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Memorandum

Memorandum

TO : Water Systems Automation Team

Denver, Colorado
DATE: May 4, 1973

THROUGH: Chief, Hydraulics Branch WEW 5/11/73
Chief, Division of General Research HGC 5/14/73

FROM : R. A. Dodge

SUBJECT : Summary of Laboratory Tests of an Automated Constant Head Orifice Turnout

<u>Introduction</u>

<u>Purpose</u>. - The purpose of the laboratory studies was to demonstrate the feasibility of automating a constant head orifice turnout (CHOTO). During the investigations, the scope was expanded to obtain basic hydraulic data on the component parts of the turnout. These data can be used for developing and checking mathematical prediction models for automating constant head orifice turnouts.

<u>Background</u>. - Water delivery through a constant head orifice turnout (Figure 1) depends on the operator setting the opening (b_1) of a rectangular orifice (measuring) gate and then regulating a 0.2 of a foot-differential head ($H_1 - H_2$) by means of a downstream circular control gate. Continual attention by the operator is required to maintain a constant discharge if the supply canal water surface varies appreciably causing the differential to deviate from the set 0.2 of a foot. Possible causes for variation of head in a supply canal are changes in demand along the canal and wind tilt of the water surface. Variation of downstream submergence head on the control gate can also cause the differential to deviate from a set value of 0.2 of a foot.

L. F. Weide conceived a cam and switch mechanism (Figures 2 and 3(b)) intended to provide automatic motorized control of a CHOTO. A supply canal fluctuation rate of 0.00056 foot per second and a tentative gate speed of 0.000267 of a gate diameter per second were suggested as control parameters. These rates were expected to be compatible with the 18-inch floatwell and 1/2-inch piping usually used in the field. The Hydraulic Structures Branch requested that the Hydraulics Branch perform tests as part of the OCCS Program to demonstrate the capability of the concept and mechanism for practical application.

<u>Preliminary Investigation</u>. - Early in the investigation, standard hydraulic computations were found inadequate in predicting the response of floatwells to external water surface changes. Also, no satisfactory information on the hydraulic characteristics of the circular control gate was available.

Although the orifice measuring gates are calibrated for differential head, the maximum opening is restricted to 75 percent of the full opening, and the approach head should not be less than four times the gate openings for a 2-cfs constant head orifice turnout. Because of the lack of information outside of this range, it was realized that no fully reliable design computations or predictions could be made for automating the system.

Test Program. - The original program was expanded to include the determination of the hydraulic and mechanical characteristics of component parts of the CHOTO. The discharge characteristics of the downstream circular control gate were determined for both free and submerged flow conditions. The orifice gate was calibrated in terms of the approach head and downstream submergence. Response time of the floatwells to nearly instantaneous (step) and continuous constant rate (ramp) changes of water surface elevations in the CHOTO were measured to help develop and verify mathematical models. Documentary runs of the combined system were recorded, with and without automatic control, to help in verifying design methods that may be developed.

Summary of Results. -

1. Automating a CHOTO such as was done during this study was fully or partially successful for five out of nine operational runs summarized in Table 1. Therefore, the concept is considered feasible.

2. Time and funding to study the full range of system possibilities were not sufficient to determine control gate speeds with full confidence for design.

3. Because of Conclusions 1 and 2, it is recommended that a mathematical model be developed for the automatic CHOTO system. A verified mathematical model would be much more versatile than a few laboratory runs and data.

4. Because of Conclusion 3, tests were directed towards obtaining data to characterize component parts of the automatic CHOTO so that an adequate mathematical model can be developed and verified for the combined system.

5. Documentary runs of the automated CHOTO were recorded on an oscillograph for possible use in developing and verifying mathematical models. These runs are summarized in Table 1.

6. The characteristics of the downstream control gate are summarized in terms of the dimensionless parameters of Equation (1). Free flow characteristics of the gate are summarized by Equation (2). Submerged flow could only be summarized by dimensionless plots in Figures 4(a) through 4(c).

7. Coefficients of discharges for the orifice gate for 0.2 foot head differential were very nearly equal to those of previous Bureau studies. However, for automation characterization, the orifice gate calibration results were analyzed in terms of Equation (3) and the dimensionless approach and submergence head of Equation (4) plotted in Figure 5.

8. Water surface elevation changes in the floatwells were recorded as they responded to step and ramp changes of water surface elevation in the CHOTO. The mathematical models were made to fit measured data for 1/2-inch-inside-diameter piping connecting the turnout and floatwell. The same models were partially successful in duplicating the response of 1-inch connecting piping. Comparison of measured data with computed data (Figures 6 to 8) suggests that further research and analysis are necessary to account for form losses and boundary layer growth at the pipe entrance. Some research and analysis may also be needed in regard to losses caused by continual alternation of flow direction in the connecting piping.

9. A change of plus or minus 0.012-foot in the differential head between floatwells was necessary for the first microswitch actuation. For subsequent operations, a plus or minus 0.006-foot change was needed with the same microswitch.

Applications. - The results and data can be used to develop and verify mathematical models of automatic CHOTO's. A mathematical model is a virtual necessity for an automated system if the system is to be designed economically and with confidence of reliable operation. The more accurate and the more detailed a mathematical model is, the narrower the range of field adjustment that needs to be designed into the system.

The analysis of the downstream control gate and the measuring orifice gate are presented in dimensionless form in Figures 4 and 5 for application to larger size CHOTO's. Recorded documentary runs that are abstracted in Table 1 should be sufficient to verify a mathematical model.

Laboratory Installation

General. - A 2-cfs constant-head orifice turnout was installed between two boxes. The larger box (Figure 3(a)) representing a supply canal, was about 8 feet by 4 feet, and had a 4-foot-long flap to vary the canal flow elevation. The smaller box representing the farm delivery was about 6 feet by 4 feet by 3 feet and had a 4-foot-long flap to vary the submergence on the control gate. A 1-foot by 1-foot slide gate was installed below the flap to lower the water surface and to provide free flow from the downstream control gate of the turnout.

Laboratory Water Supply. - Water was pumped from the laboratory supply through a 12-inch gate valve to a 20-foot-long 12-inch-diameter approach pipe and through diffuser cones and a 4-inch rock baffle for stilling action.

Measuring Gate. - The 18- by 12-inch orifice gate was simulated with 16-gage sheet metal stiffened by a 1-3/4-by 1-3/4-by 16-gage angle that projected upstream at 2 inches above the lip of the gate.

Control Gate. - An El Dorado 1-foot circular gate was used for the downstream control gate. To determine the torque required to power the gate, the leaf was loaded horizontally with a 50-pound weight to represent water pressure. The torque was measured at various gate openings by a spring balance. The maximum torque required was 10 inch-pounds.

Electrical Power, Floatwell and Switching. - The gate motor was powered through an interlock motor controller. The controller was designed to handle 220-volt powered shop equipment, but for automating the constant head orifice turnout it was wired as 110-volt reversing system. Normally opened "UP" and "DOWN" switches were provided for manual override. For most tests, 18-inch-diameter wells Figure 3(b) were connected by 1/2-inch tubing at the staff gage locations of the constant head orifice turnout. Later, 1-inch well piping was installed. The water surfaces in the wells were followed by 12-inch floats of the Stevens type. Water surface changes were transmitted to pulleys by means of beaded cables. The switching wheel and differential sensing cam shown in Figures 2 and 3(b) were connected to separate float pulley shafts. The system for connecting power to the microswitches on the wheel was made by R. H. Kuemmich. Connections to the switches were made with opposing spirals of thin brass strips insulated from each other by 1/16-inch-thick 6-inch-diameter insulating disks. The opposing spirals provided compensating spring action to help keep the switching wheel in balance when it rotated as the supply canal water surface fluctuated. Microswitches on the wheel were normally opened when in the position on a differential sensing cam as shown in Figure 2. These microswitches were in series with normally closed upper and lower gate limit switches that were set to turn off the gate power at 90 percent and 2 percent gate openings.

Laboratory Measurements

Discharge Measurements. - Calibrated venturi meters that are permanent fixtures of the hydraulic laboratory were used to measure actual rate of flow through the gates during their characterization tests.

Pressure and Gate Travel Measurements. - Head measurements were made by means of vernier hook and point gages. The gages were mounted upstream and downstream of the orifice gate, control gate, and in each of the floatwells. The instrumentation for the documentary runs was done by R. H. Kuemmich. Pressure transducers were connected to piezometers in the same cross section of the turnout as staff, hook, and point gages. Differential pressure transducers were connected between the floatwells and between each side of the measuring gate. Early in the tests to measure gate travel, a pressure transducer was connected to a flexible tube containing a constant volume of water and attached to the control gate stem. As the stem was raised the end of the tube followed and increased the water pressure in the tube. The tube volume increased causing a lowering of the water surface not representing the actual rise of the stem and gate leaf. Thus the gate opening was not accurately measured because of the expansion and contraction of the tube. The gate opening monitoring was later improved by means of a flexible plastic drive chain, a gear, and a sensitive potentiometer. Continuous time recording of all these pressures, differentials, and the gate opening was made (Figure 3(a)) with an eight-channel recorder.

Result of Investigations

Control Gate Characteristics. - The downstream control gate can discharge freely or be submerged downstream by the farm delivery. The gate does not operate like an orifice. There can be weir-like flow over the top and flow around the loose sides of the leaf. The main orifice flow area is crescent shaped. Combined flow conditions across this gate need to be characterized because discharge cannot be assigned to a firmly defined area. Dimensional analysis was used to determine parameters that define the characteristics of this gate. Assuming that:

$$Q = \phi\ (H_3,\ H_4,\ b_2,\ D,\ \mu,\ \rho,\ g)$$

Where the variables are as noted in Figure 1.

Using Q, μ, and b_2 as repeating variables, one possible resulting compact equation is:

$$\left(\frac{g\ b_2^5}{Q^2}\right)=\phi\left(\frac{\rho Q}{\mu b_2},\ \frac{D}{b_2},\ \frac{H_3}{b_2},\ \frac{H_4}{b_2}\right)$$

The term $\frac{g\ b_2^5}{Q^2}$ is an inverse form of Froude number. If frictional effects are considered negligible, then the term $\frac{\rho Q}{\mu b_2}$ can be neglected and the following incomplete compact equation can be written and used for analysis of the control gate:

$$Q_o = \left(Q \big/ \sqrt{g\, b_2^5}\right) = \phi\left(H_3 \big/ b_2,\ H_4 \big/ b_2,\ b_2 \big/ D\right) \quad . \ . \ . \ . \ . \ (1)$$

This function is shown plotted in Figure 4(a) to 4(c) in sets for

$$\left(Q \big/ \sqrt{g\, b_2^5},\ H_3 \big/ b_2,\ H_4 \big/ b_2\right)$$

at several constant values of $\left(b_2 \big/ D\right)$. The dimensionless equation for free flow, when $\left(H_4 \big/ b_2\right)$ is zero in Equation (1), was determined to be

$$Q \big/ \sqrt{g\, b_2^5} = 0.668\left(H_3 \big/ b_2\right)^{0.92}\left(b_2 \big/ D\right)^{-0.72} \quad . \ . \ . \ (2)$$

This equation can be applied for free flow. However, dimensionless plots, Figure 4, or tables of values from the plot are required to account for downstream submergence.

<u>Measuring Gate Characteristics</u>. - For convenience of using gate opening versus discharge tables, the measuring gate coefficients for constant head orifice turnouts are given in the differential head form:

$$Q = C_d\, A \sqrt{2_g\ (H_1 - H_2)}$$

Values of (C_d) for this form were determined to see how closely laboratory gate simulated a field structure. These data agreed very well with previous calibrations done by the Bureau. Application of (C_d) and tables for CHOTO in the Bureau of Reclamation's Water Measurement Manual are qualitatively restricted to ratios of approach head to gate opening (H_1/b_1) being greater than some minimum value. A ratio of 4.0 is recommended for the 2-cfs-size turnout used in the laboratory. The differential head form of (C_d) does not sufficiently characterize the measuring gate for automation because it does not fully account for velocity of approach or for the location of the differential head with respect to depth of flow in the turnout.

The more direct and comprehensive approach suggested by Rouse 1/ that accounts for both the velocity of approach and submergence was used to characterize the measuring gate. The values of (C) were determined for the equation:

$$Q = C \ A\sqrt{2g \ H_1} \quad . \ . \ . \ . \ . \ (3)$$

Where (C) is related in dimensionless functional form as:

$$C = \phi\left(\frac{H_1}{b_1}, \frac{H_2}{b_1}\right) \quad . \ . \ . \ (4)$$

The plot of this relationship is shown in Figure 5 and agrees quite closely to the Rouse curves. However, in our case we cannot have free flow because the control gate orifice restricts the flow.

Switching Characteristics. - The switching lag resulting from mechanical play of floats, pulleys, cam, and microswitches was determined, Figure 2. A plus or minus (0.010 to 0.013-foot) change of floatwell differential head was required to make the first contact with the microswitch lever rollers coming from the notch of the cam. Subsequent switching occurred at plus or minus 0.006-foot changes of differential provided there was no reversing of the acting switches. It was noted that alternate actuation of the microswitches at intervals equal to or less than 1 second would cause the gate to travel continuously in the direction of the first switch activated. The initial switching could be easily made as sensitive as subsequent switching by setting the switch rollers on the ramps of the cam. However, this was not done since data of refined switching was not considered necessary for verifying a mathematical model.

Water Surface Change and Floatwell Response. - H. T. Falvey did analyses and formulated mathematical models to determine the lag between the water surface in a floatwell and the water surface in the CHOTO with water exchange through connecting piping. One model was designed to simulate the responding water surface in the well to a ramp change of water surface at the gate. Another model was designed to simulate the response of well water surface to a step change of the water surface in the CHOTO. Both models apply momentum, continuity, and pipe friction loss equations. Entrance and exit losses were originally accounted for by taking 1-1/2 times the connecting pipe velocity head. The models considered both

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1/ Rouse, H., Editor, "Engineering Hydraulics", Wiley, 1950, page 537.

turbulent and laminar flow using the Blasius smooth pipe formula for the Darcy-Weisbach resistant coefficient:

$$f = \frac{0.316}{N_r^{1/4}}$$

for the turbulent case and

$$f = {}^{64}\!/_{N_r} \quad . \; . \; . \; . \; . \; . \; . \quad (5)$$

for the laminar case.

However, the usual minimum Reynolds number (N_R) of 2,100 for turbulence was not used and the Blasius equation was used through the transition range to a Reynolds number of 1,200.

For a continuous ramp of sufficient duration, the difference of water surface elevation between the well and the CHOTO eventually reaches a constant value. For an instantaneous step, the difference of the water elevation between the floatwell and the CHOTO returns towards zero exponentially. Measured data for 1/2-inch-diameter floatwell connecting pipes were obtained to compare with computed results using the hydraulic analysis described previously. For a step of 0.22-foot the computed time to return back to 0.01 of a foot from zero difference of water surface elevation was 5-1/2 minutes compared to a measured return time of 6-1/2 minutes.

It was assumed by H. T. Falvey that the major reason for the lack of comparison between the measured data and the computed results was the lack of knowledge of form losses for laminar flow cases. The total losses are a function of Reynolds number, or:

$$h_e = \left(\underset{\text{Entrance}}{K_{form}} + \underset{\text{Exit}}{1.0} + \underset{\text{Friction}}{f\,\frac{L}{D}} \right) \frac{V^2}{2g}$$

for laminar flow

$$f = {}^{64}\!/_{N_r}.$$

Assuming the laminar form losses behave similar to Equation (5), then:

$$K_{form} = {}^{K_1}\!/_{N_r}.$$

Measured data were used to solve for (K_1) which varied with the Reynolds number. At the critical value of the Reynolds number of 2,100 for turbulence, (K_1) was found to be about 20,000. The mathematical models were modified so that when the Reynolds number (N_R) was greater than 2,100 the head form loss term was set equal to:

$$\left\{ 1.5 - 2\left[\frac{d}{D}\right]^2 x \left[1 - \left(\frac{d}{D}\right)^2\right]\right\}\frac{V^2}{2g}$$

If (N_R) is equal to or less than 2,100 then the loss term was set as an approximation equal to:

$$\left\{ 1 - 2\left[\frac{d}{D}\right]^2 x \left[1 - \left(\frac{d}{D}\right)^2\right] + 20{,}000/N_r\right\} \frac{V^2}{2g}$$

This modification resulted in a computed maximum difference of water surface elevation between well and CHOTO that was 86 percent of the measured value. Using a (K_1) of 25,000 resulted in very close agreement (Figure 6) for the 1/2-inch connecting pipe. The diamond-shaped points of the lowest curve are computed and the solid line was measured.

J. C. Schuster suggested that the development of the boundary layer near the entrance could contribute up to 20 percent of the excess needed to make the calculation match the measured data. Not accounting for the boundary development partially explains the need to use a (K_1) of 25,000 with a correspondingly higher value of Reynolds number of 3,500 relative to 2,100 that is used for turbulence criteria.

Constant ramp rates are difficult to produce and generally do not occur. It was discovered that the water surface changes in wells are quite sensitive to small variation of rate of water surface change in the CHOTO. To compare computed water surface differences between the well and CHOTO with measured values, it is necessary to break a measured ramp into small time increments such as the upper solid line ramp curve shown in Figure 6. Separate water surface differences with respect to time are computed for ramp rates equal to incremental ramp rates. A final curve such as the lowest curve through diamond symbols is composited by matching end points of sections out of incremental curves where they have common velocity in the connecting pipe. The lack of agreement between the computed point compared with the lower dashed curve in Figure 6 is mostly due to the long time between point gage readings of the upper dashed curve.

When the (K_1) value of 25,000 was used in the step model, the computed results for 1/2-inch pipe were improved but the computed water surface in the well is slightly below the curve representing the measured surface (Figure 8), then crosses and ends up slightly above the measured curve. However, both the computed and measured curves come back to 0.01 foot at about 6-1/2 minutes.

The computations indicated that the response for 1/2-inch piping and 18-inch wells is quite insensitive to pipe length in the range of 1 to 6 feet. This is probably because of the high form losses relative to friction losses.

Measured well responses were later obtained for 1-inch connecting piping. The computed results were only partially successful in simulating measured data. The computed difference between the well water surface and the water surface in the CHOTO for a ramp change of about 0.0024 foot per second was 72 percent of the measured value at 7 minutes (Figure 7). With the 1-inch well piping and for a step of 0.17 foot of water, the well water surface returned to within 0.01 foot of that in the CHOTO in 1-1/2 minutes (Figure 8). The computed time at 0.01-foot offset was 1 minute.

These results suggest that boundary layer growth should be included in future programs and that (K_1) should be more thoroughly studied and probably be allowed to vary with the Reynolds number and pipe sizes in computations.

Documentary Runs. - Runs were recorded and are to be retained in the Hydraulics Branch for use in verifying and developing a possible mathematical model of automated CHOTO's. Although tests were made with various combinations of gate speeds, ramp rates, discharge settings, and connecting well pipe sizes, no gate speed could be recommended with full confidence. Runs made without the automation turned on showed that errors of 0.10 to 0.30 of a foot in orifice gate head differential could occur for a 0.40 foot total ramp change of the supply canal head. Significant documentary runs are summarized in Table 1. These documentary runs include cases where the gate oscillates frequently in narrow bands, critically damped cases, an unstable case where the upper limit switch was actuated, and resetting the differential from an initial 0.1-foot differential.

R. A. Dodge

Blind to: 430 (Calhoun)
243 (Hogg)
225 (Weide)
253 (Johnson, J. L.)
1532 (Dodge) (2)
1530

Table 1

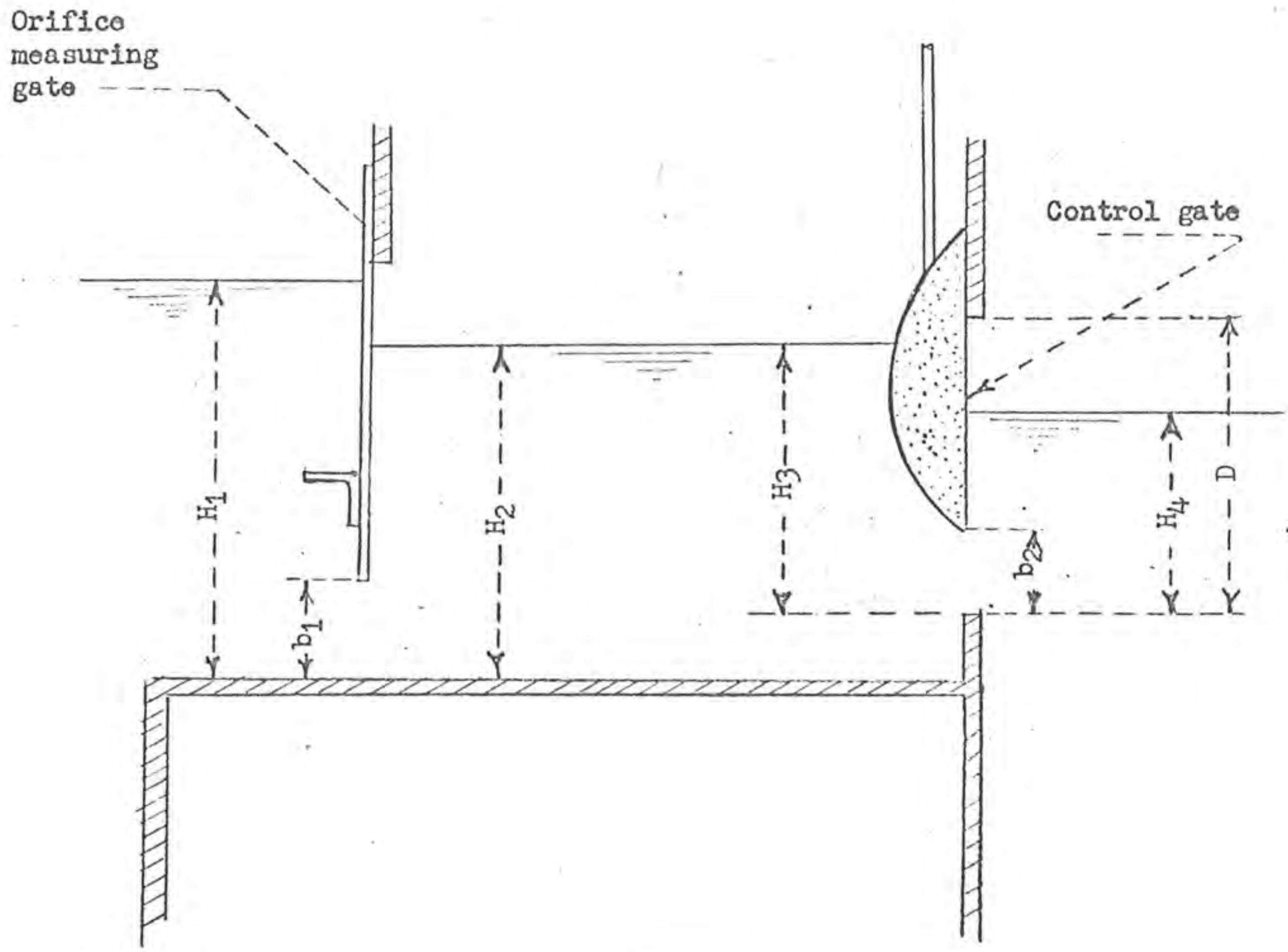
SUMMARY OF DOCUMENTARY RUNS
Automatic CHOTO

Run No.	Measuring gate opening ft	Approach head initial and final ft	Submergence on control gate ft	Control gate speed ft/sec x 10^{-4}	Ramp ft/sec x 10^{-4} or step ft	Control gate opening %	Offset from differential head ft	Offset of time min	Comments
1	0.27	1.52	1.05	3.3	6.2	24	+0.015	2.2	Ramp
		–					-0.055	8.5	
						13			Submerge lost Ramp continuing
2	0.27	1.55	1.10	3.3	6.7	24	-0.060	0.7	Ramp
							0.000		
		1.87				18 - 13	±0.02		Oscillating
3	0.138	1.80	1.56	1.2	6.8	44	+0.129	10.5	Ramp
		2.03				22	-0.006	36.5	Overdamped
4	0.138	2.04	1.56	1.7	-0.254	22	-0.095	3.0	Step
							+0.060	14.7	
		1.79				49	+0.005	27.5	
5	0.138	1.92	1.22	1.9	5.4	17	-0.051	5.7	Ramp
		1.53				34	-0.01	21.0	

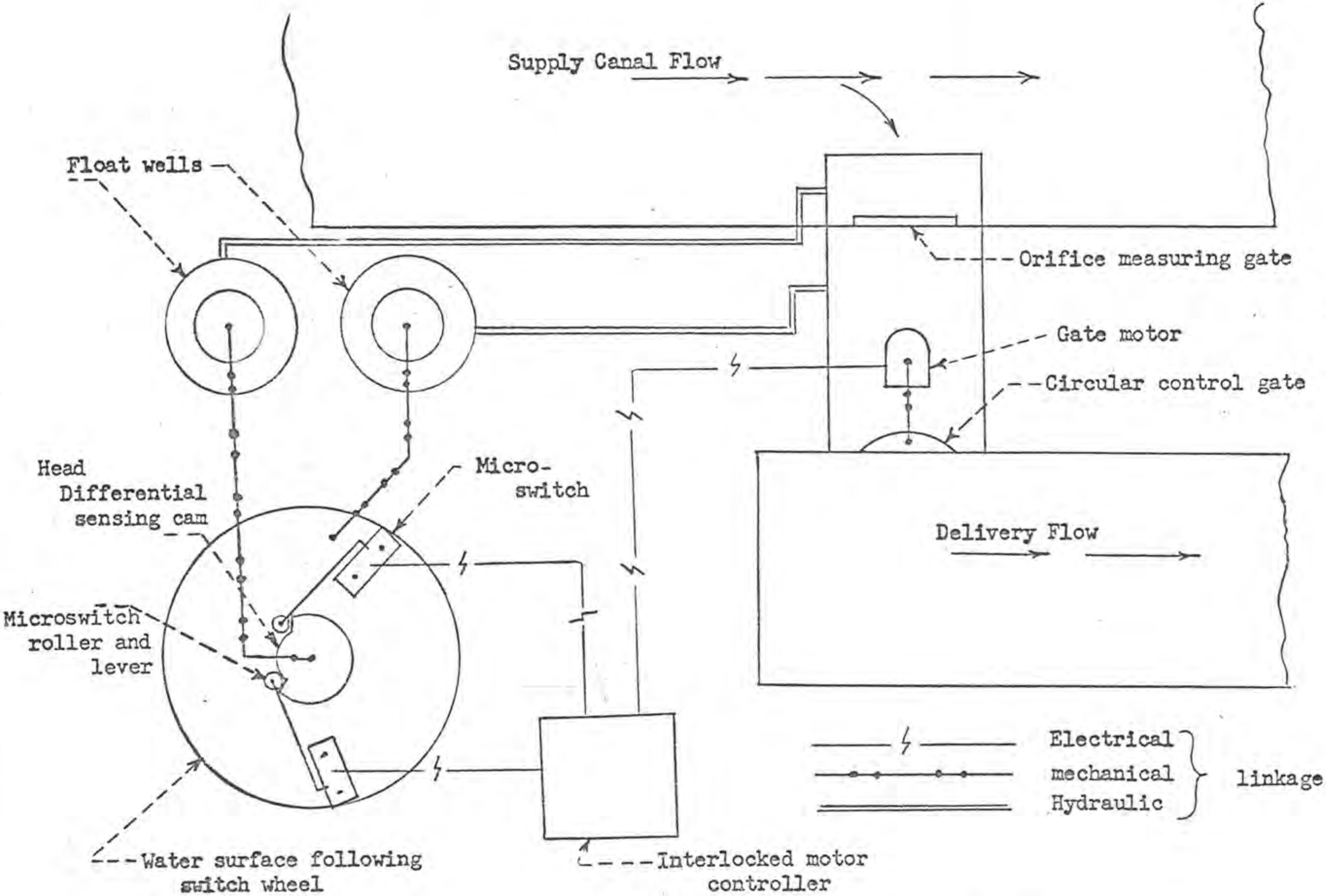
Table 1 - continued

Run No.	Measuring gate opening ft	Approach head initial and final ft	Submergence on control gate ft	Control gate speed ft/sec x 10^{-4}	Ramp ft/sec x 10^{-4} or step ft	Control gate opening %	Offset from differential ft	Offset time min	Comments
6	0.138	1.51 1.92		2.0	5.7	40 14 18 - 16	+0.131 +0.02 ±0.002	7.1 40.0	Ramp Lowest gate Oscillating
7	0.27	1.94 1.60	1.25	Off	5.3	17 17	0.000 -0.100	0	No control End of run
8	0.27	1.51 1.93	1.32	2.0	-	17 39	-0.100 +0.005	0	Diff. set by controller
9	0.27	1.51 1.93	1.26 1.33	Off	5.0	39 39		0	Ramp Controller off end of run
10	0.138	1.67 1.50	1.22	2.0	-0.17	34 18 22	-0.040 +0.010	11.4	Step Lowest gate
11		1.89 1.46	1.20	2.3	3.3	28 90	-0.04	13.3	Ramp Limit switch

Q = Discharge
ρ = Density of water
μ = Viscosity
g = Acceleration of gravity



- CHOTO -
GATE CHARACTERISTIC DEFINITION SKETCH



AUTOMATIC CONSTANT HEAD ORIFICE TURNOUT

Figure 2

Figure 3(a) - General view automatic choto and recoring system. (a) canal lateral, (b) CHOTO, (c) exit canal, (d) gate-drive, (e) float wells.

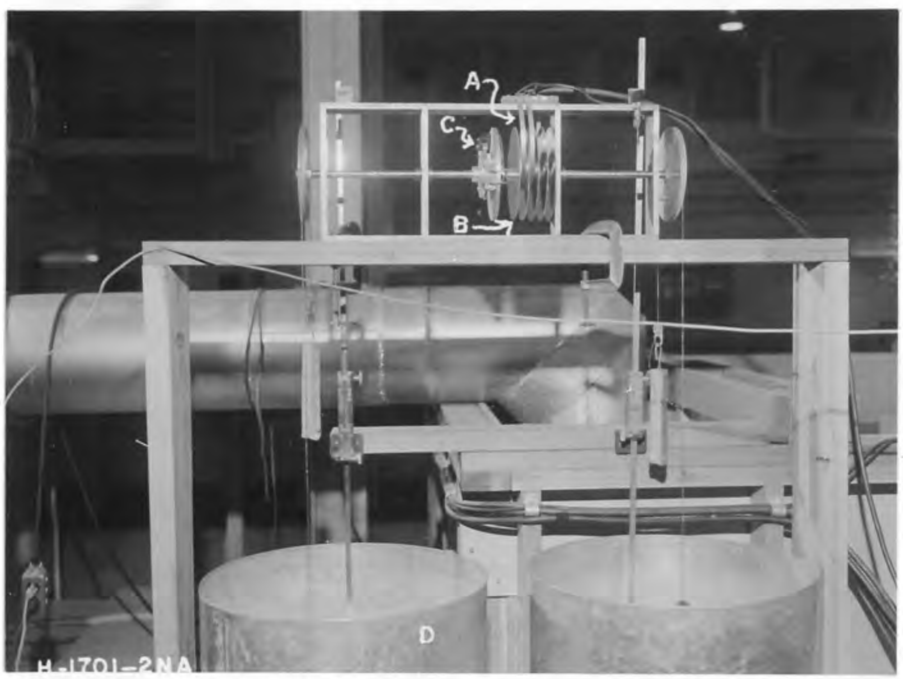
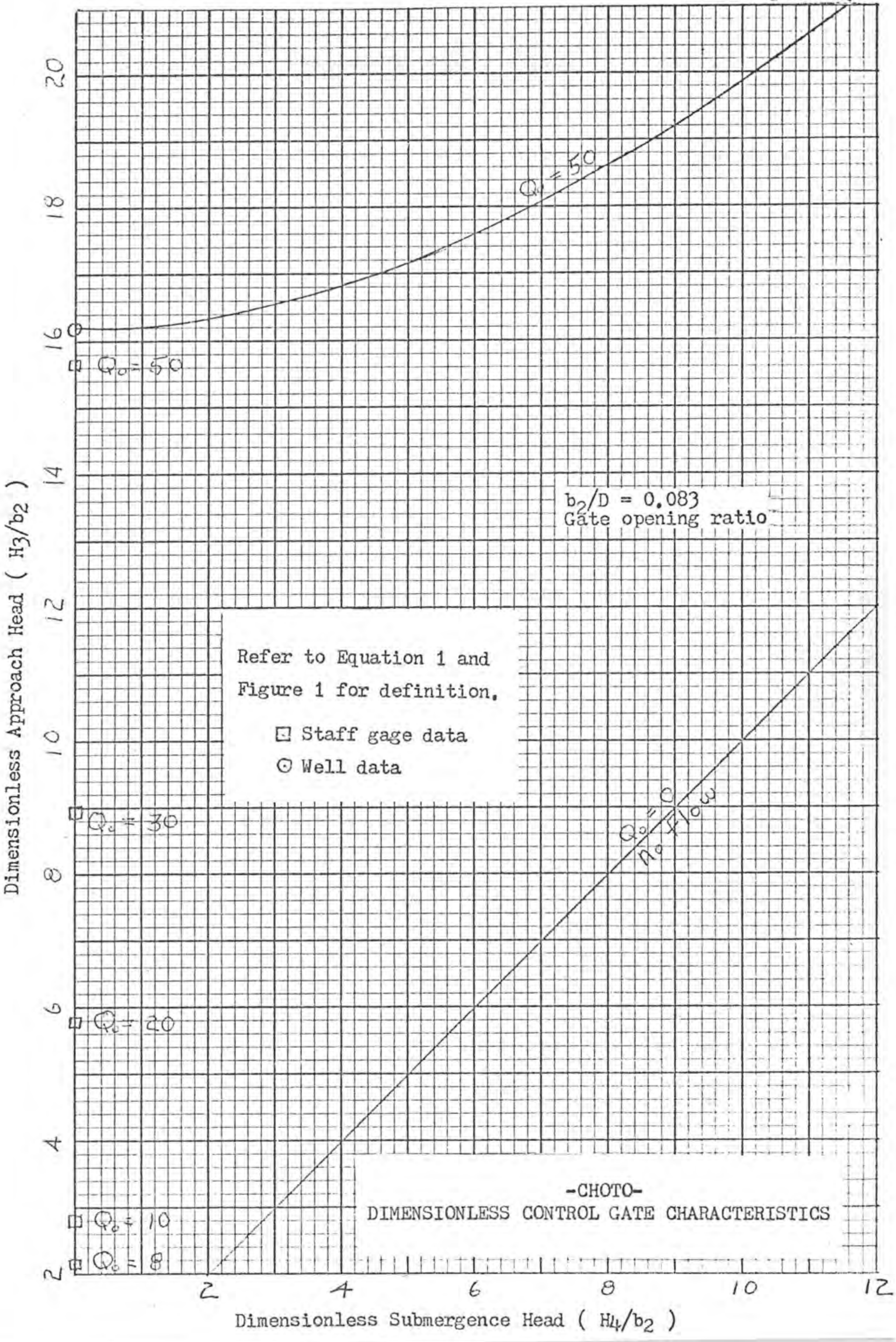
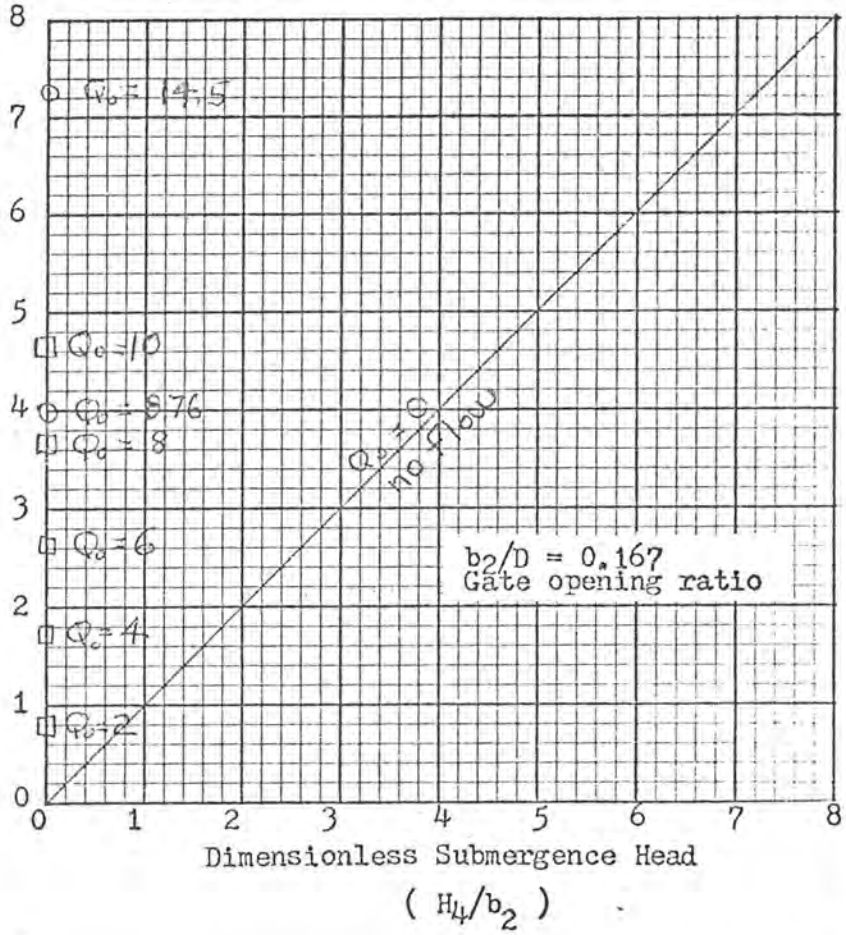


Figure 3(b) - (a) Spiral electrical connections, (b) insulating disks, (c) micro switches and (d) float wells.

Figure 4a



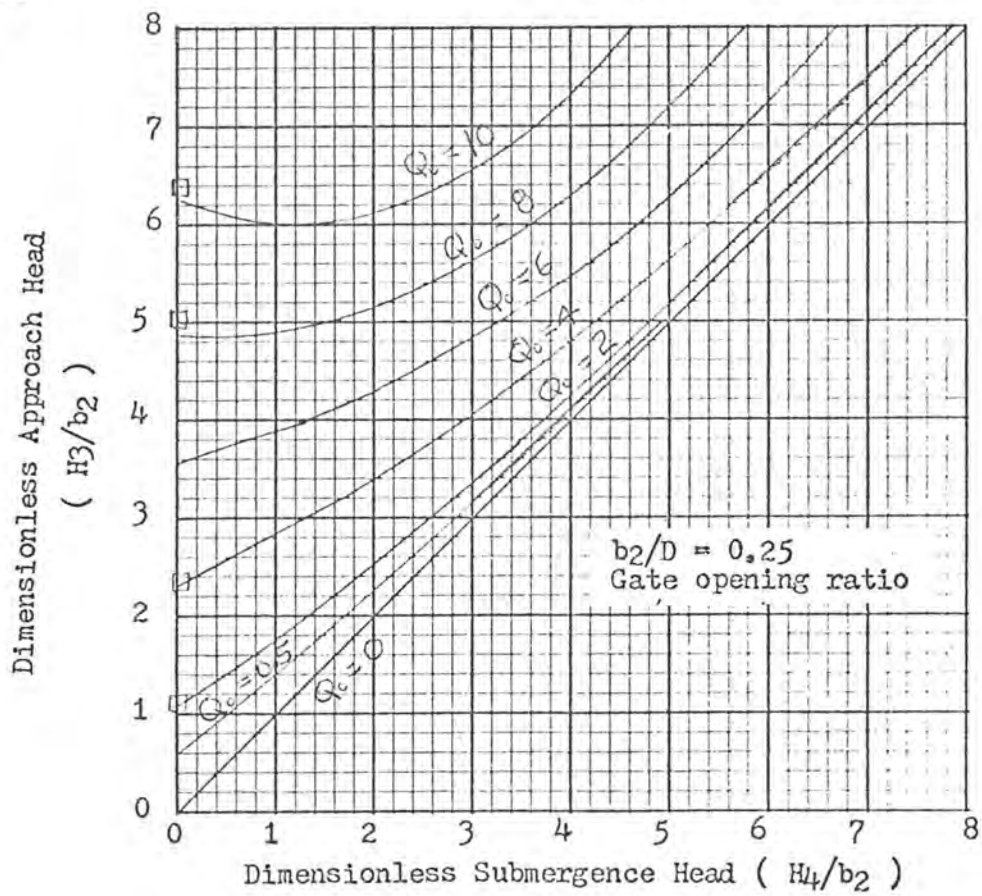
-CHOTO-
DIMENSIONLESS CONTROL GATE CHARACTERISTICS



Refer to Equation 1 and Figure 1 for definition.

□ Staff gage data

⊙ Well data



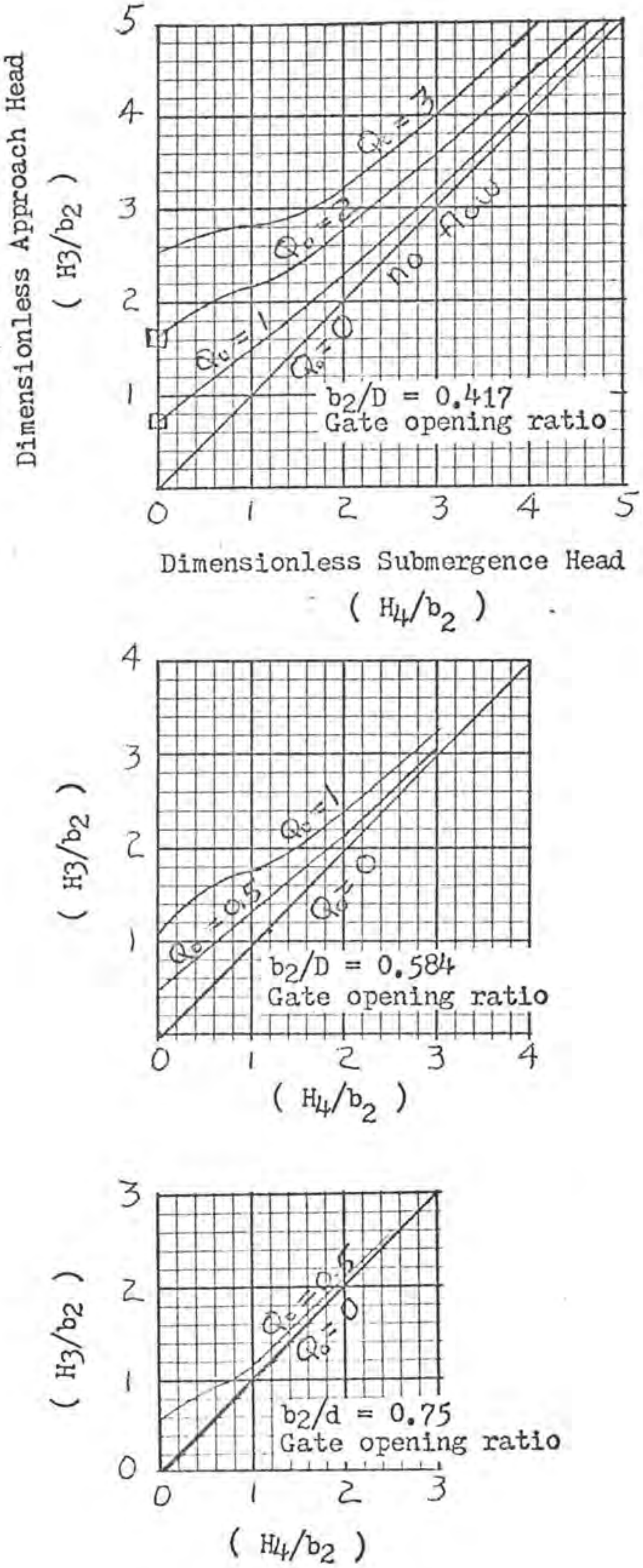
-CHOTO-

DIMENSIONLESS CONTROL GATE CHARACTERISTICS

Refer to Equation 1 and Figure 1 for definition.

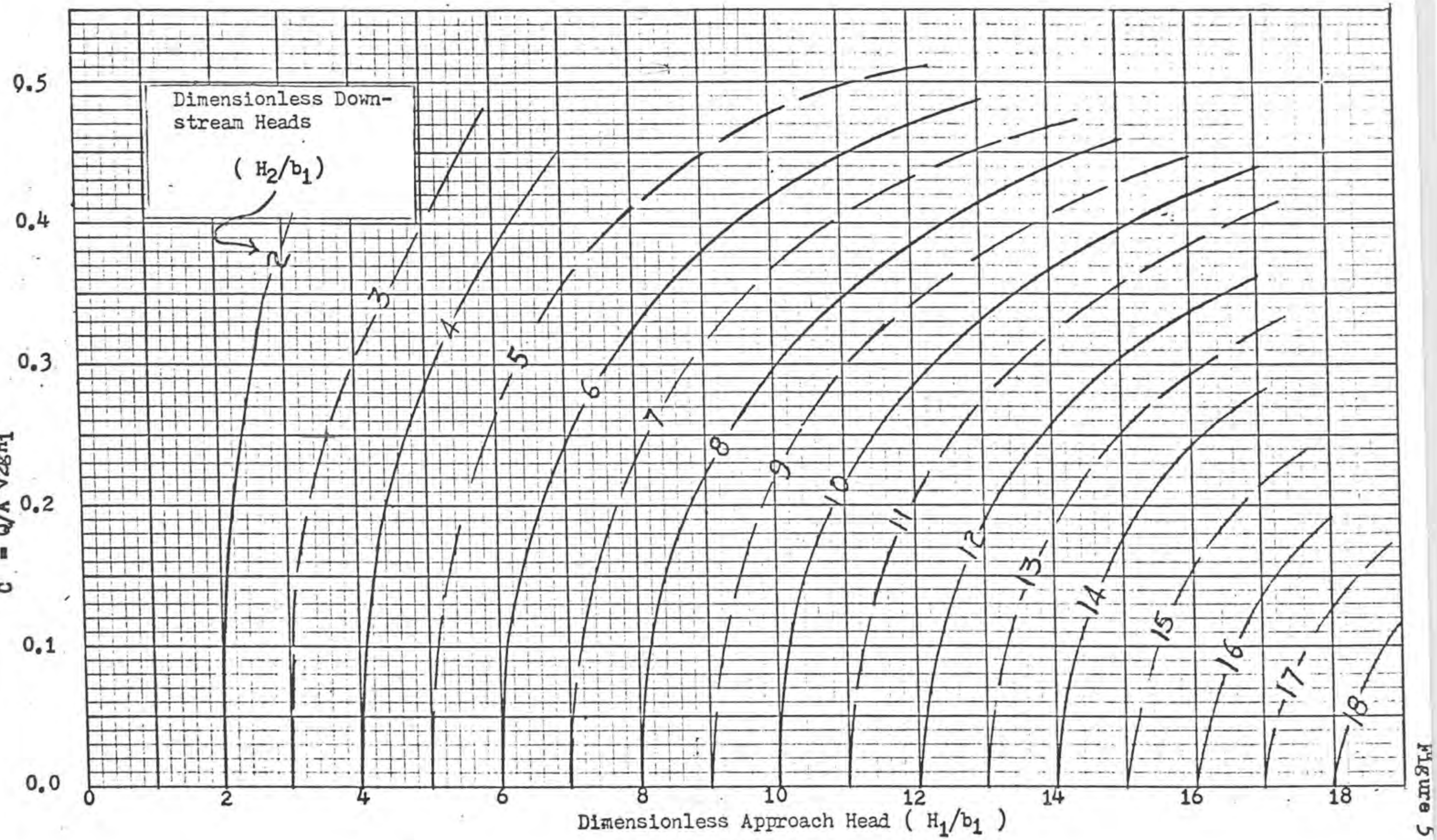
□ Staff gage data

⊙ Well data



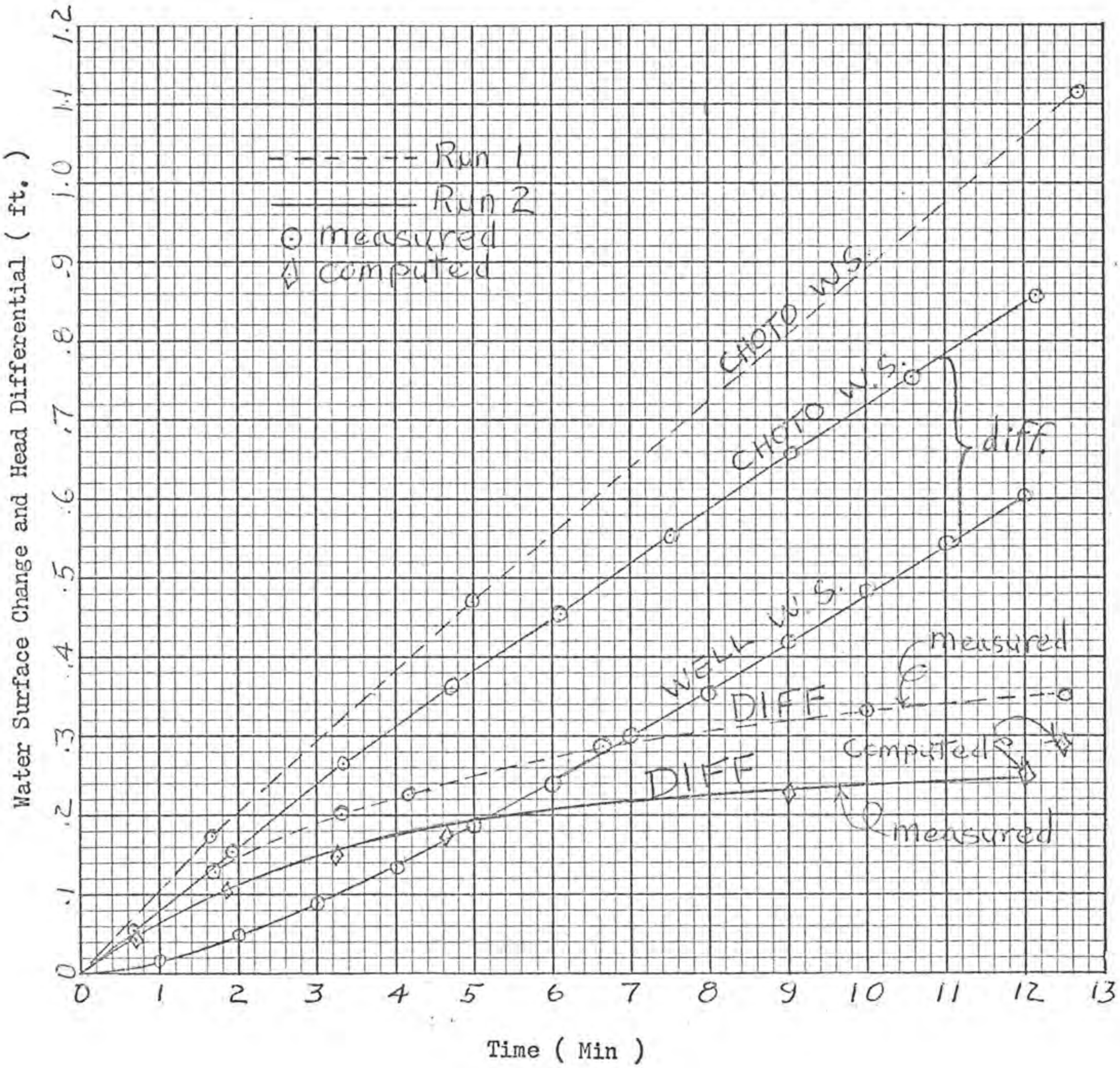
-CHOTO-

DIMENSIONLESS CONTROL GATE CHARACTERISTICS



-CHOTO -

CHARACTERISTICS OF ORIFICE GATE

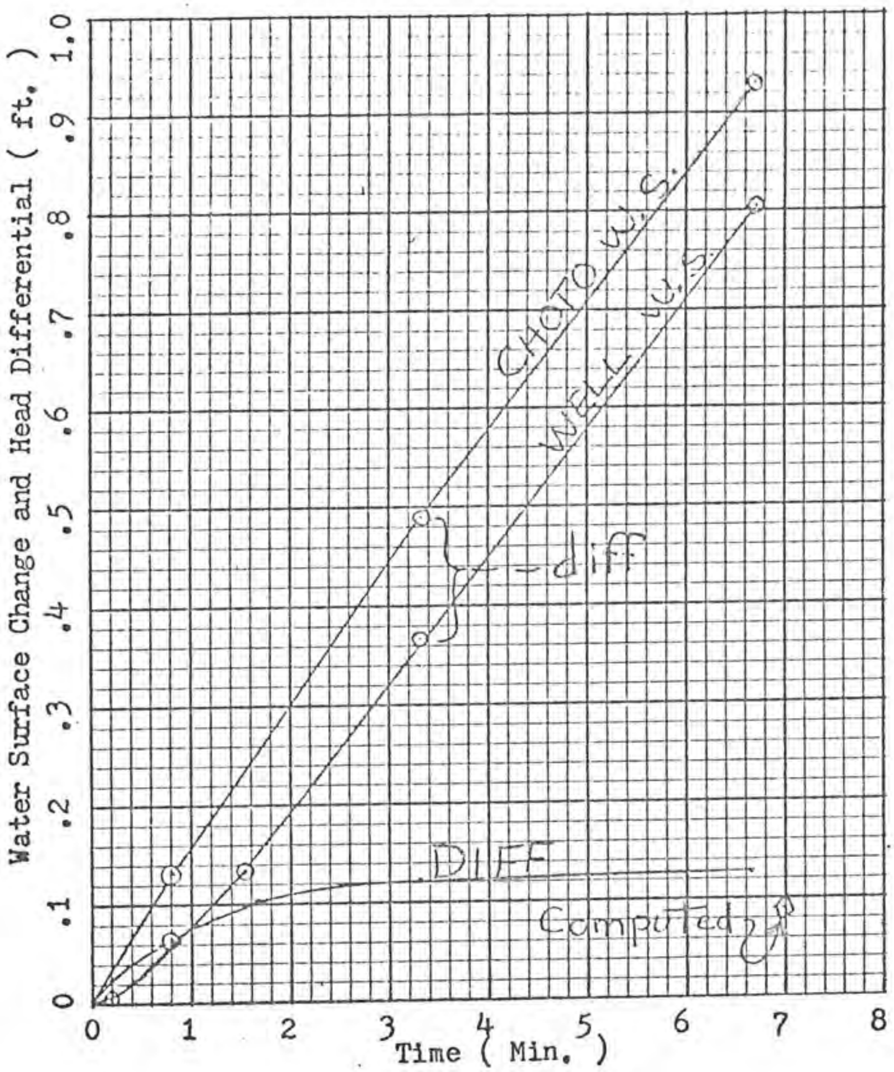


- CHOTO -

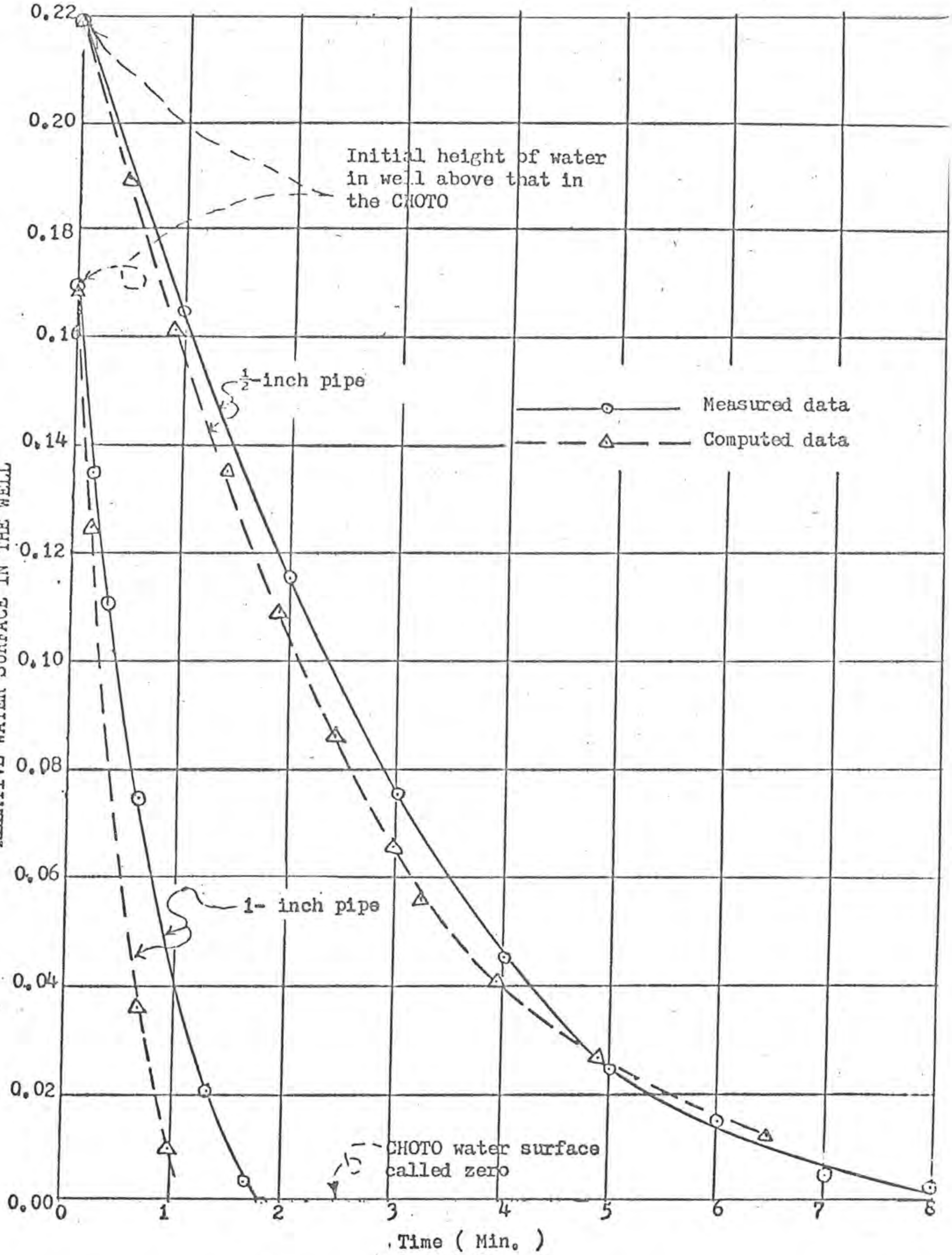
RAMP WATER SURFACE AND FLOATWELL RESPONSE

$\frac{1}{2}$ - INCH PIPING

18 - INCH STILLING WELL



-CHOTO-
RAMP WATER SURFACE AND FLOATWELL RESPONSE
1- INCH PIPING
18- INCH STILLING WELL



-CHOTO-

FLOATWELL RESPONSE TO STEP CHANGE IN THE CHOTO

Progress Report on

AN INVESTIGATION INTO AUTOMATIC CONTROL OF THE CONSTANT HEAD ORIFICE TURNOUT (CHO)

by

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September 22, 1972

ABSTRACT

The objectives of this investigation were (1) to write a computer program which would simulate the behavior of an automatically controlled Constant Head Orifice (CHO) turnout and (2) to determine the relationships of variables that would result in automatic control of a CHO turnout that would be both stable and responsive.

A key step of the first objective was development of a program, STLWL3, to duplicate the response of a stilling well to water surface fluctuations. Very good agreement was obtained between experimental data and computer results when transient resistance was taken to be 1.65 times that for steady flow. An expanded program, CHO2 which included STLWL3, was written to duplicate all aspects of the turnout. Difficulties of one sort or another invalidated two of the three sets of experimental data which were collected. A comparison between the one satisfactory set of data and the computer results indicated that incorrect basic information was given to the computer about some characteristics of the CHO. This might be the reason why agreement between certain aspects of the experimental data and the computer results was not too satisfactory for the first 20 minutes. However, the correspondence for the next 10.5 minutes was quite good; tests of greater length might be in order. Difficulties with basic data could not be overcome within the time available. Consequently, the first objective was not completely achieved. This in turn prevented any progress on the second objective.

Both objectives appear attainable. The result will be a device which is compatible with and necessary for the concept of quick canal response which is being adopted with ever increasing speed. To attain the objectives of this investigation, the basic data must be rechecked. The computer program may have to be corrected and revised. The 1.65 resistance multiplying factor should be rechecked because, if true, it would be of great interest to the engineering profession and is of paramount importance if better progress is to be made with all types of unsteady flow including that in open channels.

ACKNOWLEDGEMENT

The progress reported upon herein is due in no small measure to the outstanding cooperation of the people the writer came in contact with. He is particularly indebted to Lloyd F. Weide for the many meaningful discussions which helped the writer to understand the various facets of the problem and to keep the writer pointed in the proper direction. Few of the results would have been possible were it not for the foresight and diligence of Russell Dodge in collecting much of the basic model data. The writer is also indebted to Robert Kuemmick for his unending patience in explaining and in helping to set up the laboratory electronic equipment. A great debt of gratitude is also owed to the personnel of the computer center for their undying cooperation and commiseration when the writer made a faux pas. Sheryl States was of great assistance in helping the writer to get acquainted with the organization and for her professional attitude toward the quality of some of the graphs which went into this report.

There were other people, too many to mention, who were of assistance through their cooperation and encouraging understanding throughout the undertaking.

TABLE OF CONTENTS

INTRODUCTION

The Constant Head Orifice (CHO) turnout was developed by Reclamtion engineers in the late 1930's to provide a reliable measuring turnout from canals where the available head is insufficient to accommodate a weir or Parshall flume. Flow through the turnout is steady and measurement is reliable as long as the canal water surface is maintained at a constant elevation. However, unpredictable changes in flow conditions often make it impossible for operators to maintain the desired canal water surface. The resulting changes in flow through a turnout can create costly problems for irrigators, and water is often wasted. An automatic device is needed to perform the adjustments necessary to maintain uniform turnout flow in spite of fluctuating canal water surfaces.

A CHO turnout consists of two slide gates installed in tandem. the space between the gates is called an orifice well. The front or orifice gate is a square gate with relatively uniform flow characteristics for all conditions of openings. The rear or turnout gate is a watertight gate and is usually circular. In operation, the orifice gate is opened an amount predetermined as appropriate to the flow desired, and the turnout gate is adjusted to achieve desired differential water surfaces across the orifice gate. The rapidity with which this adjustment can be made in the field has resulted in high popularity for the CHO turnout. It has been selected as the standard turnout for many projects. The CHO concept has also been applied to many check structures where measured regulation is desired.

The concept of automation visualized at this time anticipates overall operation quite similar to the above-described manual operation. Adjustment of the orifice gate would still be manual, either local or remote. However, the automatic controller would adjust the turnout gate opening as required to maintain a uniform difference between water surface elevations upstream and downstream from the orifice gate; closing the gate when the difference is greater than desired and opening the gate when the difference is less than desired. This feedback type control is expected to maintain steady flow through the turnout.

Funding for initial study of automating a CHO turnout was provided by the OCCS committee in 1969. A laboratory model of a turnout was built and fitted with equipment to perform the designers concept of automatic control. Initial test runs showed that rate of turnout gate movement was critical. The controller would hunt (frequently reverse its direction) if the gate moved either too fast or too slow. Study of experimental data also revealed that time required for a stilling well to properly reflect its intended water surface was influential in determining proper rate of gate movement. Complex analysis of stilling well response combined with the numerous sets of physical conditions to be encountered in adapting controllers to existing structures make study of these items most appropriate for computerized mathematical analysis. Therefore, further studies were deferred pending development of a computer program to simulate operation of a CHO turnout. Experimental data from the laboratory model will be needed to verify the computer program.

The progress reported here covers work funded from the Water Systems Automation budget in 1972. Without fully recognizing the complexities involved, but being aware of the progress required for completion of the project, this work was ambitiously initiated with the following objectives:

1. Write and verify a computer program which simulates in all respects the operation of an automatically controlled CHO turnout.

2. By means of the computer program, determine combinations of variables that will result in an automatic controller that does not hunt and is suitably responsive. These combinations should be checked against a laboratory model and possibly a field model.

COMPUTER PROGRAM

General

Variations with time in the main canal depth, Y1, cause changes in the orifice well depth, Y2, and in the lateral depth, Y3 (weir well depth, Appendix B, Figure B1). Stilling well S1 senses Y1 and stilling well S2 senses Y2. The difference S1-S2 is related to Y1-Y2. The difference between S1 and S2 is used to control the movement of the gate, B2, in an effort to keep Y1-Y2 at some constant value. When Y1-Y2 is constant, as in the case of steady flow, the discharge does not vary. However, when Y1 changes with time, the flow throughout the CHO is unsteady with the result that S1 and S2 lag in value Y1 and Y2. Therefore, S1-S2 is not truly indicative of Y1-Y2. One important facet of the computer work was the development of a program which simulated the response of a stilling well to water surface fluctuations. This program goes under the name of STLWL3 and is presented in the next section. The grouping of the stilling well variables which would lead to a tolerable lag is a part of the second goal of this investigation.

After the stilling well program was developed, it was included as a part of a larger program which simulated the overall behavior of a CHO. This larger program goes under the name CHO1. In an effort to facilitate the comparison of the computer and experimental responses, the program CHO1 was expanded so that the computer graphed these data; the name of the enlarged program is CHO2.

STLWL3 (Schematics and details - Appendix A)

The program STLWL3 sets forth the unsteady response of a stilling well to free surface variations of the body of liquid to which the stilling well is connected. Although written for the investigation of a CHO, STLWL3 can be used by itself for the investigation of any stilling well because it is self-contained.

The response of a stilling well is basically an unsteady flow problem. As a consequence, Newton's second law of motion is the chief governing equation. The continuity and energy equations were also needed. Calculations were carried forward using the finite time increment DELT1. In setting up the necessary relationships, account was taken of the mass of the liquid and of the resistance to flow. Because of the permitted variations in diameter of the pipes which comprise the stilling well system, different accelerations, velocities, and displacements were included in the analysis.

In the first attempt at developing a program for the stilling well, the acceleration at the end of a DELT1 period was based on the velocities and positions which existed at the beginning of the period. The result was satisfactory as long as DELT1 was sufficiently small. A program which was not as sensitive to the magnitude of DELT1 was then formulated wherein the magnitude of the acceleration at the end of a period was based on the averages of the velocities and displacements which existed over the DELT1 time increment; the name of this program is STLWL3.

Two types of resistance to flow were included in the analysis, boundary resistance and form resistance. Both were evaluated as though the flow were steady. In ascertaining the boundary resistance, the pipes were assumed to be smooth and the flow turbulent regardless of the magnitude of the Reynolds number. Form losses were considered to be equal to the steady-state loss coefficient times the velocity head. The relationship between the magnitude of steady-state losses and unsteady-state losses for the same velocity is not well documented. On the basis of a few experiments, they are presently being taken by engineers to be equal. However, to increase the flexibility of STLWL3, a factor, ZMUL, was introduced into the program so that the unsteady-state resistance could be a ZMUL multiple of the steady state resistance. When ZMUL equalled one, the resistance was the same as that for the steady state; when ZMUL equalled zero, there was no resistance whatsoever; when ZMUL exceeded one, the unsteady flow resistance exceeded the steady state resistance.

Russell Dodge of the Bureau of Reclamation had collected four sets of experimental data for stilling wells which could be used to check the validity of STLWL3. Test No. 1 is depicted in Figure 1. The variation of the liquid level, Y, with respect to time is practically linear and is therefore called a ramp input. The line connecting the stilling well to the chamber where Y varied was a 1/2-inch rubber tube without any fittings. The difference between the level Y and that in the stilling well, S, for the experimental data is indicated by the solid line, YMS (Y minus S); it is this line which is to be duplicated by the computer program. The abrupt jump in the experimental data for time greater than 900 seconds is assumed to be due to some kind of error rather than being real. The computer results are depicted by dotted lines. When ZMUL is equal to one, the agreement between the experimental data and the computer results is not good. However, when ZMUL equals 1.65 the agreement is very good. The universality of the 1.65 factor for this type of apparatus can only be demonstrated through further comparisons between experimental and computer results.

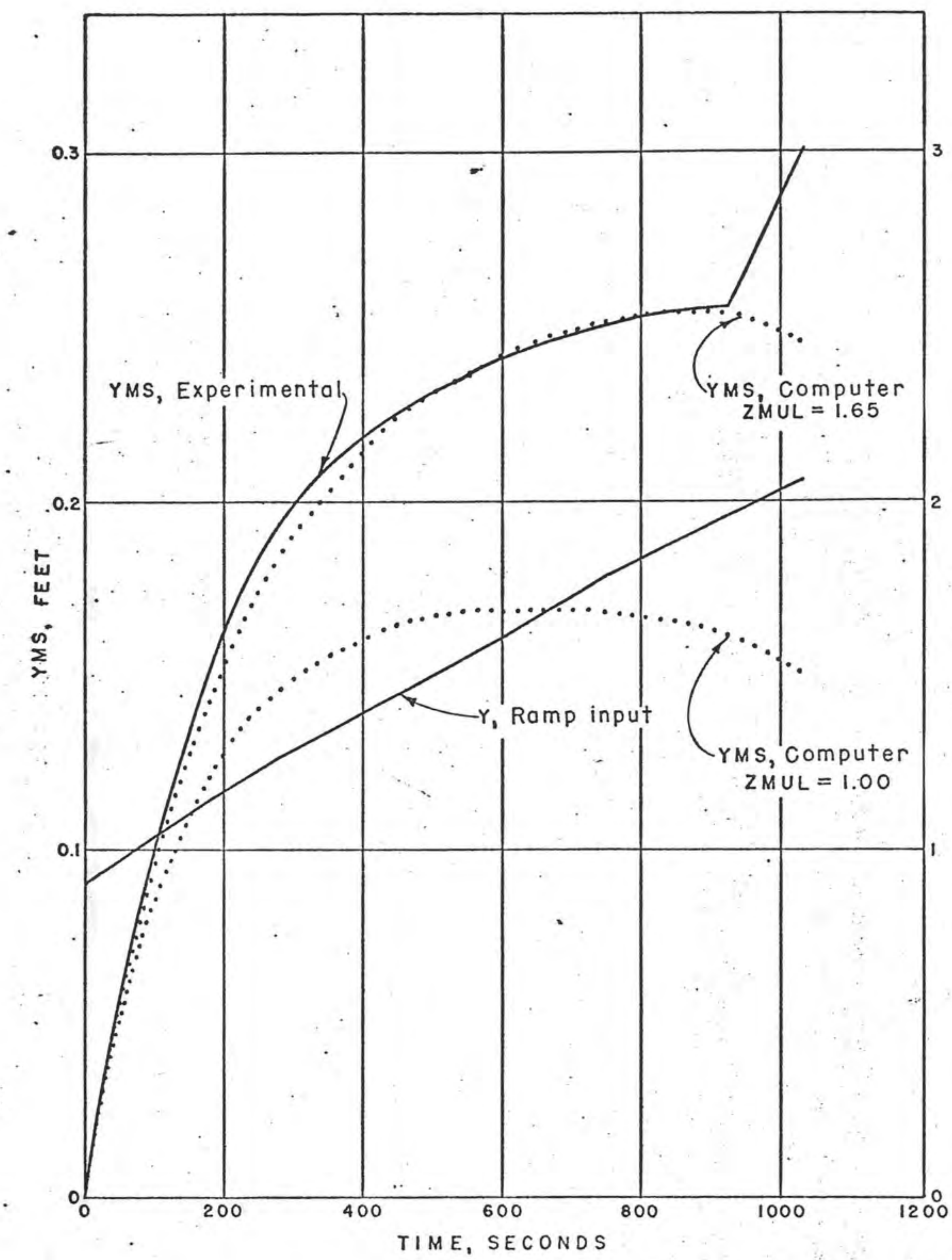

FIGURE I, TEST #1 [$\frac{1}{2}$" LINE-RAMP INPUT]

The apparatus used for Test No. 2 is the same as that for Test No. 1. The variation of Y in this case is called a step input because at time equal to zero, Y is increased abruptly by about 0.2 foot and is then kept constant, Figure 2. With ZMUL equal to the previously found value of 1.65, the agreement between the experimental and computer results is very good.

For Test No. 3 a different setup was used. The line to the stilling well was a 1-inch PVC plastic pipe with a number of fittings (elbows, union, and a gate valve). The effects of these fittings were taken into account in the computer simulation. The results for this test where Y varied in a step fashion are depicted in Figure 3. With ZMUL equal to 1.65, the computer results are indistinguishable from the experimental results.

The physical set up for Test No. 4 (ramp input) is the same as that for Test No. 3. The results are depicted in Figure 4. The agreement between the experimental and computer results is good for the first 200 seconds after which the computer results differ markedly. A close examination of the input data discloses that Y does not vary linearly with time; in fact, there is a very slight change in slope of the input data line at a time of 200 seconds. It seems as though the computer solution is quite sensitive to variations in the rate of change of Y. When the rate of change in Y for the computer solution is taken to be that indicated by "Y approximate," the correspondence between the computer and experimental results, depicted in Figure 5, is greatly improved. This sensitivity should be kept in mind when collecting and interpreting the experimental data so that due attention is given to its correctness.

From Figures 1-5, it appears as though the unsteady resistance is about 1.65 times that for steady flow. If true, the fact that the unsteady resistance is higher than the steady is significant and would be of great interest to the engineering profession because heretofore they have been assumed to be equal. Whether or not the 1.65 is a universal factor is unknown; this particular value may be unique to the apparatus. The value of the factor may be a function of the physical situation.

There are three facets of this part of the investigation which encourage caution in accepting the notion of increased resistance and of the value of 1.65:

1. The resistance in the computer solution for steady-state conditions was based on handbook values. The steady-state resistance for the actual apparatus should be measured experimentally and compared with the handbook values; they might differ by the 1.65 factor. This would not be a difficult undertaking; it was not investigated here because of the limited amount of time available.

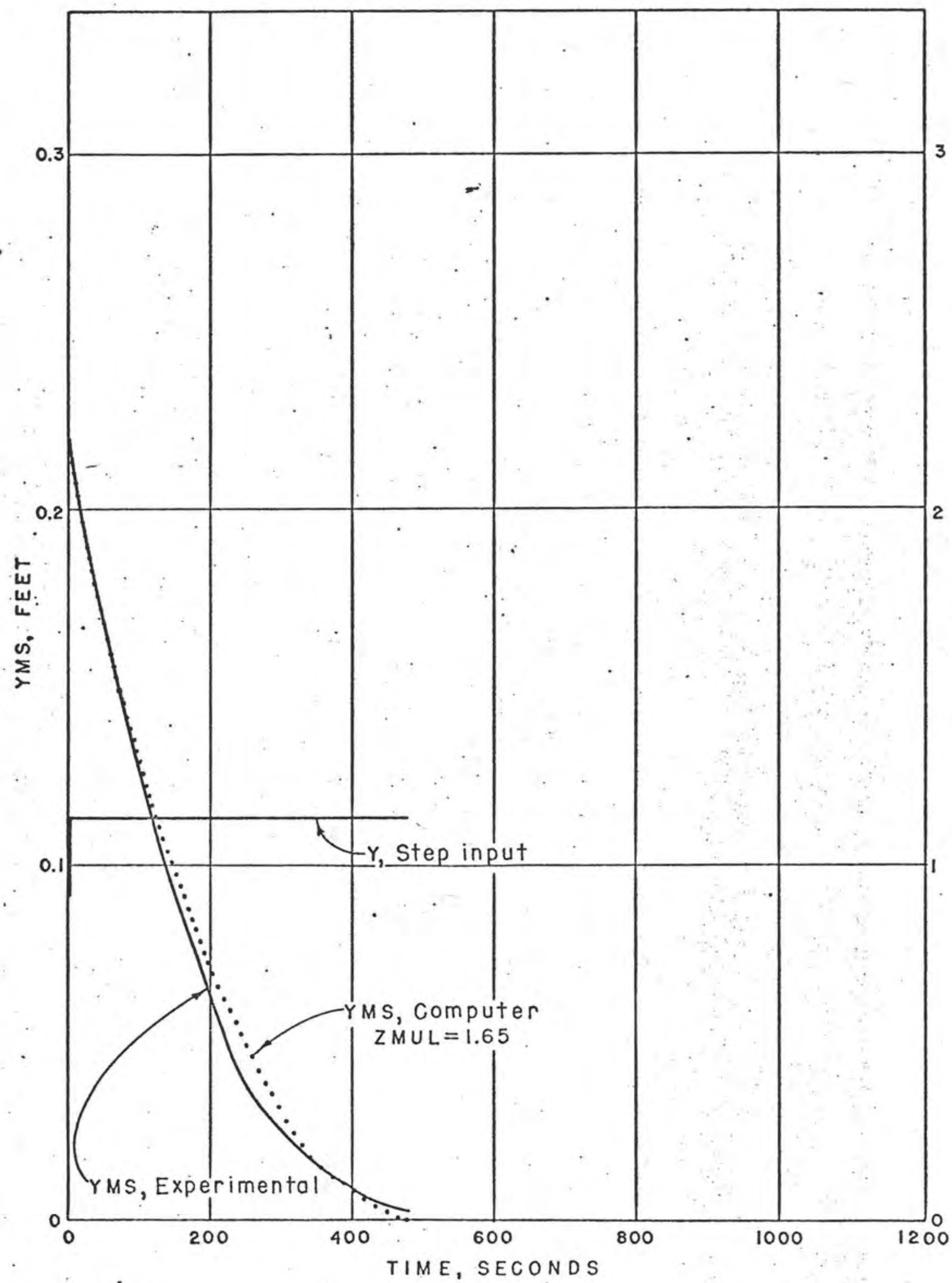

FIGURE 2, TEST #2 [$\frac{1}{2}$" LINE-STEP INPUT]

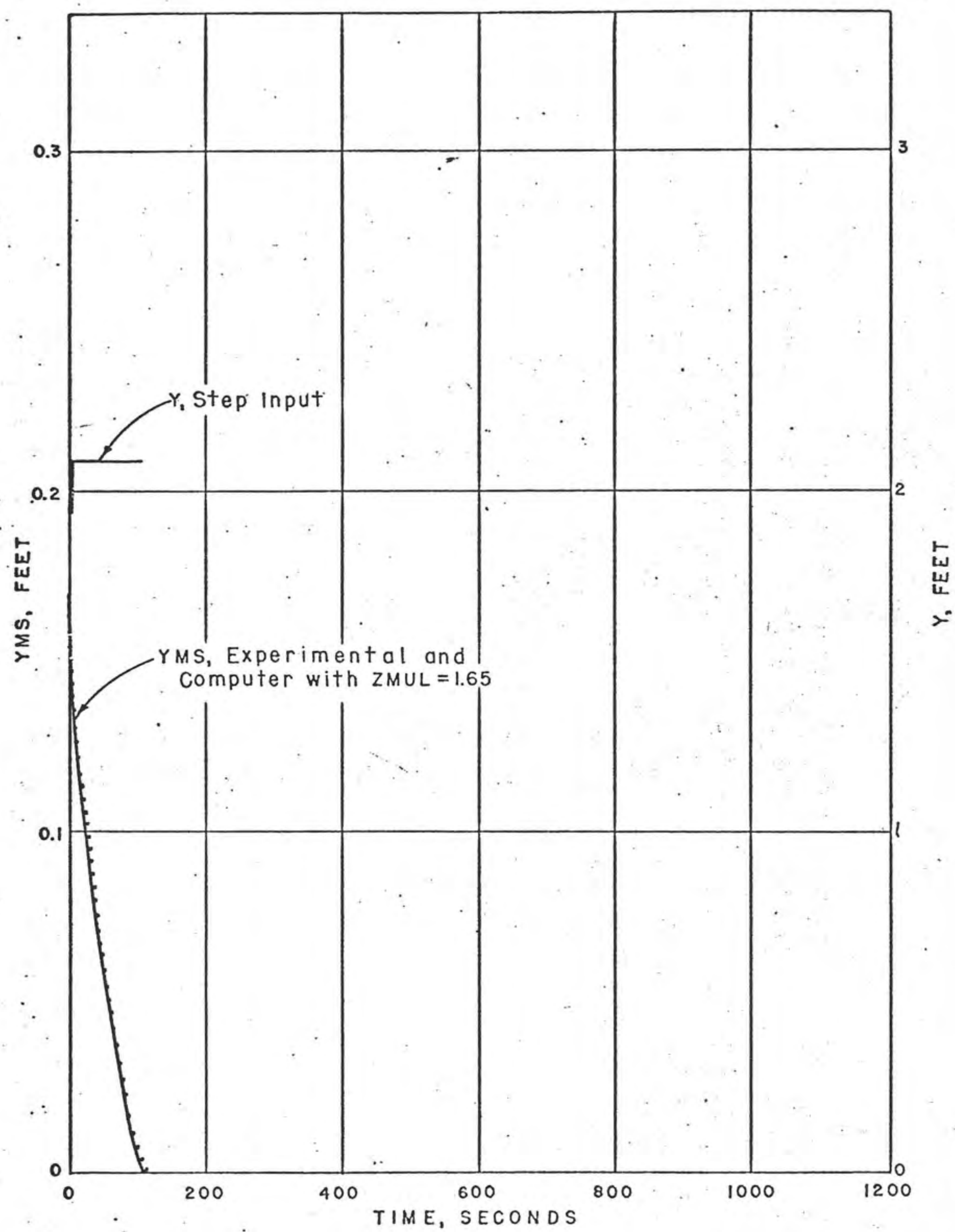

FIGURE 3, TEST #3 [1" LINE-STEP INPUT]

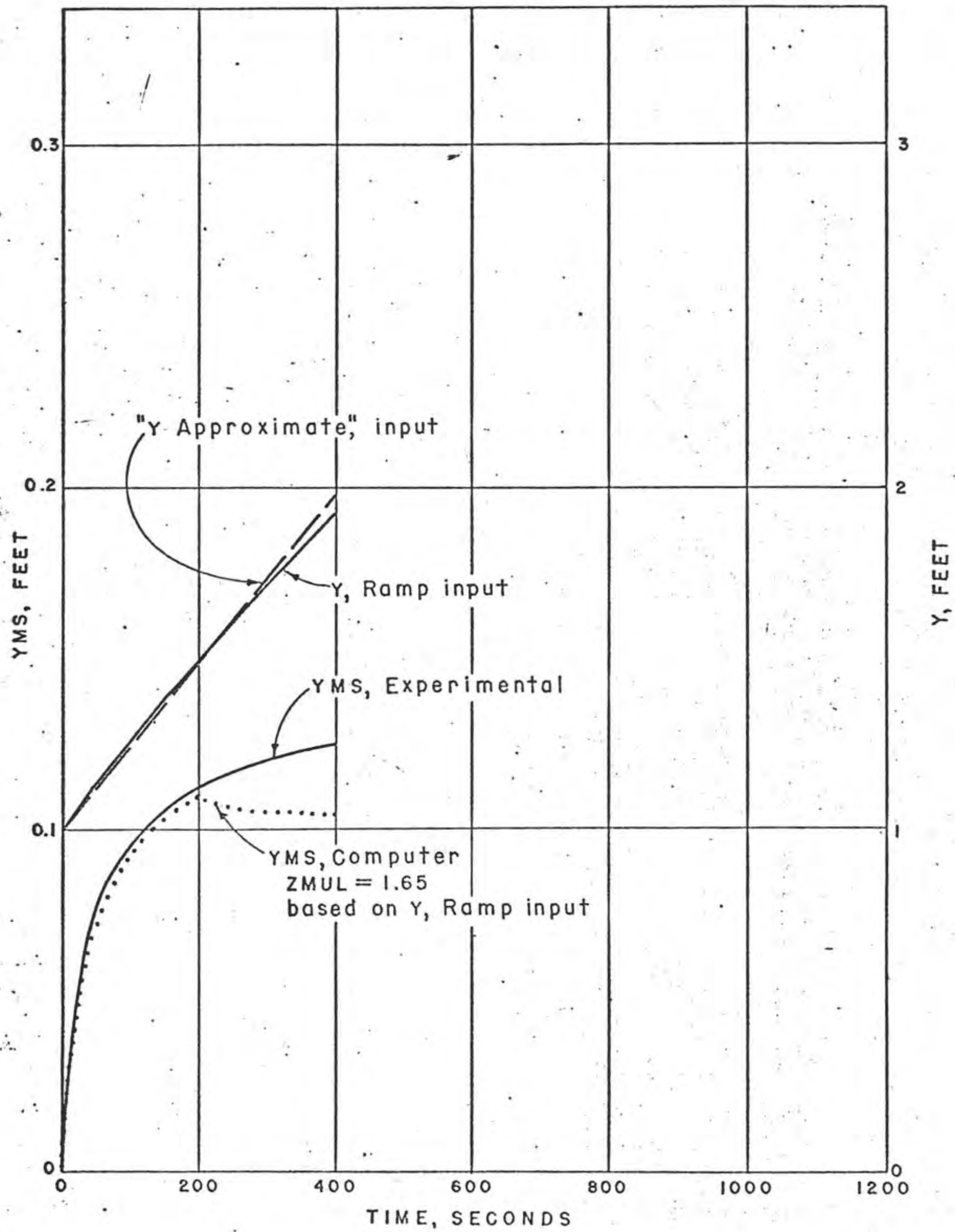

FIGURE 4, TEST #4 [1" LINE-RAMP INPUT]

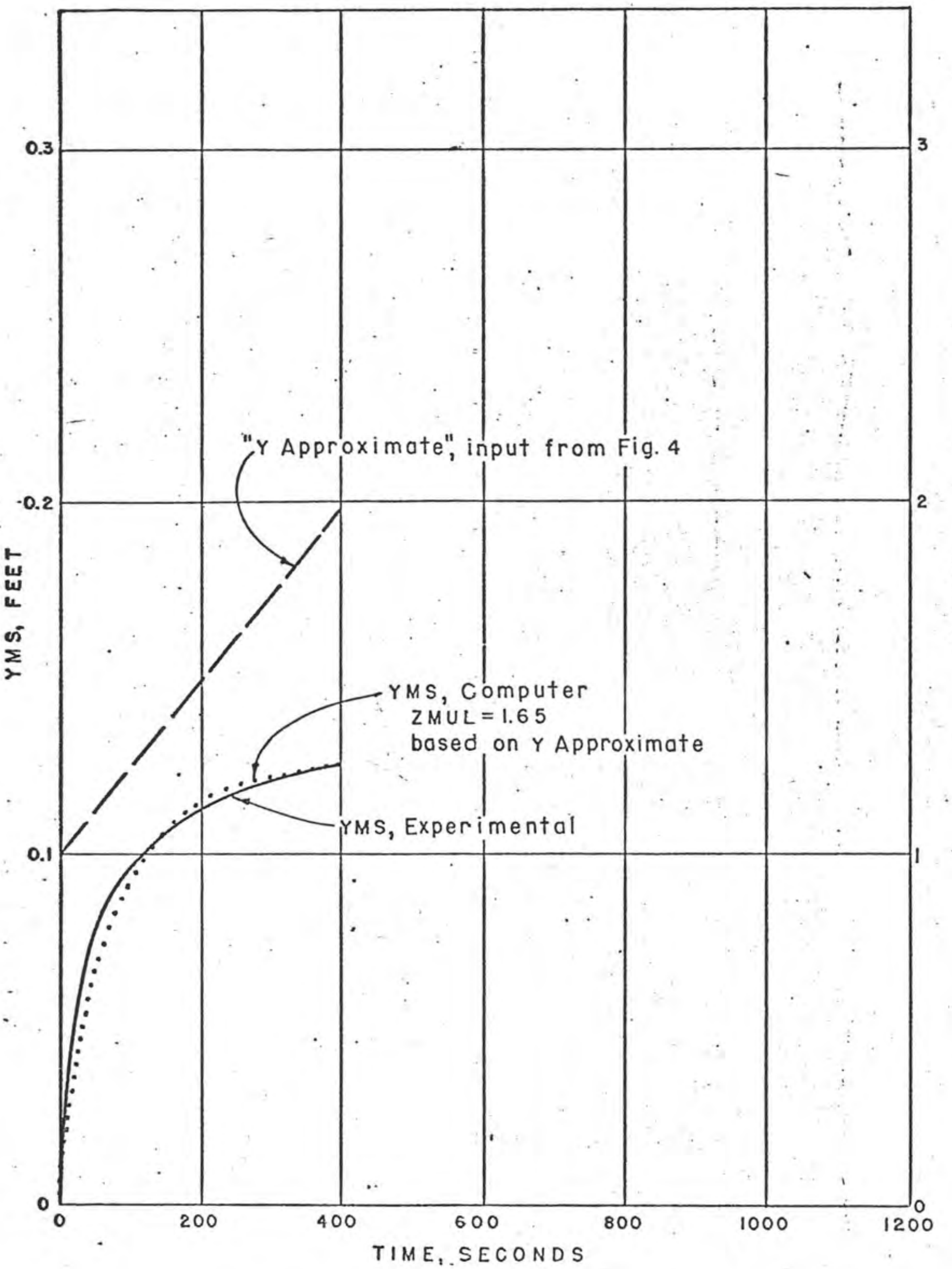

FIGURE 5, MODIFIED TEST #4

2. Twice during the course of working with the experimental apparatus, the 1/2-inch rubber line clogged completely for no apparent reason. The apparatus was partially disassembled after the second occurrence and some gelatinous material was found in the tube. This could have clogged the pipe and could have led to the 1.65. The pressure of time prevented a repetition of the experiments of Russell Dodge with thoroughly cleaned lines. This gelatinous material may not have had a significant effect on the response of the stilling wells because after it was found, the lines were cleaned and the before and after response of the stilling wells in succeeding tests seemed to be the same.

3. The computer program should be exposed to additional proving before considering it to be satisfactory. In the interest of continued progress with the investigation, STLWL3 was accepted for the time being. This seemed reasonable in light of the agreement between the experimental and computer results depicted in Figures 1-5.

CHO1 (Schematics and Details - Appendix B)

This program is designed to simulate all behavioral and operational aspects of the CHO. It was written for execution on the Bureau of Reclamtion's Honeywell computer; the output is in tabular form. The program applies specifically to the CHO model in the laboratory of the Bureau of Reclamation; portions will have to be changed if this program is to be applied to CHO's with different characteristics.

The program was written for responses of the CHO to variations of Y1 with respect to time. The responses, Y2 and Y3, are dependent variables. If the physical situation was such that Y3 were an independent variable instead of a dependent variable, CHO1 could easily be modified to accommodate this situation.

A change in Y1 brought about modifications in Y2 and Y3. The variations in Y2 and Y3 were evaluated through the application of the conservation of mass principle. After Y2 and Y3 were determined, values of S1 and S2 were ascertained through what amounted to the application of STLWL3 to each stilling well. The difference, S1-S2, was then used to govern the movement of the control gate, B2. This concluded the evaluation of the basic variables for one DELT1 time increment except for determining quantities which are simple functions of the basic variables. A total of 30 items of information was printed out for each time increment. This is many more than are needed to judge the performance of the CHO. The extra printout items are helpful in proving the program. Additional confirmation is necessary before the program can be accepted without question.

CHO2 (Details and Results - Appendix C)

The computer results can best be compared with the experimental data through graphs. The plotting by hand of the experimental data and the numerical results from CHO1 is a tedious job. This tedium was eliminated through an expansion of CHO1 so that the computer performed the task. The expanded program is CHO2 and is operable on the CDC computer at NOAA; CHO2 furnishes some of the results in graphical form and all of the 30 items printed out by CHO1. The graphical results from CHO2 will be used to depict the agreements between the computer results and the experimental data.

Three sets of experimental data were collected from the laboratory model of the CHO for comparison with the computer results from CHO2. The variations in water levels were sensed by means of seven pressure transducers whose signals were amplified by a Sandborn Series 350 amplifier. A potentiometer connected to the control gate was used to keep track of the gate position. The results were graphed by an eight-channel strip recorder. The quantities measured were Y1, Y2, Y3, S1, S2, Y1MY2 (Y1 minus Y2), S1MS2, and B2. Some of the strip chart results were not very satisfactory. There appeared to be drift in some of the output, and at times the recorder trace made unaccountable jumps. It is felt that with more time the abnormal instrument behavior could have been overcome and eliminated. As a consequence of these malfunctions, two of three sets of data were considered to be unsatisfactory.

The data collected on August 10, 1972, appear fairly satisfactory and will be the basis for judging the degree to which the computer results simulate the experimental data. As the initial test for CHO2, this is a taxing set of data because the gate hunted. After the program and basic data have been properly adjusted and evaluated, this type of situation should not present any problems for the computer. On the graphs, the computer results are indicated by points and the experimental data by continuous solid lines. The agreement between the two is perfect when the two sets of data plot as a single line. When they do not agree, there are two characteristics of the differences which are worthy of consideration: (1) the magnitude of the differences and (2) the periodicity of the experimental data as compared with the computer results. The resistance adjustment factor was taken to be 1.65 throughout this work. The stilling well lines were the 1/2-inch rubber tubes mentioned earlier.

The variation of Y1MS1 with respect to time is depicted in Figure 6. The variable Y1 represents the variation of the main channel water surface elevation with respect to time; it is one of the independent variables as far as the CHO is concerned. Stilling Well No. 1,

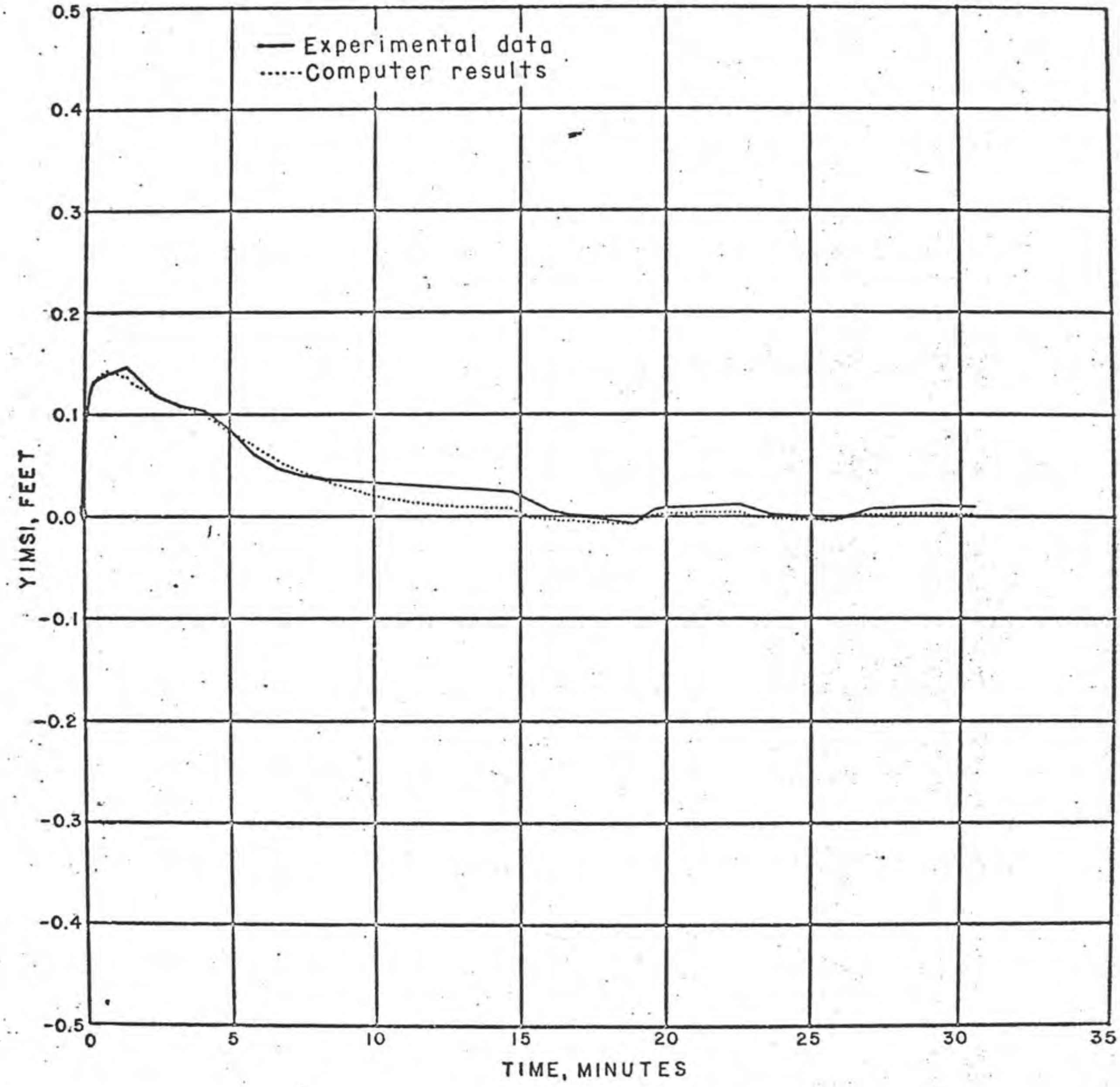

FIGURE 6, YIMSI VERSUS TIME

S1, is connected directly to the chamber wherein Y1 varies. Therefore S1 is completely independent of the response of the CHO. The evaluation of Y1MS1 is based on that portion of CHO2 which is comparable to STLWL3. Because the agreement between the experimental data and the computer results depicted in Figures 1-5 is fairly good, it comes as no great surprise that there is good agreement for this portion of the results of August 10, 1972. At no point do the computer results disagree with the experimental results by more than 0.02 foot. The periodicities of the computer and experimental data are approximately equal.

Before comparing additional results, attention needs to be drawn to an important point. All of the variables which are still to be considered are highly interdependent mathematically. An error in one, no matter what the cause, will result in an error in all of the others. These errors in succeeding work might be self-cancelling or could be additive. The agreement between the computer results and the experimental data may be extremely dependent upon the validity of the discharge relationships for the orifice and control gates, upon the proper evaluation of Y1, upon the proper setting and evaluation of the gate switches, and upon the validity of the computer program down to the smallest detail.

The difference between Y1 and Y2, Y1MY2, is shown in Figure 7. The hunting characteristics of the system for the conditions under which the test was run are portrayed by the line for the experimental data. A CHO is supposed to keep the difference Y1MY2 within some bounds about the initial value; the value oscillates about the initial position as it should for this hunting condition. On the whole neither the agreement in magnitude nor the periodicity between the two sets of results is too good.

The magnitudes of Y2MS2, Figure 8, are fair while the periodicities are better. The reason the agreement for Y2MS2, Figure 8, is not as good as that for Y1MS1, Figure 6, is due to that fact that Y1 in Y1MS1 represents actual experimental data whereas Y2 and S2 are both computed values.

The plots of S1MS2 are shown in Figure 9. The differences between the experimental data and computed results are similar to those for Y1MY2, Figure 7. Neither the agreement in magnitude nor periodicity depicted in Figure 9 is too good. Again, the hunting behavior of the system is apparent. A comparison of the experimental data for Y1MY2 and S1MS2 discloses that they are similar in trend but that S1MS2 lags in time Y1MY2 as might be expected.

In general, the agreements for the plot of Y2MY3, Figure 10, are poor. This could be due to cumulative and additive error effects.

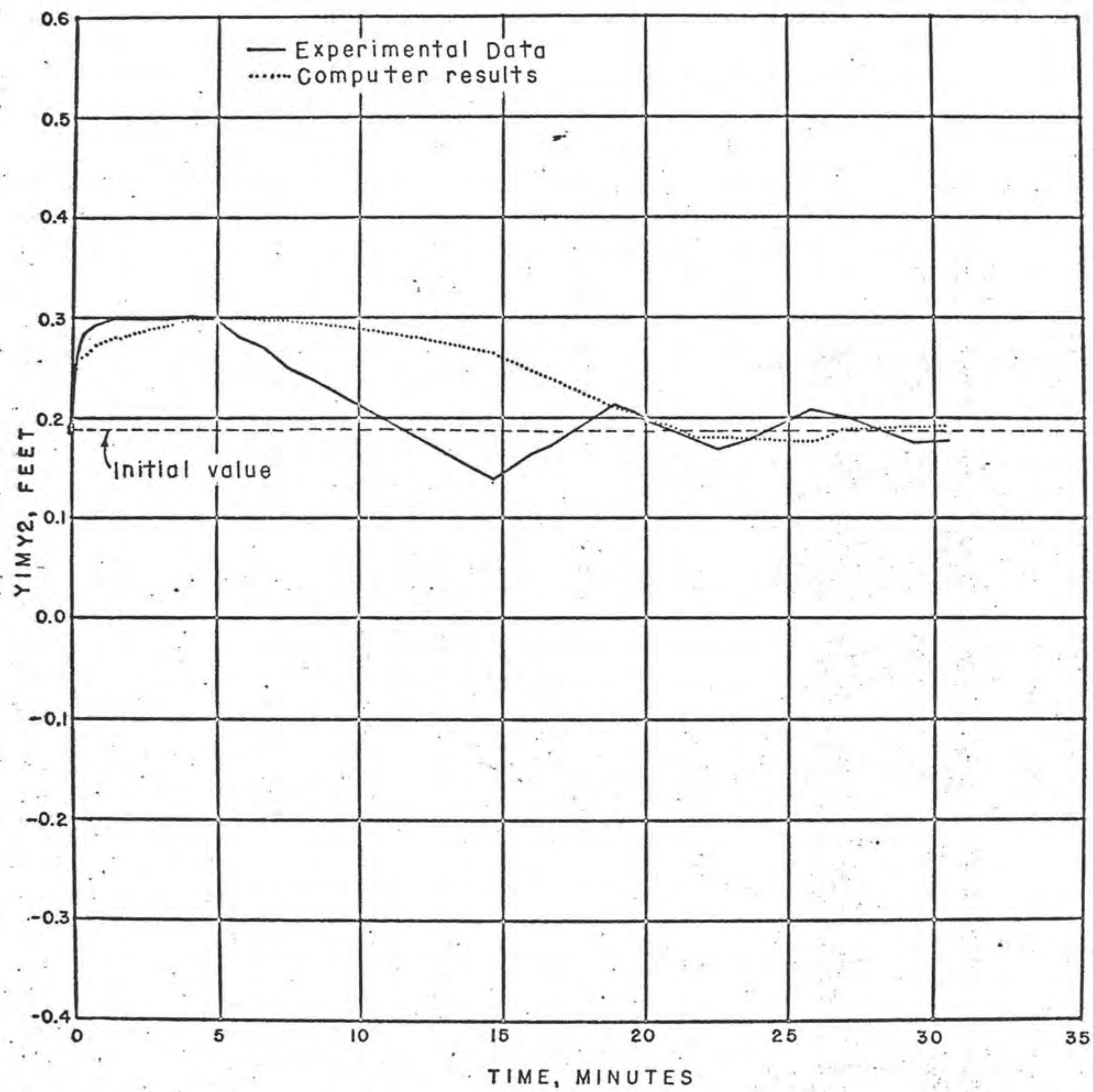

FIGURE 7, YIMY2 VERSUS TIME

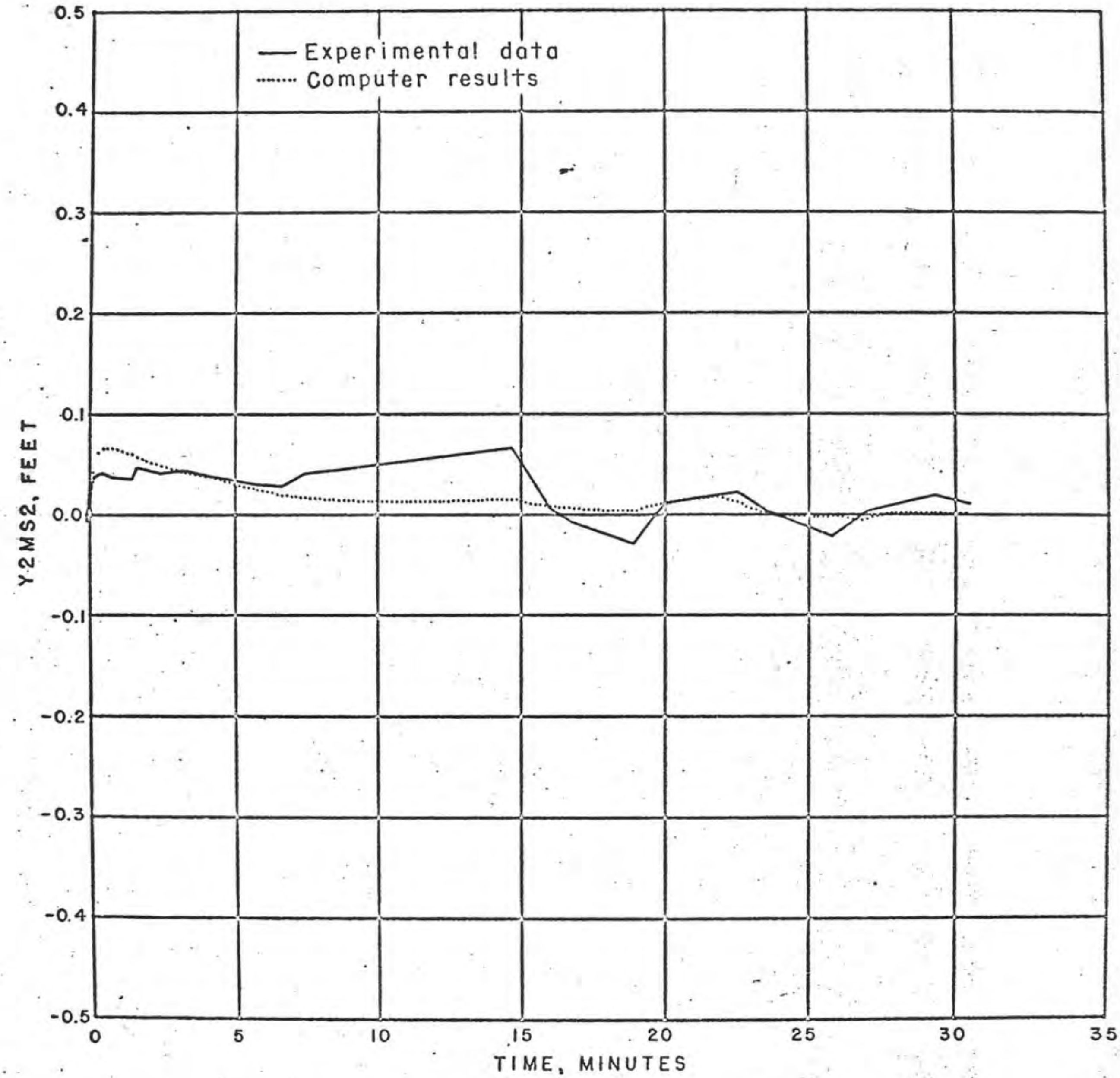

FIGURE 8, Y2MS2 VERSUS TIME

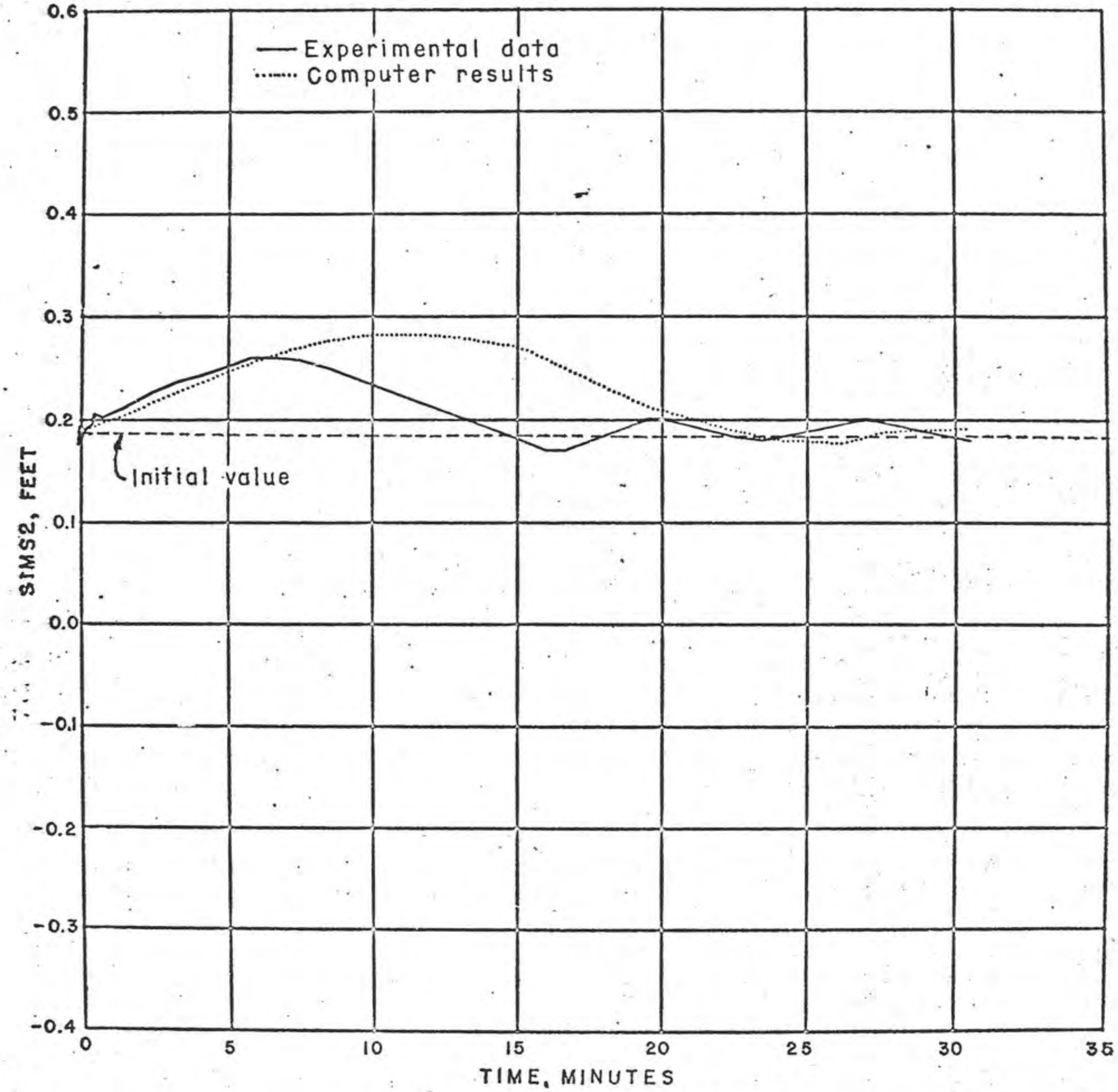

FIGURE 9, SIMS2 VERSUS TIME

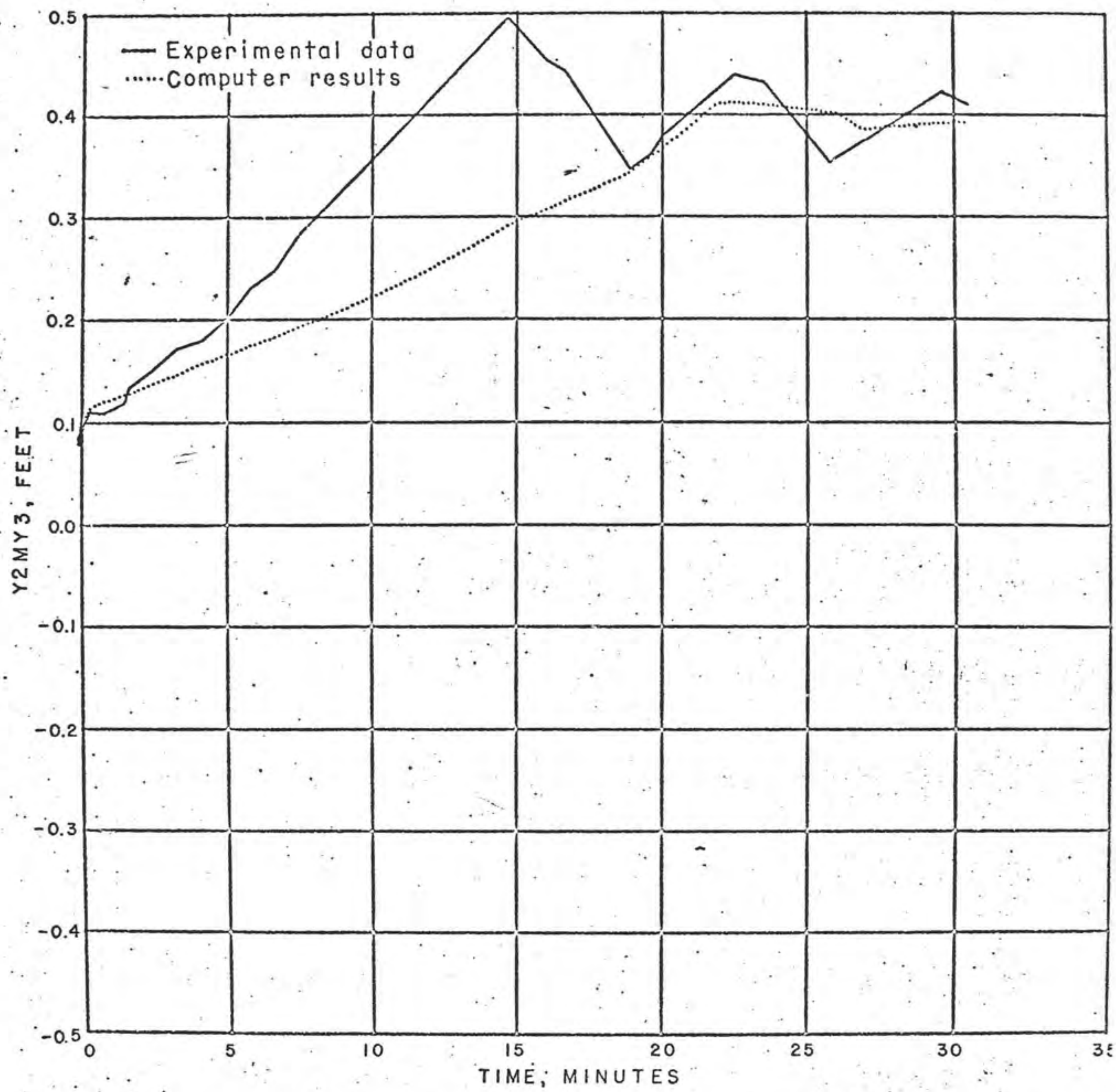

FIGURE 10, Y3MS3 VERSUS TIME

The results for the control gate opening, B2, are shown in Figure 11. The calibration data for the orifice and control gates were collected and presented in graphical form by Russell Dodge. Because of the way the computer program was written, these results had to be put into another form before they could be used; these transformations could be the source of errors. An important fact apparent from Figure 11 is that the initial computed control gate opening does not agree with that which existed experimentally. This implies that the initial data for one or both gates are incorrect and/or the data transformations are not warranted. This error could and probably does have a detrimental effect on all succeeding results. The rates of gate movement which can be gleaned from the slopes of the lines in Figure 11 for both the experimental data and the computer results appear to be the same. This is as it should be because the actual rate of gate movement was measured, and it is this value which was used by the computer when it moved tha gate. It is encouraging to note from Figure 11 that the gate starts to move in the model and in the computer at about the same time. The hunting which could only be implied previously is depicted in no uncertain terms by the experimental data line. The computer also hunts, but it is difficult to talk about its periodicity. After about 20 minutes, the magnitude of the hunting in both the model and computer appear to be almost equal, about 0.020 foot. In fact, all the graphs, Figures 6-11, indicate that the differences between the experimental data and the computer results after 20 minutes are quite acceptable. It almost seems too good to be true, but perhaps it took the computer 20 minutes to overcome the initial discrepancy regarding the gate opening shown in Figure 11; a run of longer length would have tended to refute or substantiate this thought.

The variable QRAT represents the ratio of the actual discharge to the initial discharge, Figure 12. Only the computer results are plotted because experimental data were not collected. Although no comparison can be made between the experimental data and the computer results, an interesting fact is brought out by this figure which lends some credence to the recent conjecture regarding 20 minutes. After 20 minutes, QRAT seems to vacillate about a value of one as it should for a hunting gate which is operating properly.

Summary, Conclusions, and Recommendations for the Computer Program

Summary, conclusions, and recommendations relative to the computer program are as follows:

STLWL3 - 1. The stilling well computer results agree very well with the experimental results upon the introduction of a resistance modification factor of 1.65.

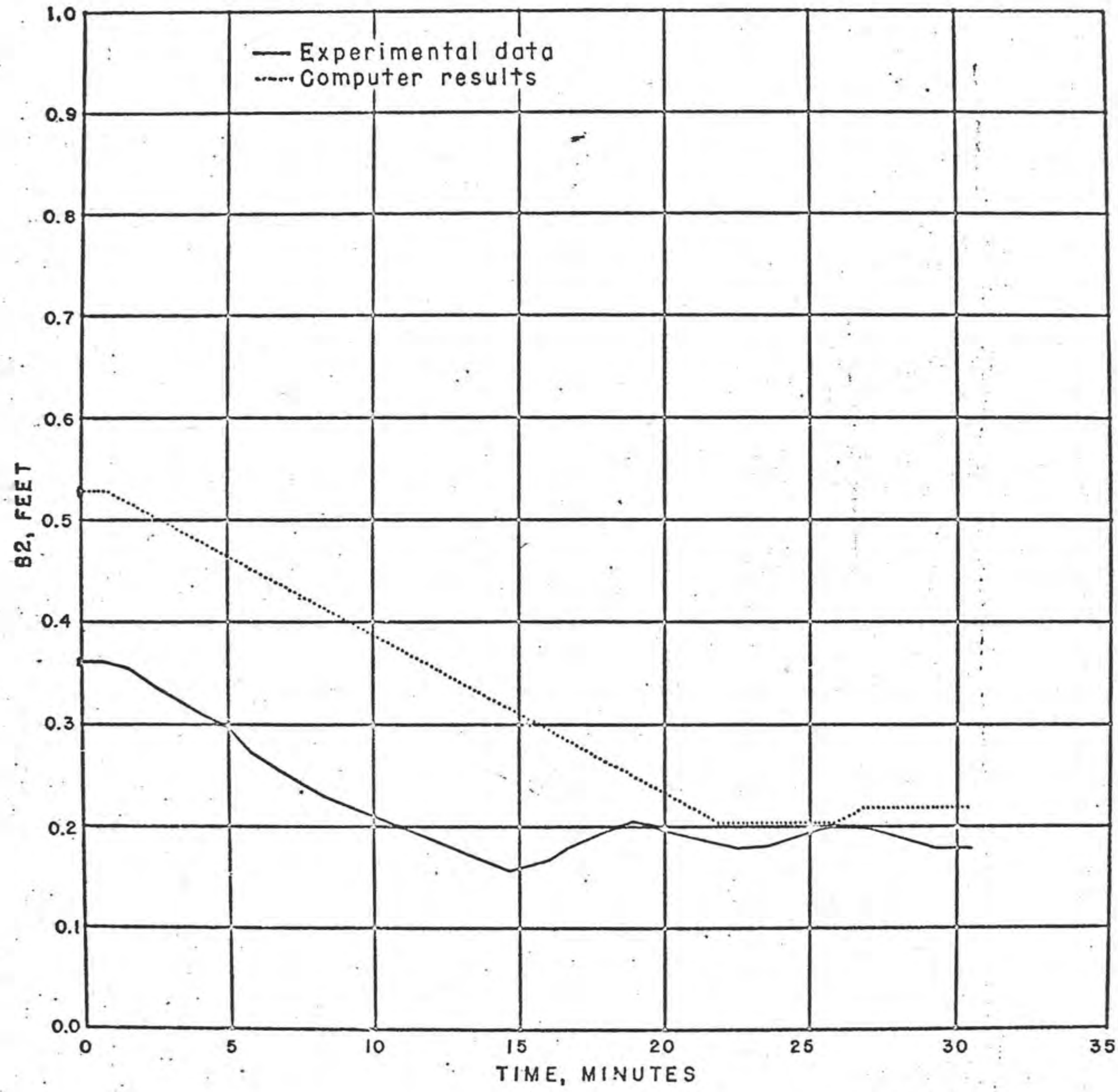

FIGURE 11, B2 VERSUS TIME

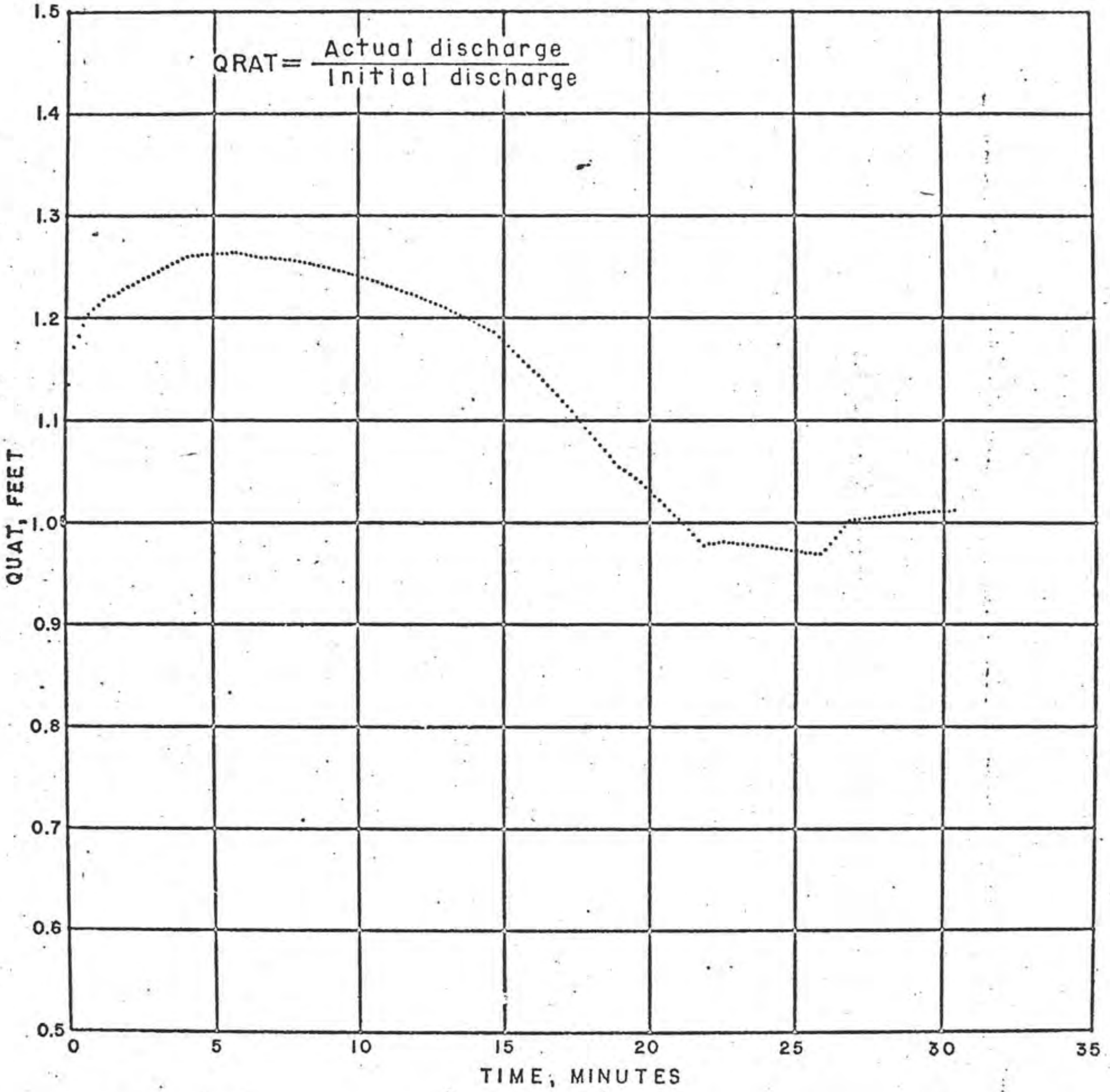

FIGURE 12, QRAT VERSUS TIME

2. The stilling well responses appear to be very sensitive to changes in the rate of change of the water level being monitored as evident by Figures 4 and 5. This point should be kept in mind when collecting data.

CHO2 - In general the correspondence between the computer results and the experimental data can be considered to be fairly good in light of the outright discrepancy in the discharge relationship for one or both gates, Figure 11. The difference between the experimental data and the computer results are due to one or more of the following factors:

1. In setting forth the behavior of some aspects of of the system, certain simplifying assumptions were made in the computer program. These may be incorrect or may have to be made more precise.

2. Logical errors could exist in the program. Aside from an outright logical error as the agreement between the experimental data and the computer results is improved, it may become desirable in the interest of furthering this improvement to modify some of the logical approaches. The possibility of doing this will only become apparent through close monitoring as the investigation is continued. The program should be proved further because lack of time prevented much of this.

3. There may be outright errors in some simple numerical procedures in the program. Close scrutiny of the program and of the 30 items of output information from it might uncover deficiencies of this nature.

4. The discharge relationship for the orifice gate may be in error and should be checked. There is a marked difference between this curve and that used for field installations. In addition, the data should be collected in such a fashion that they are exposed to as little manipulation as possible before insertion into the computer.

5. The discharge relationship for the control gate may be in error. Here again it would be best if the data were collected in a form which is easily handled and manipulated by the computer.

6. The depth Y1 may not have been read with sufficient accuracy.

7. The pressure transducers, amplifiers, and the recorders malfunctioned. Most of this can be overcome through replacement, repair, and procedural techniques.

8. Characteristics of the switches may not have been accurately determined and the switches may have been set improperly.

At this point the sensitivity of the CHO to changes in any of the variables is unknown. As a consequence, the accuracy to which quantities must be measured and the tolerance to which the equipment must be set is unknown. Some of this may have to be very precise while much less stringent conditions may be satisfactory for other things in order to achieve a satisfactory correspondence between the experimental data and the computer results. The required order of accuracy of things will only become apparent as the correspondence between the experimental data and the computer results is improved.

CRITERIA ESTABLISHMENT

Because the first objective of the problem was not fully met, it was impossible to proceed to the second. It is firmly felt that the first objective can be achieved. After this, work on the second objective can be initiated. The behavior of the CHO could be judged to be satisfactory or unsatisfactory on the basis of Figures 7, 11, and 12. This second objective represents a very complex but interesting problem; its solution should be of great practical value. At this point it is difficult to envision the interacting effects of the numerous independent variables. Variables or conditions which would affect the behavior of the system are:

1. The rate of change of Y1 and the length of time over which it occurs
2. Whether the control gate is in the submerged, transitional, or free-flow state
3. The size and discharge characteristics of the control gate
4. The size of the orifice well
5. The relative sizes of the pipes of the stilling wells
6. The magnitude of the dead zone in the switching gear and the magnitude of the "on-off" play in the switches
7. The rate of gate movement up and the rate of gate movement down

GENERAL RECOMMENDATIONS

As a result of this investigation, the following recommendations are made:

1. The objectives of this investigation are good, realistic, and attainable; they should be carried to fruition. The meeting of the first objective will mean the successful simulation by computer of a great many interacting hydraulic effects. In addition it will invalidate or substantiate the approaches used in coping with various aspects of unsteady flow; information about this would be of value to the engineering profession. The meeting of the second objective will result in the development of a practical structure which will find increased need as we move from the slow-acting hand-controlled systems of the past and present to the rapid responding automatic systems of the future. This study may also demonstrate that it is less expensive to simulate a complex system on the computer than by means of a hydraulic model.

2. The resistance for unsteady flow is uncertain; for lack of good information it is taken to be equal to that for steady flow. Unsteady flow occurs in situations such as:

   a. Stilling wells
   b. Hydraulic actuators
   c. Dash-pots
   d. Hydraulic switching devices
   e. Open channel flow

   If unsteady flow resistance is 1.65 times that for steady flow, this fact would be of great interest to the engineering profession. This should be investigated. The amount of effort involved in confirming this would not be great.

3. The CHO can act in the submerged, transitional, and free-flow modes. One of the three cases should be solved successfully before proceeding on to the other two. The cases in order of increasing difficulty are thought to be free flow, submerged flow (the situation programed in CHO2), and transitional flow.

4. If knowledge is not already available about the variation of Y1 with time, it may be well to initiate immediately a program to collect information so that realistic conditions under which the CHO might be expected to operate could be established.

5. In pursuing the objectives of this investigation, it would be well to have a single person perform or be responsible for both the computer and the experimental work. This would insure compatibility between the two.

Appendix A

STLWL3

Appendix B

CH01

Appendix C

CHO2