the flow were increased too rapidly.

After the level of the dense layer in the reservoir passed the top of the diffuser, the valve could be kept fully opened until the level rose to the floor of the flume. At this point the discharge had to be decreased to prevent mixing in the flume as the front of the

density current hits the gate. When a dense layer covered the floor of the flume, the discharge was increased to a value that would allow a more rapid filling.

When the desired depth of the dense layer was obtained, the flow was shut off and the system allowed to come to rest.

With the reservoir entrance valve closed, the circulating pump is started and the lines again bled to clear them of all leftover liquids and air.

The discharge control valve is then closed and the reservoir entrance valve opened. The entrance valve is left open for the duration of the experiment, all control of discharge is by means of the control valve, and the split-pulley reducer which changes the pump speed.

Opening the gate is a sensitive operation since carelessness can easily result in large waves and resultant mixing in the flume. The gate is opened very slowly to the desired height and at the same time the control valve is opened to start the flow. It was found that if the control valve was opened first there was less opportunity for a backflow as the gate was opened. It was also found that a small amount of grease on the rubber seals facilitated the operation of the gate. Once the operation was started, changes in discharge were made slowly. This prevented disturbances due to surges and waves caused by sudden changes in discharge.

After the run was started, a clearly defined and visible separation streamline was observed.

Procedure for taking data - Samples were obtained for specific gravity determinations as follows:

Density current: from tap in bottom of flume at the upstream end.

Fresh layer: from top of reservoir (care must be taken not to create a disturbance which will affect the interface.)

Wedge: by means of a siphon inserted to the desired depth. This method was also used for any additional layers that had formed due to mixing.

Depths in the reservoir and at station 60 were measured with fixed point gages mounted on the equipment. The gate opening and streamline profiles were measured with a ruler on the side of the flume and a traveling point gage on the flume.

D. Method of making computations and plotting curves

Computations for

Density Difference

Let G_w = the specific gravity of the lighter layer

G_m = " " " " " heavy "

ρ_1 = the density of the lighter layer

ρ_2 = " " " " heavy "

$$\rho_2 = \frac{G_m}{G_w} \rho_1$$

$$\frac{\Delta \rho}{\rho} = \frac{\rho_2 - \rho_1}{\rho_2} = \frac{\frac{G_m}{G_w} \rho_1 - \rho_1}{\frac{G_m}{G_w} \rho_1} = 1 - \frac{G_w}{G_m}$$

E. Discussion of sources of error and probable precision of results

The results of this investigation indicate a greater accuracy than may be warranted by a consideration of accuracy of measurements. Temperature differences in the two layers were reduced by allowing both fluids to come to approximate room temperature by standing overnight. In spite of this, differences of 2-3°C occurred. Also, when conducting experiments at low velocities (no turbulence), a temperature gradient of 1/2°C often existed between the top and bottom of the dense fluid downstream of the gate.

To overcome this temperature (hence density) discrepancy, every effort was made to measure specific gravity by siphoning or tapping directly from the flume for each set of experimental data. The Westphal balance used in determining density is accurate only to the third decimal place.

Measurements of still water surfaces were made by a point gage to 0.1 mm and then converted to inches accurate to three significant figures. Since depth of density current and the interface profile were normally measured on the side of the flume using a one-inch square grid plus a rule divided into tenths of an inch this depth became an approximate average when interfacial waves existed. Point gage measurements offer no additional accuracy due to the difficulty in determining the exact interface and in addition tend to disturb the dense current causing unnecessary mixing.

The rate of flow as measured by a calibrated Venturi meter was assumed correct to three significant figures.

IV RESULTS

Profiles of separation streamlines obtained during experimental runs are presented in Figure 4.

A plot of relative gate opening against a Froude number at the gate is presented in Figure 5.

The general chronological development of an average experimental run culminating in drawdown of the fresh layer begins with four inches of dense layer under eight inches of fresh water upstream from the closed sluice gate. Downstream from the gate the depth of the salt water is twelve inches. As the gate is slowly raised to approximately three inches, the control valve is slowly opened to cause flow of the heavier liquid through the gate. A streamline of the type shown in

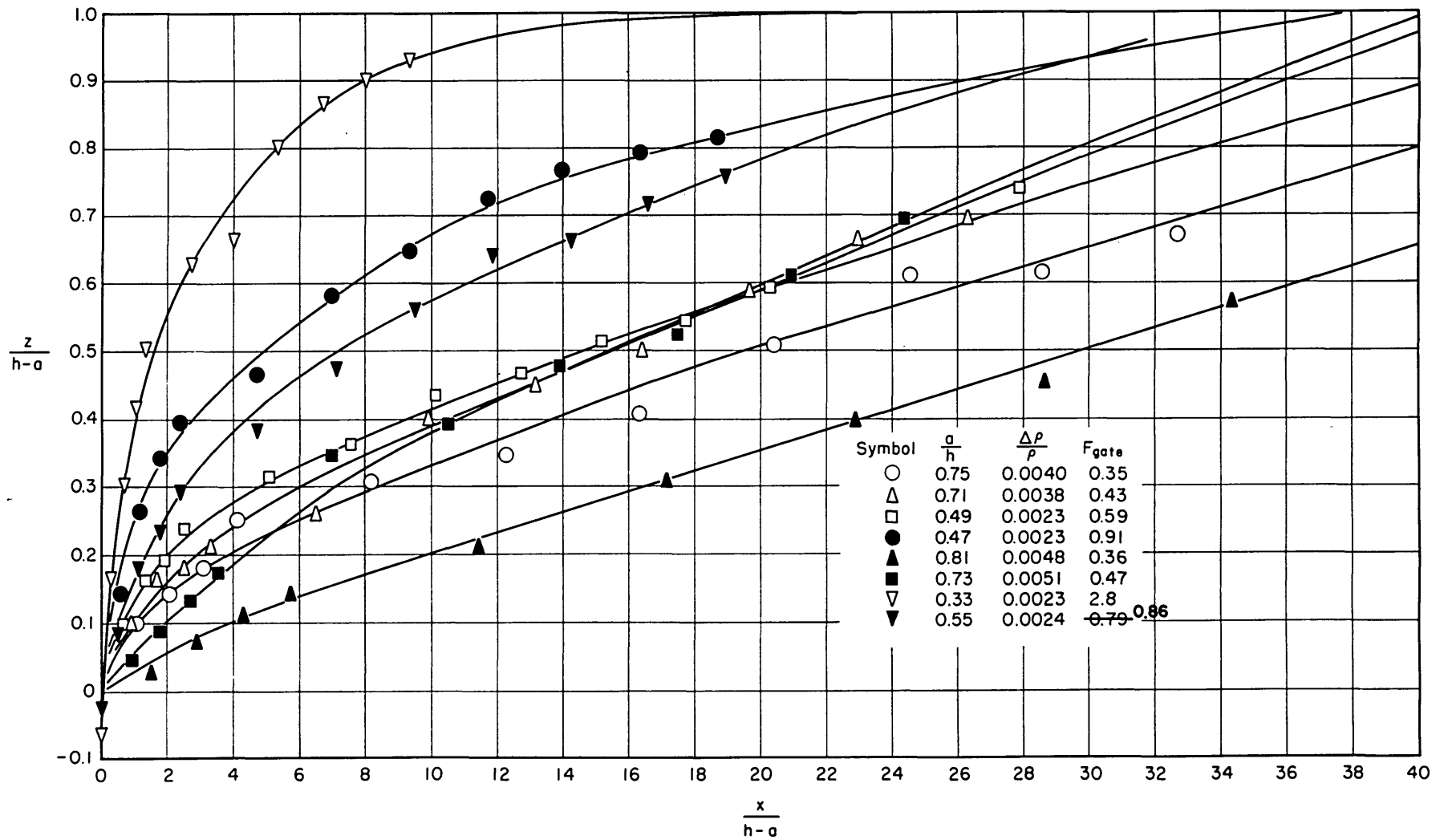


Fig. 4. Dimensionless Profiles of Separation Streamlines

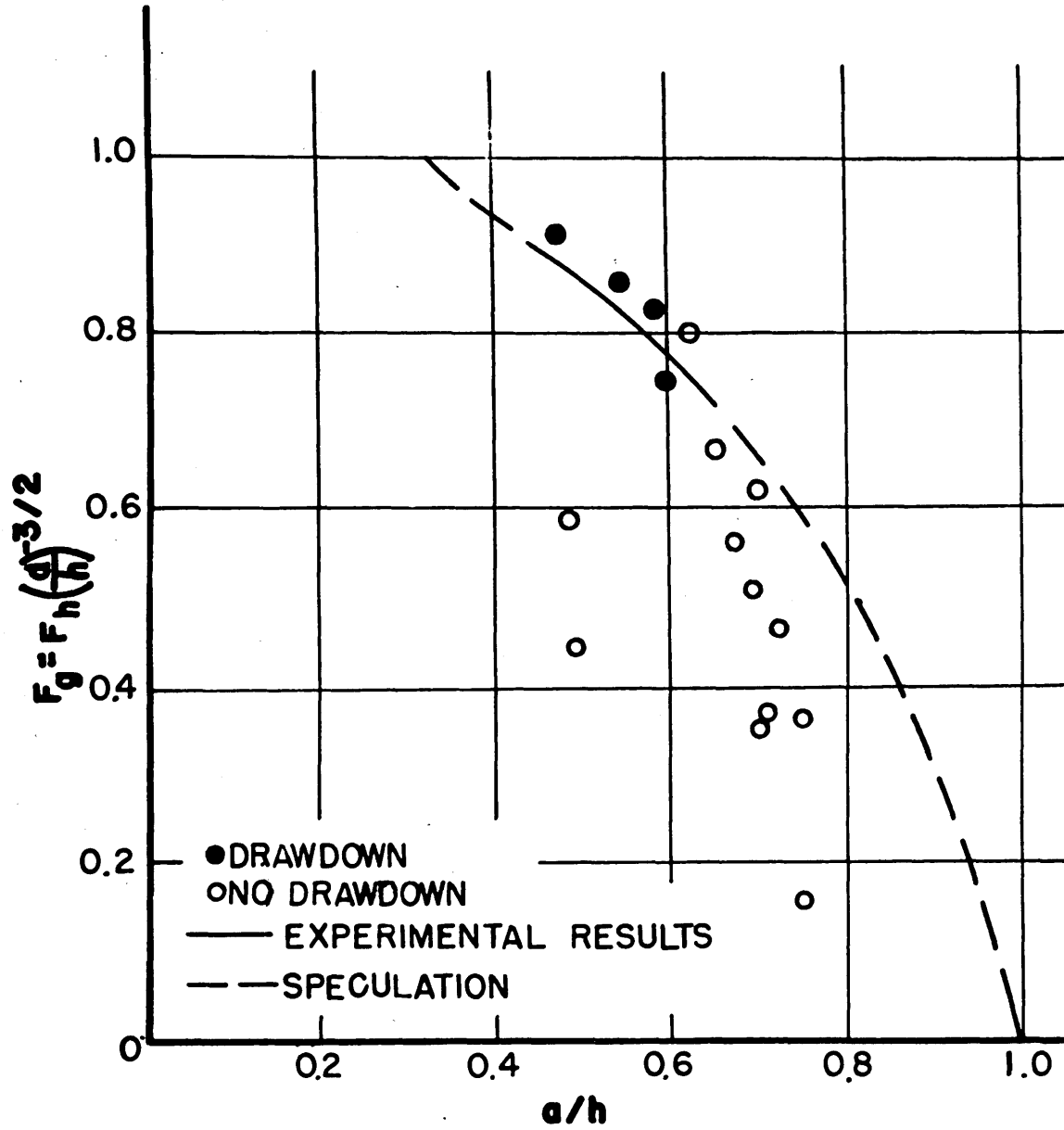


FIGURE 5 LIMITING CONDITIONS FOR DRAWDOWN

difference and gate opening. The experiments indicated that drawdown occurred at a value of F_g which was dependent upon the relative gate opening $\frac{a}{h}$. Figure 5 is a plot of the experimental runs indicating the values F_g and $\frac{a}{h}$ associated with each run. Those runs for which drawdown occurred are indicated. The solid portion of the curve represents the approximate critical drawdown condition based on the experimental data. The dashed portion of the curve is based on speculation as to what may occur. It is reasonable to assume that as $\frac{a}{h}$ approaches unity drawdown will occur for lower values of F_g , until at the point where $\frac{a}{h}$ equals unity the gate no longer controls the flow of the dense layer. On the other hand it is not reasonable to assume that as $\frac{a}{h}$ becomes very small drawdown will necessarily occur for higher values of F_g . On the contrary, it is more probable that for a very small $\frac{a}{h}$ ratio drawdown will not occur but detrimental mixing will. One of the difficulties in obtaining the critical drawdown condition is the lack of a precise measureable definition. Gariel (4) defined drawdown in terms of the percentage of fresh water flowing under the gate. This is difficult to measure, however some similar approach may be practicable in future work.

The critical drawdown condition may be obscured by interfacial waves at the gate which in breaking will also cause excessive mixing. In addition, various degrees of mixing occur in the reservoir, in the transition section, and at the gate, for any appreciable discharge. Over a period of time this mixing will either increase the volume of the dense layer or form a third layer of some intermediate density. The criteria of F approximately equal to unity for mixing has been verified experimentally. (5)

Figure 4 can be observed to form almost immediately. Below this separation streamline, the dense fluid flows under the gate. Next to the gate and above this streamline is a wedge which initially has the same density as the density current. The rate of flow through the gate is increased slowly to minimize surges which withdraw the dense fluid in the wedge. As discharge and velocity head increase, a reduction in interface elevation occurs in the transition from the reservoir causing small waves and some small amount of mixing. Over an appreciable time this mixing produces a third layer of intermediate density between the lower current and the fresh water which spreads down into the wedge. Within the wedge there is a velocity pattern as illustrated in Figure 1. The dense fluid withdrawn from the wedge is eventually replaced by the third layer having a density between that of the salt and fresh water. This process of replacing the wedge fluid with a third layer may be augmented if the discharge is increased too rapidly thereby causing a surge under the gate. The smaller the density difference between the density current and the supernatant fluid the more sensitive is the interface to disturbances causing mixing.

During the time necessary to bring the discharge to the point of incipient drawdown (an hour and one half to two hours), the general tendency is for the reservoir depth of the dense layer to increase due to intermittent withdrawal of fluid from the wedge. This intermittent withdrawal occurs as a transient condition as the discharge is increased in discrete increments and this volume withdrawn increases the entire volume of the dense layer. Thus $\frac{a}{h}$ is constantly decreasing. Therefore it is difficult to obtain experimental information on drawdown for values of $\frac{a}{h}$ approaching unity. If a high enough discharge is reached, a steady state drawdown or flow of two layers through the gate is observed. After the entire wedge is withdrawn, the fresh

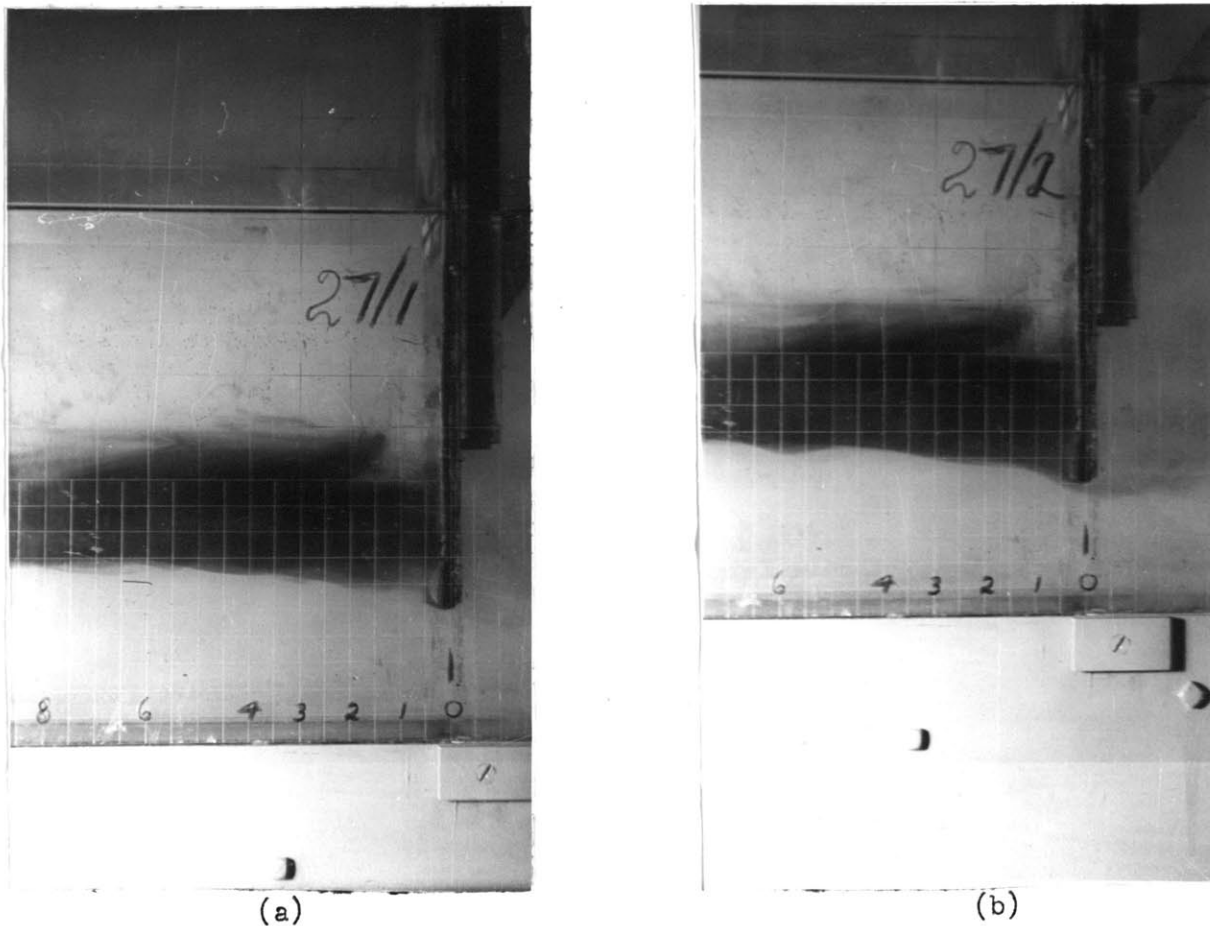
water layer is discharged through the gate in the same manner. As drawdown continues both the volume of the dense fluid and h increases more rapidly. The increase in h again reduces the $\frac{a}{h}$ parameter and ultimately the drawdown stops. In most of this investigation h_r in the reservoir was not kept constant. If the discharge is again increased drawdown again occurs but at the reduced $\frac{a}{h}$ value. This sequence is illustrated in Figure 6.

On the final experimental run, h_r was kept constant by draining salt water from the reservoir. Drawdown occurred and continued until almost all of the fresh water was withdrawn from the reservoir and flume.

V DISCUSSION OF RESULTS

The plot of separation streamlines presented in Figure 4 permits a relative comparison of shapes since the ordinate for all curves varies from zero to unity. The value of a Froude number at the gate, $F_g = \sqrt{\frac{q^2}{g'a^3}}$, the $\frac{a}{h}$ ratio, and the density difference, $\frac{\Delta\rho}{\rho}$, are given for each curve. The profiles indicate that for increasing values of F_g the curvature of the separation streamline increases. If an equation for the separation streamline could be determined, the volume of the wedge could be computed. It might then be possible to predict at what rate the discharge could be increased before the wedge would be entirely withdrawn through the gate by intermittent withdrawal.

The experimental data was analyzed with the objective of determining a correlation between the condition under which drawdown occurs and the physical characteristics of the flow. It was found that these physical characteristics could best be represented by F_g which is a dimensionless form of the discharge involving the density

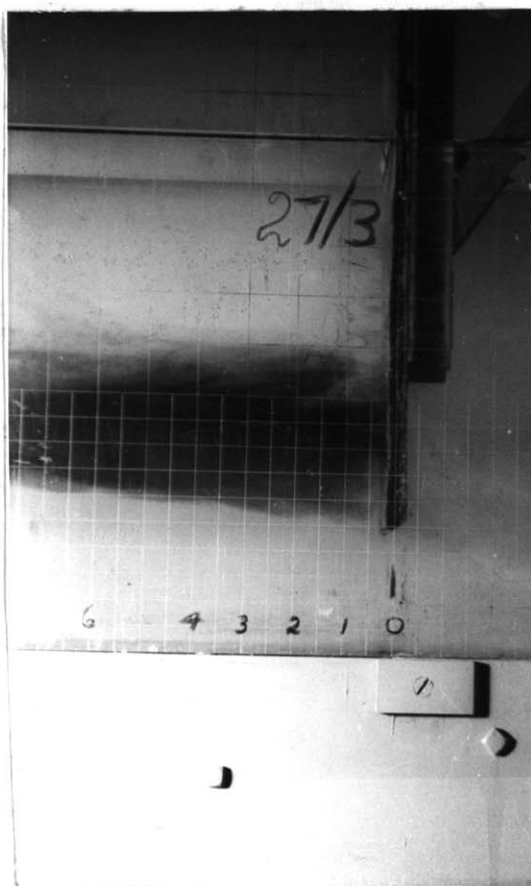


(a) $Q = 14 \text{ in}^3/\text{sec}$. Drawdown occurring but obscured by interfacial waves. $F_g \approx 1$. Specific gravity of wedge = 1.0000, Specific gravity of density current = 1.0013.

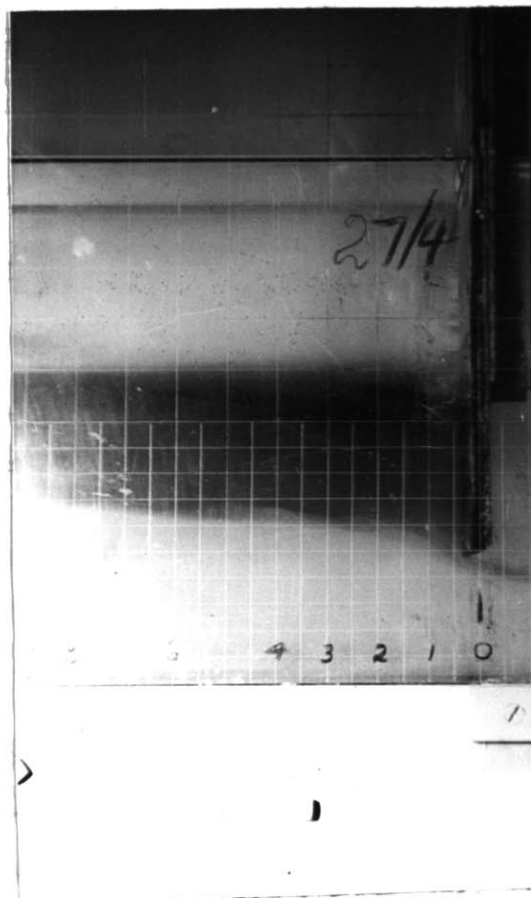
(b) Q increased to approximately $14.5 \text{ in}^3/\text{sec}$. Drawdown readily discernable.

(Identification of layers: bottom light layer is density current, middle dark layer is wedge dyed with potassium permanganate, upper light layer is fresh water.)

Figure 6: DRAWDOWN OF SUPERNATANT FLUID, RUN 11



(c)



(d)

- (c) Interfacial waves obscuring drawdown and mixing density current and wedge, reducing $\frac{\Delta\rho}{\rho}$ and $\frac{a}{h}$.
- (d) Additional increase of discharge, Q , again causes drawdown.

Figure 6 (cont.): DRAWDOWN OF SUPERNATANT FLUID, RUN 11

An example of the application of the results presented in Figure 5 is given here for the Kingston steam plant. The skimmer wall at Kingston has a gate opening of fifteen feet and an effective total width of 315 feet at mid-depth of the trapezoidal channel. No attempt was made to correct for contraction of the flow due to piers in the curtain wall. Various $\frac{a}{h}$ values were assumed and maximum allowable discharges were calculated for different values of $\frac{\Delta\rho}{\rho}$, as shown in Table 1 below.

Table 1

Maximum Allowable Discharges for Kingston Skimmer Wall

a/h	h ft	F_g	$\frac{\Delta\rho}{\rho} = 0.001$		$\frac{\Delta\rho}{\rho} = 0.002$	
			q cfs/ft	Q cfs	q cfs/ft	Q cfs
0.5	30.0	0.86	9.41	2960	13.21	4150
0.6	25.0	0.77	8.44	2660	11.85	3740
0.7*	21.42	0.65	7.12	2240	10.00	3150
0.8*	18.75	0.51	5.58	1760	7.85	2475

*Limiting conditions for drawdown are assumed from extrapolation of data in Figure 5.

The difference in experimental conditions and those at Kingston should be emphasized. First, the sharp demarcation of the density current will not exist at Kingston, instead there will be a gradual density gradient due to the thermal gradient. Second, channel roughness or transitions may produce excessive mixing at high discharges.

Drawdown was not observed during the first set of experimental runs. On most of these runs excessive mixing due to turbulence at the diffuser precluded continuing the experiments to high enough values of F_g . On those runs where critical conditions as defined by Figure 5



Figure 7: PHOTOGRAPH OF INTERFACIAL WAVES

were reached, drawdown if it occurred was obscured by the excessive mixing and turbulence caused by the diffuser and baffle.

VI CONCLUSIONS

With an essentially constant source of the density current, drawdown of the lighter fluid, i.e., essentially steady flow of two layers under the gate, will occur under certain conditions. These conditions are a function of the relative gate opening and the Froude number F_g .

VII RECOMMENDATIONS

Because of the limitations of time and the equipment available for the experimental work on which the results of this investigation are based, these results are not sufficiently extensive. Accordingly, the authors feel that further studies are necessary.

In particular it is recommended that:

A. The reservoir be further refined to enable assurance of constant head conditions by provision for removing the excess dense fluid produced by mixing, and replacing the fresh water lost to mixing.

B. That the conditions of drawdown and mixing be precisely defined to permit better evaluation of test data.

C. An extensive series of experiments be conducted under controlled conditions of density difference, relative gate opening, and discharge to obtain additional data on incipient drawdown conditions, in particular at values of $\frac{a}{h}$ approaching unity.

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SLUICE GATE DISCHARGE OF STRATIFIED FLOW

Appendix 1

Summary of Results

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

Summary of Results

Before Addition of the Reservoir

Run #	a	h	a/h	$\Delta\rho/\rho$	Q	F _g	*Mixing	*Draw-down
	in.	in.			in ³ /sec			
2a	2.0	3.0	.67	.0041	9.1	.56		
2b	2.0	3.0	.67	.0041	12.0	.75	X	
4a	2.0	4.1	.49	.0044	7.4	.45		
4b	2.0	4.3	.47	.0044	13.5	.81	X	
4c	2.0	4.5	.45	.0042	16.5	1.01	X	
4d	2.0	5.4	.37	.0039	25.5	1.67	X	
5a	2.9	4.1	.71	.0021	7.4	.37		
5b	2.9	4.3	.68	.0020	12.5	.64	X	
5c	3.8	7.0	.54	.0015	26.0	1.02	X	
7a (1)	1.62	2.5	.65	.0032	6.9	.67		
7a (2)	1.62	3.0	.54	.0028	8.8	.91	X	
7b (1)	1.75	2.5	.70	.0031	4.1	.35		
7b (2)	1.75	2.8	.63	.0031	7.9	.70		
7f	1.75	3.0	.58	.0026	11.6	1.11	X	

* X indicates condition occurred

On these runs mixing occurred primarily due to disturbances at the diffuser.

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

Summary of Results

After Addition of the Reservoir

Run #	a	h	a/h	$\Delta p/p$	Q	F_g	*Mixing	*Draw-down
	in.	in.			in ³ /sec			
9a	3.0	4.00	.75	.0052	5.2	.16		
9c	3.0	4.15	.73	.0051	15.4	.47		
10a	2.90	3.88	.75	.0040	9.8	.36		
10b	2.90	4.12	.71	.0038	11.6	.43	X	
10c	2.90	4.90	.59	.0038	20.0	.74	X	X
11a	2.50	3.63	.69	.0023	8.6	.51		
11b	2.50	4.05	.62	.0020	12.5	.80		
11c	2.50	4.33	.58	.0020	13.0	.83	X	X
12a	1.50	3.08	.49	.002	4.6	.59		
12b	1.50	3.22	.47	.0023	7.1	.91	X	X
12d	1.50	4.50	.33	.0023	26	2.8	X	X
13	2.0	7.69	.54	.0024	10.5	.86		X

* X indicates condition occurred

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

Appendix 2

Tabulation of Profile Data

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 2.0 \text{ in.}$

$Q = 7.4 \text{ in}^3/\text{sec}$

Date : 8 March 1954

$\frac{a}{h_{60}} = .488$

$h_{60} = 4.1 \text{ in.}$

Run No: 4a

$F_{\text{gate}} = .445$

$\frac{\Delta p}{\rho} = .0044$

Party : J and R

Sta.	h	z	$\frac{z}{h-a}$	$\frac{x}{h-a}$
in.	in.	in.		
0	2.0	0	0	0
1	2.3	0.3	.143	0.476
2	2.7	0.7	.333	0.952
3	2.9	0.9	.428	1.43
4	3.1	1.1	.523	1.90
5	3.3	1.3	.620	2.38
6	3.4	1.4	.666	2.86
7	3.5	1.5	.715	3.33
8	3.55	1.55	.738	3.80
9	3.6	1.6	.762	4.28
10	3.6	1.6	.762	4.76
11	3.7	1.7	.810	5.23
12	3.7	1.7	.810	5.71
13	3.8	1.8	.857	6.20
14	3.8	1.8	.857	6.66
15	3.9	1.9	.904	7.15
16	3.9	1.9	.904	7.62
17	3.95	1.95	.928	8.10
18	4.0	2.0	.952	8.57
19	4.0	2.0	.952	9.04
20	4.0	2.0	.952	9.52

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 2.0 \text{ in.}$

$Q = 13.5 \text{ in}^3/\text{sec}$

Date : 8 March 1954

$\frac{a}{h_{60}} = .465$

$h_{60} = 4.3 \text{ in.}$

Run No: 4b

$F_{\text{gate}} = .810$

$\frac{\Delta \rho}{\rho} = .0044$

Party : J and R

Sta.	h	z	$\frac{z}{h - a}$	$\frac{x}{h - a}$
in.	in.	in.		
0	2.0	0	0	0
1	2.40	0.4	.174	.435
2	2.75	0.75	.326	.870
3	3.1	1.1	.478	1.30
4	3.3	1.3	.565	1.74
5	3.4	1.4	.609	2.17
6	3.50	1.5	.652	2.61
7	3.51	1.51	.656	3.04
8	3.65	1.65	.718	3.48
9	3.7	1.7	.740	3.92
10	3.7	1.7	.740	4.35
11	3.8	1.8	.783	4.78
12	3.85	1.85	.805	5.22
13	4.0	2.0	.870	5.65
14	4.0	2.0	.870	6.09
15	4.1	2.1	.913	6.52
16	4.1	2.1	.913	6.95
17	4.15	2.15	.935	7.39
18	4.15	2.15	.935	7.83
19	4.2	2.2	.957	8.26
20	4.2	2.2	.95	8.70

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 1.62$ in. $Q = 6.9$ in³/sec Date : 15 March 1954
 $\frac{a}{h} = .648$ $h = 2.5$ in. Run No: 7a (1)
 $F_g = .666$ $\frac{\Delta\rho}{\rho} = .0032$ Party : J and R

Sta.	h	z	$\frac{z}{h - a}$	$\frac{x}{h - a}$
in.	in.	in.		
0	1.62	0	0	0
1	1.70	.08	.0909	1.14
2	1.75	.13	.148	2.28
3	1.80	.18	.204	3.42
5	1.94	.32	.364	5.67
7	1.98	.36	.409	7.95
9	2.00	.38	.431	10.21
11	2.10	.48	.545	12.50
13	2.15	.53	.602	14.79
15	2.18	.56	.636	17.08
17	2.20	.58	.660	19.41
19	2.20	.58	.660	21.60
21	2.25	.63	.716	23.90

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 1.62 \text{ in.}$ $Q = 8.8 \text{ in}^3/\text{sec}$ Date : 15 March 1954
 $\frac{a}{h} = .541$ $h = 3.00 \text{ in.}$ Run No: 7a (2)
 $F_g = .909$ $\frac{\Delta\rho}{\rho} = .0028$ Party : J and R

Sta.	h	z	$\frac{z}{h-a}$	$\frac{x}{h-a}$
in.	in.	in.		
0	1.62	0	0	0
1	1.80	.18	.130	.725
2	2.00	.38	.276	1.45
3	2.10	.48	.348	2.18
5	2.20	.58	.420	3.63
7	2.25	.63	.456	5.08
9	2.30	.68	.493	6.53
11	2.40	.78	.565	7.97
13	2.45	.83	.601	9.42
15	2.50	.88	.638	10.88
17	2.55	.93	.674	12.32
19	2.60	.98	.710	13.79
21	2.65	1.03	.746	15.21

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 1.75$

$Q = 4.1 \text{ in}^3/\text{sec}$

Date : 15 March 1954

$\frac{a}{h} = .700$

$h = 2.5 \text{ in.}$

Run No: 7b (1)

$F_g = .354$

$\frac{\Delta\rho}{\rho} = .0031$

Party : J and R

Sta.	h	z	$\frac{z}{h-a}$	$\frac{x}{h-a}$
in.	in.	in.		
0	1.75	0	0	0
1	1.80	.05	.067	1.33
2	1.87	.12	.160	2.67
3	1.87	.12	.160	4.00
5	1.92	.17	.226	6.68
7	1.99	.24	.320	9.35
9	2.00	.25	.333	12.00
11	2.00	.25	.333	14.70
13	2.10	.35	.468	17.35
15	2.12	.37	.494	20.00
17	2.16	.41	.547	22.70
19	2.18	.43	.574	25.40
21	2.20	.45	.600	28.00

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 1.75$ in. $Q = 7.95$ in³/sec Date : 15 March 1954
 $\frac{a}{h} = .625$ $h = 2.8$ in. Run No: 7b (2)
 $F_g = .685$ $\frac{\Delta\rho}{\rho} = .0028$ Party : J and R

Sta.	h	z	$\frac{z}{h - a}$	$\frac{x}{h - a}$
in.	in.	in.		
0	1.75	0	0	0
1	1.93	.18	.172	.955
2	2.05	.30	.286	1.91
3	2.16	.41	.391	2.86
5	2.19	.44	.420	4.76
7	2.25	.50	.476	6.66
9	2.30	.55	.523	8.58
11	2.37	.62	.591	10.50
13	2.43	.68	.649	12.40
15	2.50	.75	.715	14.30
17	2.56	.81	.773	16.20
19	2.58	.83	.791	18.10
21	2.58	.83	.791	20.00

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 3.0 \text{ in.}$ $Q = 11.2 \text{ in}^3/\text{sec}$ Date : 23 April 1954
 $\frac{a}{h} = .813$ $h = 3.7 \text{ in.}$ Run No: 9b
 $F_g = .353$ $\frac{\Delta\rho}{\rho} = .0048$ Party : J and R

Sta.	h	z	$\frac{z}{h-a}$	$\frac{x}{h-a}$
in.	in.	in.		
0	3.00	0	0	0
1	3.02	.02	.0286	1.43
2	3.05	.05	.0714	2.86
3	3.08	.08	.114	4.29
4	3.10	.10	.143	5.72
8	3.15	.15	.214	11.14
12	3.22	.22	.314	17.16
16	3.28	.28	.400	22.88
20	3.32	.32	.457	28.60
24	3.40	.40	.572	34.32
28	3.40	.40	.572	40.04
32	3.43	.43	.615	45.76

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 3.0 \text{ in.}$ $Q = 15.4 \text{ in}^3/\text{sec}$ Date : 23 April 1954
 $\frac{a}{h} = .725$ $h = 4.15 \text{ in.}$ Run No: 9c
 $F_g = .470$ $\frac{\Delta\rho}{\rho} = .0051$ Party : J and R

Sta..	h	z	$\frac{z}{h - a}$	$\frac{x}{h - a}$
in.	in.	in.		
0	3.00	0	0	0
1	3.05	.05	.0435	.870
2	3.10	.10	.0870	1.74
3	3.15	.15	.131	2.61
4	3.20	.20	.174	3.48
8	3.40	.40	.348	6.96
12	3.45	.45	.392	10.44
16	3.55	.55	.478	13.92
20	3.60	.60	.521	17.40
24	3.70	.70	.610	20.88
28	3.80	.80	.695	24.36
32	3.85	.85	.740	27.84

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 2.9$ in. $Q = 9.8$ in³/sec Date : 26 April 1954
 $\frac{a}{h} = .748$ $h = 3.88$ in. Run No: 10a
 $F_g = .350$ $\frac{\Delta\rho}{\rho} = .0040$ Party: J and R

Sta.	h	z	$\frac{z}{h-a}$	$\frac{x}{h-a}$
in.	in.	in.		
0	2.90	0	0	0
1	3.00	.1	.102	1.02
2	3.04	.14	.143	2.04
3	3.08	.18	.184	3.06
4	3.15	.25	.255	4.08
8	3.20	.30	.307	8.16
12	3.24	.34	.347	12.24
16	3.30	.40	.409	16.32
20	3.40	.50	.510	20.40
24	3.50	.60	.614	24.48
28	3.50	.60	.614	28.56
32	3.56	.66	.675	32.64

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 2.9 \text{ in.}$ $Q = 11.6 \text{ in}^3/\text{sec}$ Date : 26 April 1954
 $\frac{a}{h} = .706$ $h = 4.12$ Run No: 10b
 $F_g = .431$ $\frac{\Delta\rho}{\rho} = .0038$ Party : J and R

Sta.	h	z	$\frac{z}{h-a}$	$\frac{x}{h-a}$
in.	in.	in.		
0	2.90	0	0	0
1	3.02	.12	.0984	.820
2	3.10	.20	.164	1.640
3	3.12	.22	.181	2.460
4	3.16	.26	.213	3.280
8	3.22	.32	.262	6.560
12	3.39	.49	.402	9.840
16	3.45	.55	.451	13.120
20	3.51	.61	.500	16.400
24	3.62	.72	.590	19.680
28	3.71	.81	.665	22.96
32	3.75	.85	.697	26.24

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 1.5$ in. $Q = 4.6$ in³/sec Date : 30 April 1954
 $\frac{a}{h} = .486$ $h = 3.08$ in. Run No: 12a
 $F_g = .730$ $\frac{\Delta\rho}{\rho} = .0015$ Party : J and R

Sta.	h	z	$\frac{z}{h-a}$	$\frac{x}{h-a}$
in.	in.	in.		
0	1.5	0	0	0
1	1.64	.14	.0985	.633
2	1.76	.26	.165	1.266
3	1.81	.31	.196	1.899
4	1.88	.38	.241	2.532
8	2.00	.50	.317	5.064
12	2.07	.57	.361	7.596
16	2.19	.69	.437	10.128
20	2.24	.74	.468	12.660
24	2.31	.81	.513	15.192
28	2.36	.86	.544	17.724
32	2.44	.94	.595	20.256

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 1.5$ in. $Q = 7.1$ in³/sec Date : 30 April 1954
 $\frac{a}{h} = .466$ $h = 3.22$ in. Run No: 12b
 $F_g = .910$ $\frac{\Delta\rho}{\rho} = .0023$ Party : J and R

Sta..	h	z	$\frac{z}{h - a}$	$\frac{x}{h - a}$
in.	in.	in.		
0	1.50	0	0	0
1	1.75	.25	.145	.582
2	1.95	.45	.262	1.164
3	2.09	.59	.344	1.746
4	2.18	.68	.396	2.328
8	2.30	.80	.465	4.656
12	2.50	1.00	.582	6.984
16	2.61	1.11	.646	9.312
20	2.75	1.25	.726	11.640
24	2.82	1.32	.768	13.968
28	2.86	1.36	.791	16.296
32	2.90	1.40	.815	18.624

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

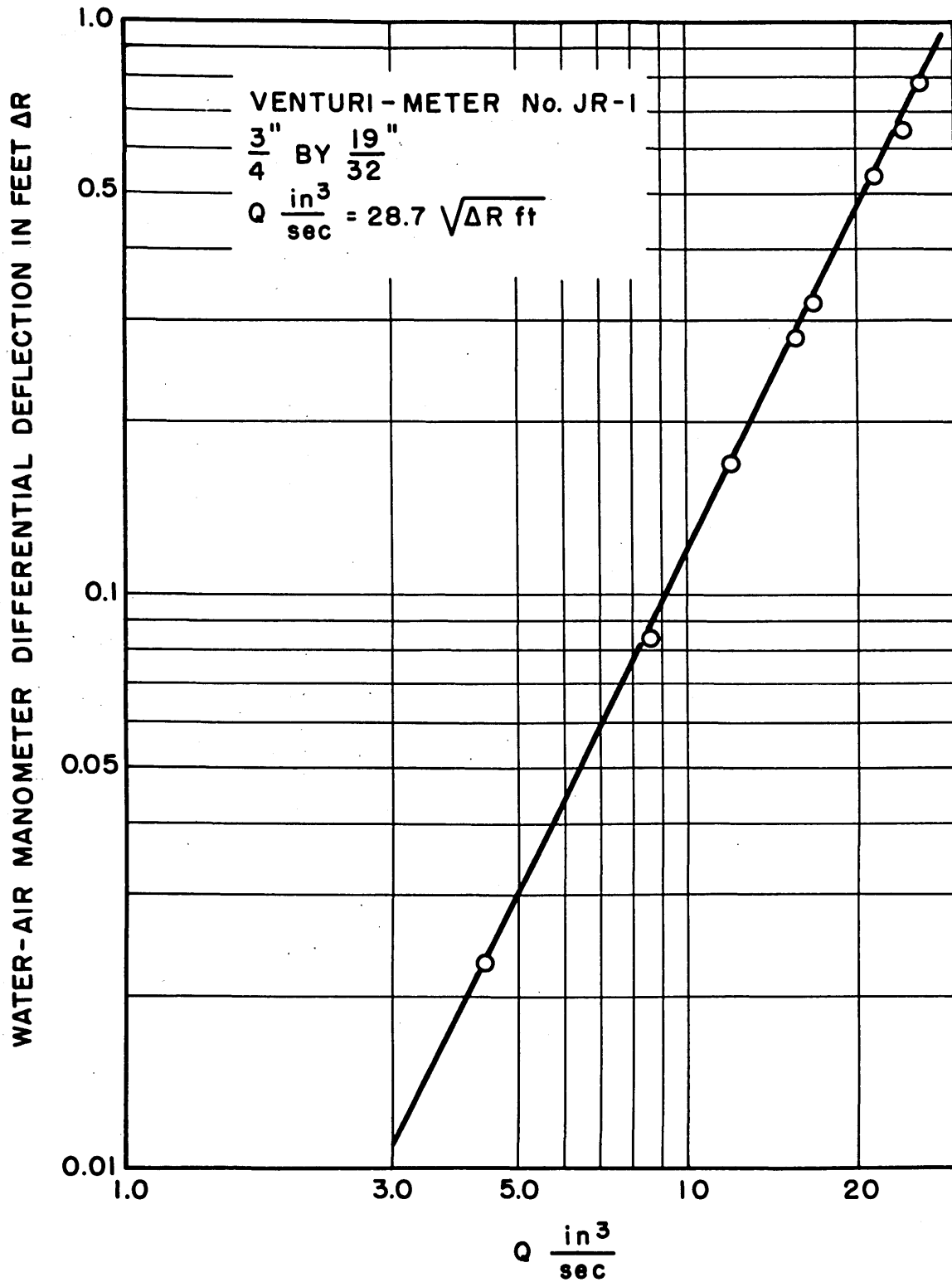
$a = 1.5$ in. $Q = 26$ in³/sec Date : 30 April 1954
 $\frac{a}{h} = .333$ $h = 4.5$ in. Run No: 12d
 $F_g = 2.8$ $\frac{\Delta p}{\rho} = .0023$ Party : J and R

Sta.	h	z	$\frac{z}{h - a}$	$\frac{x}{h - a}$
in.	in.	in.		
0	1.30	-.2	-.067	0
1	2.00	+.5	+.167	.333
2	2.41	-.91	-.303	.667
3	2.75	1.25	.417	1.000
4	3.01	1.51	.503	1.333
8	3.40	1.90	.633	2.67
12	3.50	2.00	.667	4.00
16	3.91	2.41	.803	5.33
20	4.10	2.60	.867	6.67
24	4.20	2.70	.900	8.00
28	4.30	2.80	.933	9.33
32	4.30	2.80	.933	10.67

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

$a = 2.0$ in. $Q = 10.5$ in³/sec Date : 13 May 1954
 $\frac{a}{h} = .545$ $h = 3.69$ in. Run No: 13
 $F_g = .790$ $\frac{\Delta \rho}{\rho} = .0024$ Party : J and R

Sta.	h	z	$\frac{z}{h - a}$	$\frac{x}{h - a}$
in.	in.	in.		
0	1.95	-.05	-.0296	0
1	2.15	+.15	+.089	.592
2	2.30	-.30	-.178	1.18
3	2.40	.40	.236	1.77
4	2.50	.50	.296	2.36
8	2.65	.65	.384	4.73
12	2.80	.80	.473	7.10
16	2.95	.95	.562	9.46
20	3.08	1.08	.640	11.82
24	3.12	1.12	.663	14.20
28	3.21	1.21	.716	16.55
32	3.29	1.29	.763	18.90



SLUICE GATE DISCHARGE OF STRATIFIED FLOW
 APPENDIX 3 CALIBRATION CHART

SLUICE GATE DISCHARGE OF STRATIFIED FLOW

Appendix 4

Tabulation of Data for Venturi-Meter Calibration

Calibration Data
Venturi Meter JR-1
3/4" x 19/32"

Run #	wt. of water	γ	t	Q	Q	q	ΔR
	lbs.	lbs/ft ³	sec.	in ³ /sec	gpm	in ² /sec	ft.
1	51.9	62.30	331.4	4.34	1.128	.964	.023
2	109.0	62.37	360.2	8.46	2.20	1.88	.084
3	154.7	62.37	361.2	11.88	3.09	2.62	.170
4	208.5	62.37	377.8	15.30	3.98	3.40	.282
5	385.0	62.40	646.2	16.5	4.29	3.66	.322
6	364.4	62.40	613.0	16.5	4.29	3.66	.323
7	382.9	62.40	500.0	21.3	5.54	4.73	.545
8	283.4	62.40	330.0	23.8	6.19	5.29	.655
9	351.8	62.40	380	25.6	6.66	5.69	.790

$$Q = c\sqrt{\Delta R}$$

$$Q = 28.7\sqrt{\Delta R}$$

ΔR = Manometer differential in feet

Q = Discharge in cubic inches per second