HYDRAULIC MODEL STUDIES

OF THE SANTA ROSA TURNOUT TUCSON AQUEDUCT

CENTRAL ARIZONA PROJECT

by

K. W. Frizell

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Memorandum

To: Construction Engineer, Phoenix, Arizona
Attention: 330-2470/Contreras

From: Acting Chief, Research and Laboratory Services Division

Subject: Hydraulic Model Study - Santa Rosa Turnout - Tucson Aqueduct - Central Arizona Project, Arizona (Your Letter Dated September 7, 1988) (Hydraulic Research)

As requested in your letter, we have prepared a final report entitled "Hydraulic Model Studies of the Santa Rosa Turnout, Tucson Aqueduct, Central Arizona Project" (enclosed). A copy of video taken during the tests will be sent directly to Mr. Paul Contreras of your office.

The report will be submitted as a GR (General Research) report and will be published through the Denver Office. At that time, additional copies will be sent to you.

Again, reiterating the findings summarized in the previous report dated June 29, 1988, the flow conditions in the outlet tubes at Santa Rosa are typical of turbulent pipe flow. The observed hydraulic performance of the model does not explain the large fluctuations indicated by the ultrasonic flowmeters in question.

DeWayne O Campbell

Enclosure

cc: Regional Director, Boulder City, Nevada, Attention: LC-200 (w/o encl)
Project Manager, Phoenix, Arizona (w/o encl)

bc: D-3750 (w/encl)
D-3750A (w/encl)
D-3751 (file) (w/encl)
D-3752 (w/encl)

WBR:KWFrizell:flh:10/5/88:236-6156
(Misc.corresp.3752:017)

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K.W. Frizell

Hydraulics Branch
Research and Laboratory Services Division
Denver Office
Denver, Colorado

October 1988

ACKNOWLEDGMENTS

This study was conducted with the cooperation of Mr. Paul Contreras, Arizona Projects Office, Phoenix, Arizona. The funding for the study was provided by the APO.

CONTENTS

TABLES

FIGURES

CONTENTS--Continued

PURPOSE

Hydraulic tests were performed to study the flow conditions in two of the barrels of the Santa Rosa Turnout structure. Santa Rosa and several smaller turnouts on the Central Arizona Project (CAP) have experienced erratic readings on their permanently installed, four-path ultrasonic flowmeters. Large fluctuations in discharge (± 40 percent) have been noted since the turnouts have been in service. Questions have arisen concerning the hydraulic characteristics of these turnout structures and whether some flow related phenomena are responsible for the discharge fluctuations presently being measured.

INTRODUCTION

The Santa Rosa Turnout is located on the Tucson Aqueduct, CAP, Arizona, figure 1. It features an intake structure off the main canal with seven individually gated barrels (7-ft diameter), a four-path ultrasonic flowmeter on each barrel, a common weir chamber at the end of the barrels, and finally seven short barrels leading into a distribution canal, figure 2. In addition to the Santa Rosa turnout, there are several other smaller turnout structures on the CAP which incorporate similar designs.

Unreliable operation and output from the ultrasonic flowmeters has been a concern since the flowmeters were first installed. Readings from the flowmeters are responsible for tracking water deliveries and ultimately for billing the water users.

Two flowmeter manufacturers are responsible for the flowmeters on all the CAP turnouts. One type of flowmeter has given acceptable results while the other type has been inconsistent. The manufacturer attributes the poor performance to a flawed hydraulic design. They claim that their meters are truly representing the actual flow. The Hydraulics Branch, Research and Laboratory Services Division, Denver Office, was requested to undertake a physical model study of two of the barrels on the Santa Rosa Turnout by the Arizona Projects Office. The purpose of the model study was to determine the actual flow conditions in the Santa Rosa turnout and, if necessary, to determine what modifications could be made to improve the flow conditions.

SUMMARY AND CONCLUSIONS

- All operations at normal conditions yielded satisfactory hydraulic performance. Model results did not indicated the large discharge fluctuations which are presently being recorded by the flowmeters at the prototype installations.

- Velocity profiles measured at the meter locations in the model showed some skewness, most notably due to tailwater effects. However, the profiles remained consistent with time for a given flow condition.

- Discharge fluctuations measured by monitoring storage in the model and inflow, revealed results which were within ± 0.6 percent of the set point.

- Operation of the sluice gate at very small openings caused noticeable secondary currents and flow reversal directly downstream from the gate. These effects were not prevalent at the downstream metering station however.

- Formation of an air cavity behind the sluice gate at small openings and high heads causes entrainment of air bubbles in the barrels. The amount of air may be significant enough to effect flowmeter readings especially on the upper path.

HYDRAULIC TESTS

The Model

The hydraulic tests were carried out in the Hydraulic Laboratory of the Research and Laboratory Services Division. Two barrels of the Santa Rosa Turnout were modelled in a 1:7.385 Froude based scale model. Froude numbers in the model and prototype were chosen to be equal:

$$\frac{U^2}{gL}_m = \frac{U^2}{gL}_p$$

This insured dynamic similarity for a geometrically similar model due to the influence that the free surface (gravity forces) has on the hydraulics of the turnout. With a geometric or length scale of 1:7.385, the velocity ratio and discharge ratio were 1:2.718 and 1:148.21 respectively.

The model included a portion of the intake, the wall mounted sluice-type gates, the barrels in which the ultrasonic flowmeters are installed, and two bays of the common weir chamber all the barrels empty into. Baffle walls were located in this chamber to insure that the barrels remain full of water and a slide gate was placed on the end of an additional 35 feet (prototype) of conduit downstream from the chamber to control the tailwater level, figure 3. Details of the models' major features are shown in figures 4-8.

Test Procedure

The typical test procedure involved setting a discharge and adjusting the control gates and the downstream slide gates to give the desired headwater and tailwater elevations. When a steady state was achieved, the measurements and observations were made. These included velocity profiles, discharge measurements, headwater fluctuations and observations of the basic hydraulic performance. A synopsis of the test runs made is shown in Table 1. The first 12 runs were at normal operating conditions, while the second group of runs were at a head elevation of one foot below the top of canal lining.

Instrumentation and Measurements

Velocity profiles were measured at two locations; 1) 2.5 diameters downstream from the control gates, and 2) at the centerline of the ultrasonic flowmetering station. The measurements were made with a pitot-static tube connected to a differential pressure transducer, figure 9. The transducer output was passed through a digital low-pass filter, set with a cutoff frequency of 30 Hz. This filter effectively reduced the 60 cycle noise as well as the carrier frequency of the amplifier (3400 Hz). The filtered output was input to HP 3457A Multimeter. A sample of 100 points, acquired at a rate of 60 per second, were taken at eleven points on each of four diametrical traverses, figure 10. The multimeter stored the mean, minimum, maximum, and standard deviation of each data sample. These data were then used to evaluate the shape and steadiness of the velocity profile. Profiles at the station 2.5 diameters downstream from the control gates were sometimes impossible to measure with this system due to unsteadiness and flow reversal, figure 11.

Measurement of the discharge fluctuations was done by recording flowrates through a venturi meter along with head levels in the model headbox. The flowrate fluctuations were recorded from a pressure transducer placed across the venturi meter which was input to a PID controller used to maintain steady discharges to the model, figure 12. The head level fluctuations were measured with a capacitance-type wave probe, figure 13. With the combination of the flow into the model and storage in the model, the discharge fluctuations could be calculated.

TEST RESULTS

Velocity Profiles

Velocity profiles corresponding to test runs 1-12 are shown on figure 14 a-l. These plots indicated the mean profile along the vertical path as well as the absolute minimums and maximums collected at each location. The basic shapes of the profiles are typical for turbulent pipe flow, with point velocity fluctuations of reasonable magnitude. Due to the relatively large model (1:7.385), modelling of the turbulent velocity fluctuations in the pipe is quite good. At scales this large, viscous (Reynolds number) effects are minimized. The flow has not yet reached a fully developed stage, but when a theoretical profile based on the power law is overlaid onto the measured profiles and corrections for the hydrostatic pressure distribution is made, they match quite well, figure 15. There is a maximum fluctuation in point velocities measured of approximately 15 percent. However, even with this fairly large variation in point velocities, the discharge fluctuations show almost no variation.

Discharge Fluctuations

Since the velocity profile data were not conclusive in describing the actual fluctuations in discharge, these were measured as previously discussed. Not all test conditions were repeated for these measurements due to the repeatability of the few which were tested. The discharge fluctuations were evaluated by measuring the head fluctuations in the headbox and also mointoring the actual inflow to the model. If the discharge through a gate is evaluated by:

$$Q = C_d A_g (2g\Delta H)^{1/2}$$

where: C_d = coefficient of discharge
A_g = area of the gate opening
g = gravitational constant
ΔH = head drop across the gate

In this equation, only the head will fluctuate. This fluctuation in head can be translated into a fluctuation in discharge. However, the variation in the flowrate delivered to the model through the venturi meter has a larger error than that attributable to the fluctuating head. Table 2 shows the test conditions under which discharge fluctuations were measured along with the value and an estimate of the uncertainty.

DISCUSSION

Many factors can effect the performance of an ultrasonic flowmeter. Skewed velocity profiles and air entrainment are two of the most common. The flowmeter essentially solves the equation:

$$Q = \iint v\,dx\,dy$$

where v = axial velocity at one point in the pipe
Q = total flow in the pipe
x,y = axes perpendicular to flow in the pipe

The inside integral, vdx, is solved for by making an acoustic measurement with high frequency transducers. A pair of transducers are placed on opposite sides of the pipe at an angle of 65° to the pipe axis. Transducer #1 (upstream) sends a pulse downstream where the signal is picked up by its pair, transducer #2, and then sent on to a receiver. A signal is then sent in the reverse direction, from transducer #2 to #1. The difference in time between the transmit and receive pulse is measured by a microprocessor and is related to the velocity by the following equation:

$$v = \frac{L_p \Delta T}{2\, T_{1\text{-}2}(T_{1\text{-}2} + \Delta T) \cos \phi}$$

where L_p = path length
$T_{1\text{-}2}$ = travel time in water of a pulse from transducer #1 to transducer #2
ΔT = difference in travel time between upstream and downstream direction of pulse
ϕ = angle of path to pipe axis

In order to integrate the velocity in the y-direction, multiple pairs (paths) of transducers are installed in the pipe and are rung in turn by a transceiver. Typically, four paths are used, providing four average velocities at specified locations in the y-direction over the diameter of the pipe. By spacing the paths correctly, the Gaussian Quadrature technique of numerical integration can be used:

$$Q = \iint v\,dx\,dy = \int (v_p L_p \tan \phi)\, dy$$

$$= D \sum_{n=1}^{4} W_n v_{pn} L_{pn} \tan \phi_n$$

where W_n = Gaussian weighting constants
n = path number
v_p = average component of axial velocity along the path
D = average diameter of the pipe

Typically one hundred valid samples of downstream transit times and one hundred valid samples of upstream transit times are collected and used to compute an average discharge Q, over a period of approximately 15 seconds.

Gate Effects

Gate operation can effect the performance of an ultrasonic flowmeter in so much as the velocity profile can be greatly modified. At Santa Rosa, the wall-mounted control gates at the entrance to the barrels are typically lowered into the flow during normal operation. Due to the gate leaf shape in conjunction with the circular conduit, one should expect strong secondary currents in the form of longitudinal swirl to emanate from the corners where the conduit and gate leaf intersect, figure 16. There is also separation and return flow directly behind the gate. However, at the flowmetering station, an additional 8-diameters downstream, evidence of these effects are not noticeable. Injection of tracer particles at this station yields smooth streaklines, figure 17. The tracing of particles with the flow shows some evidence of weak secondary currents which are probably the main source for the fluctuations in the point velocities reported.

Air Entrainment

The discharge of an air-water-mixture cannot be accurately measured with an ultrasonic flowmeter due to changes in the sonic velocities of the two discrete phases. The gate configuration at Santa Rosa has an air vent pipe directly downstream from the wall-mounted control gate. This air vent can pose a possible means to allow air to be mixed into the flowing water. This fairly large scale model should allow for good representation of the air entrainment due to the gate operation. At normal operating levels, no air was observed entering the barrels. However, at high heads (1 ft below top of lining), an air cavity formed behind the gate at partial openings. This cavity was fed by the air vent pipe and air bubbles were continually breaking loose from the cavity and passing downstream. The air bubbles remained near the top of the pipe due to their size and relative velocity of the flow in the conduit. There was a significant enough amount of air that readings on the upper path of the installed ultrasonic flowmeters might be effected.

In conclusion, there are hydraulic characteristics which can greatly effect the operation of ultrasonic flowmeters in flowing water systems. However, the scale model of the Santa Rosa Turnout did not indicate the same type or magnitude of the discharge fluctuations presently being measured in the field, figure 18.

Run No.	$Q(ft^3/s)$	U.S. Canal El.(ft)	El. over weir(ft)
1	50	1538.83	free flow
2	100	1538.83	free flow
3	225	1538.83	free flow
4	300	1538.83	free flow
5	50	1538.83	5.0
6	100	1538.83	5.0
7	225	1538.83	5.0
8	300	1538.83	5.0
9	50	1538.83	10.0
10	100	1538.83	10.0
11	225	1538.83	10.0
12	300	1538.83	10.0
13	50	1547.83	free flow
14	100	1547.83	free flow
15	225	1547.83	free flow
16	300	1547.83	free flow
17	50	1547.83	5.0
18	100	1547.83	5.0
19	225	1547.83	5.0
20	300	1547.83	5.0
21	50	1547.83	10.0
22	100	1547.83	10.0
23	225	1547.83	10.0
24	300	1547.83	10.0

Table 1: Summary of Test Runs, 5/2/88-6/10/88.

Run No.	Q (ft^3/s)	Head (ft)	$Q_{venturi}$ (ft^3/s)
DF1	299.70	1538.83 ± 0.077	299.70 ± 2.09
DF2	300.24	1538.83 ± 0.068	300.24 ± 1.95
DF3	300.72	1538.83 ± 0.051	300.72 ± 2.41

Average head fluctuation: 0.34 percent of total head on gate.
Average venturi fluctuation: 0.716 percent of set flowrate.

Table 2: Discharge Fluctuation Summary.

Figure 1: Location of the Santa Rosa turnout on the Central Arizona Project.

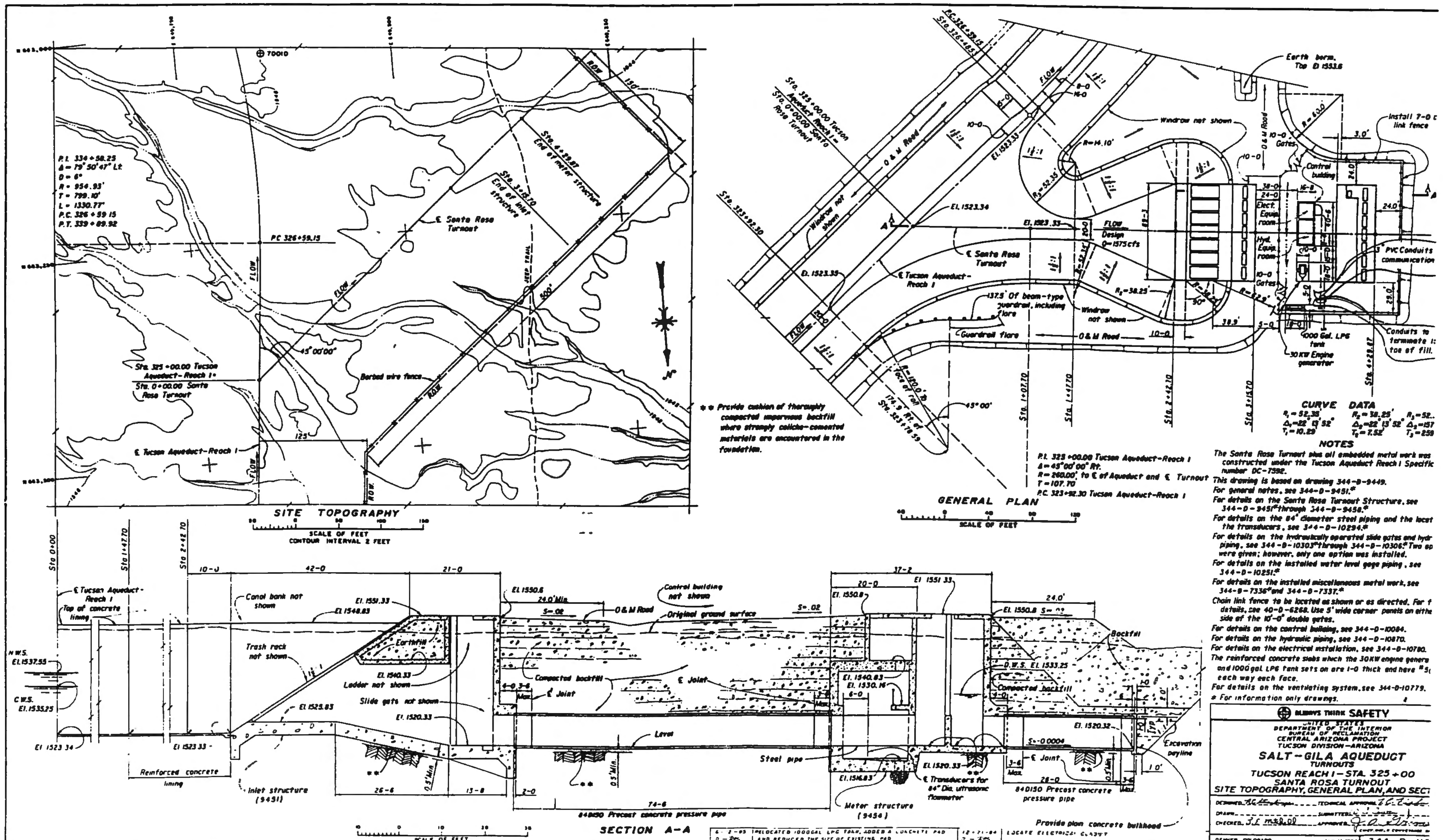


Figure 2: Detail of the Santa Rosa Turnout.

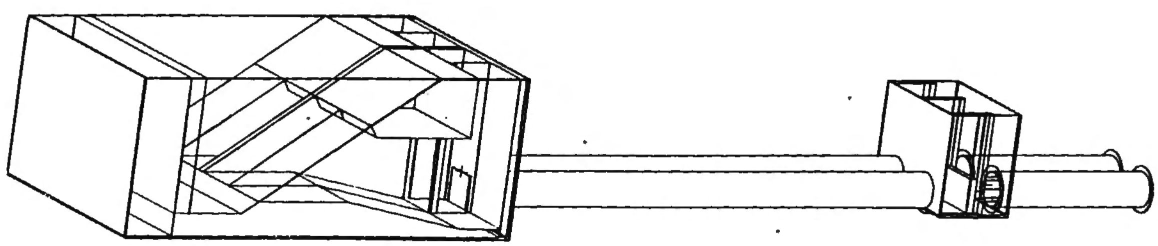


Figure 3: Extents of the 1:7.385 scale hydraulic model.

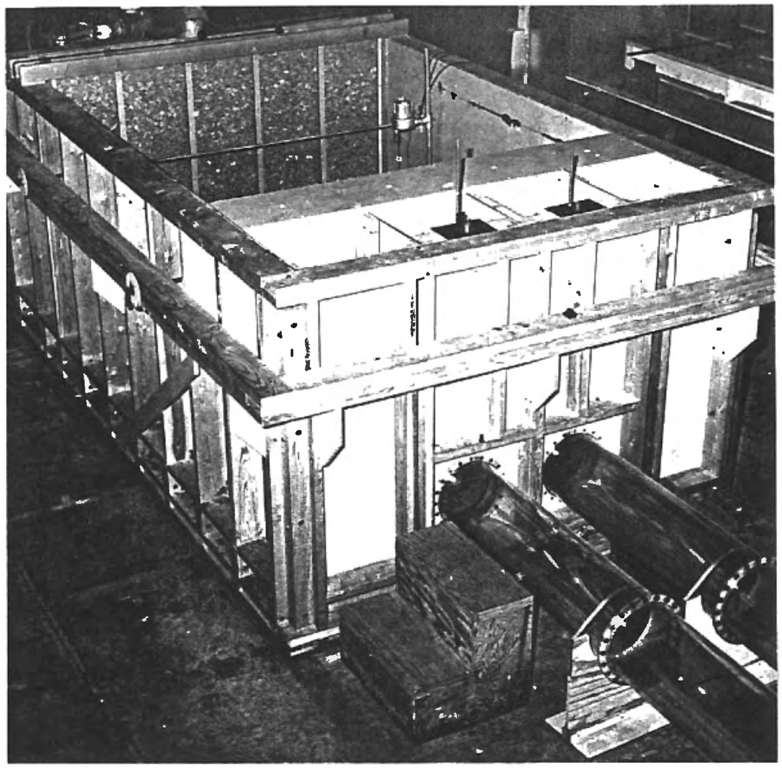


Figure 4: Model headbox, with baffle and two barrel inlets (trashracks not installed).

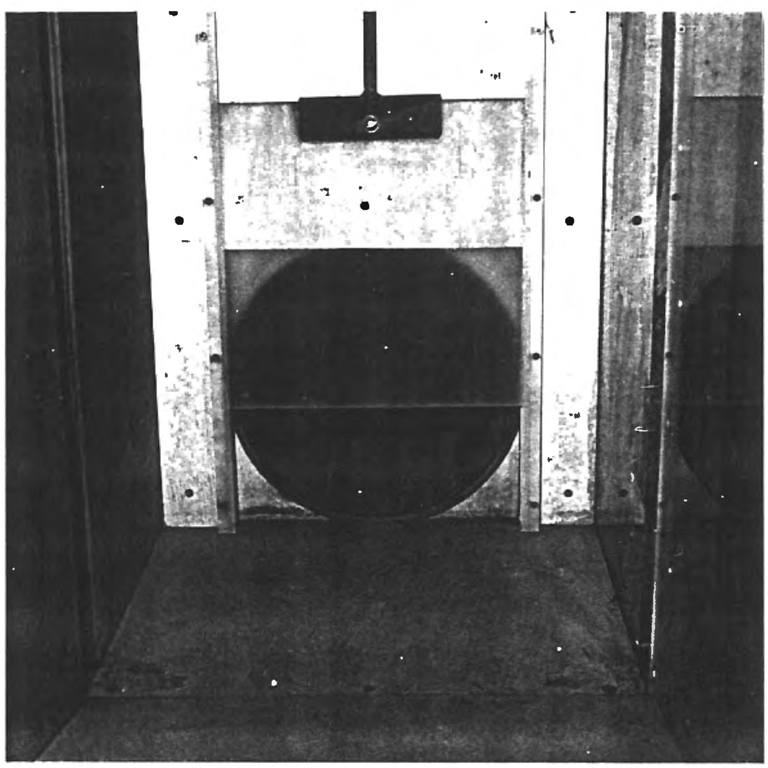


Figure 5: Wall mounted sluice gate.

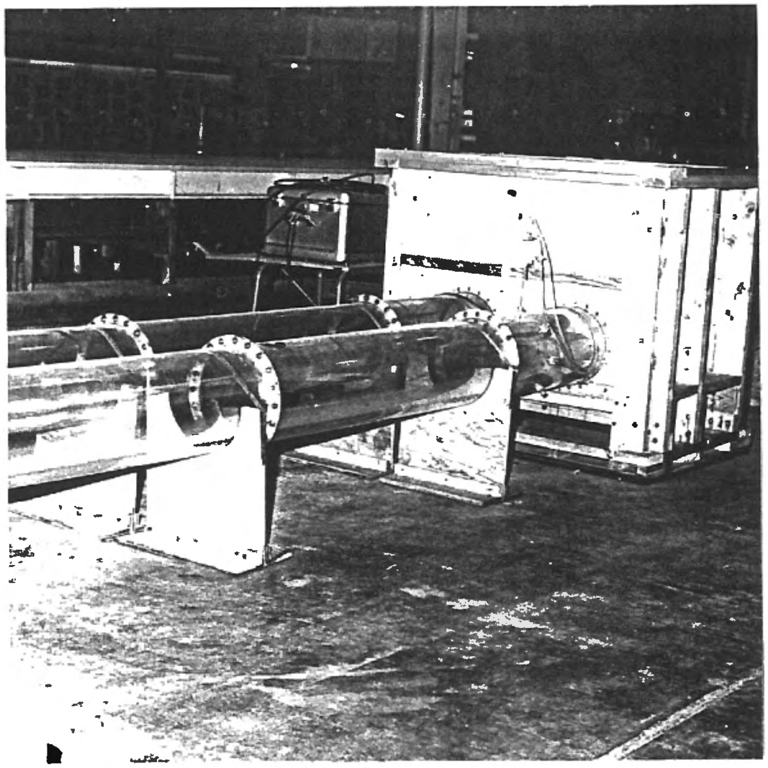


Figure 6: Acrylic plastic pipe (I.D. 11.425 inch) simulating barrels 1 and 2.

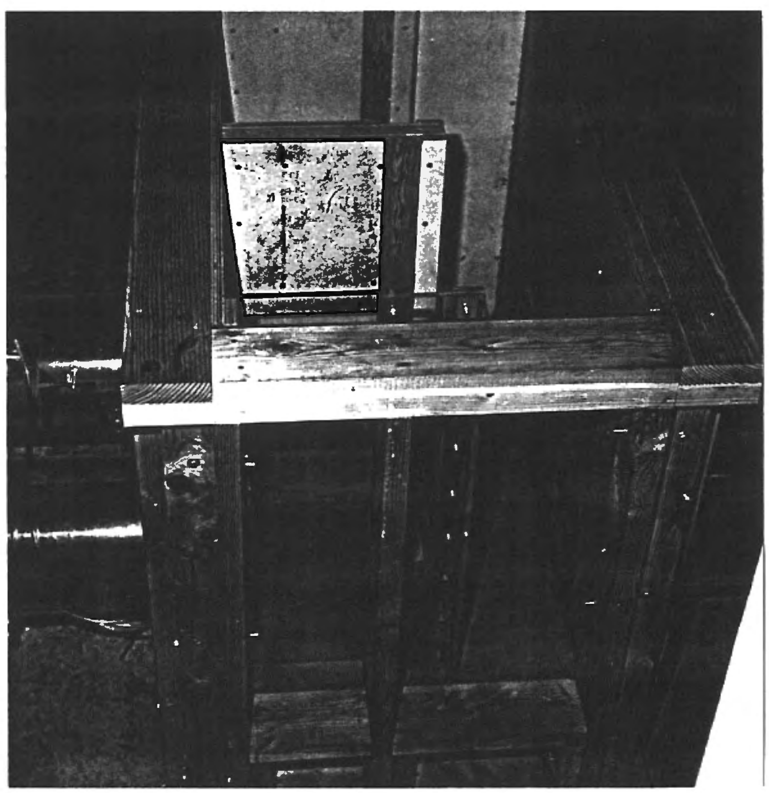


Figure 7: Common baffle weir chamber.

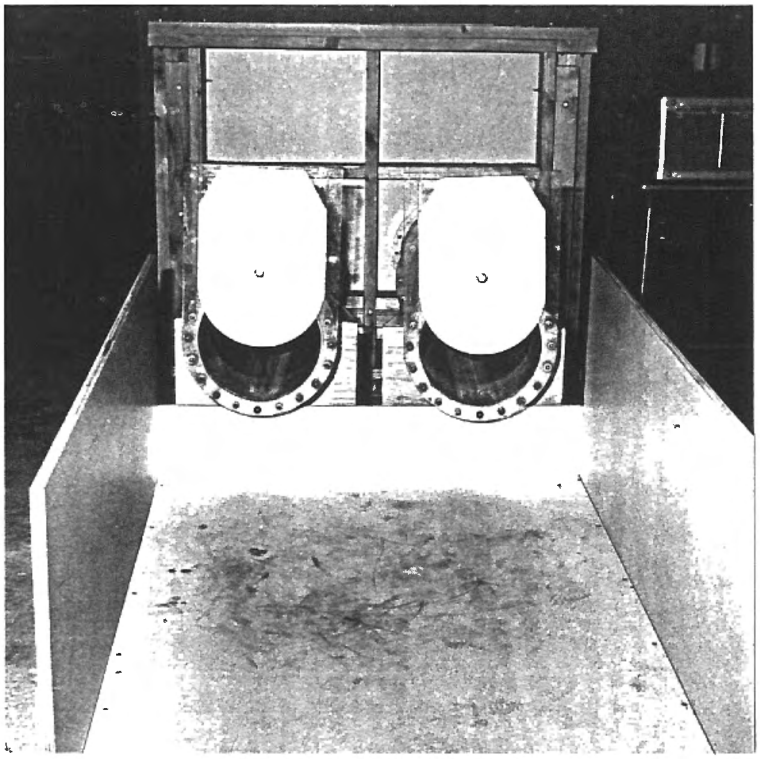


Figure 8: Slide gates used to control tailwater.

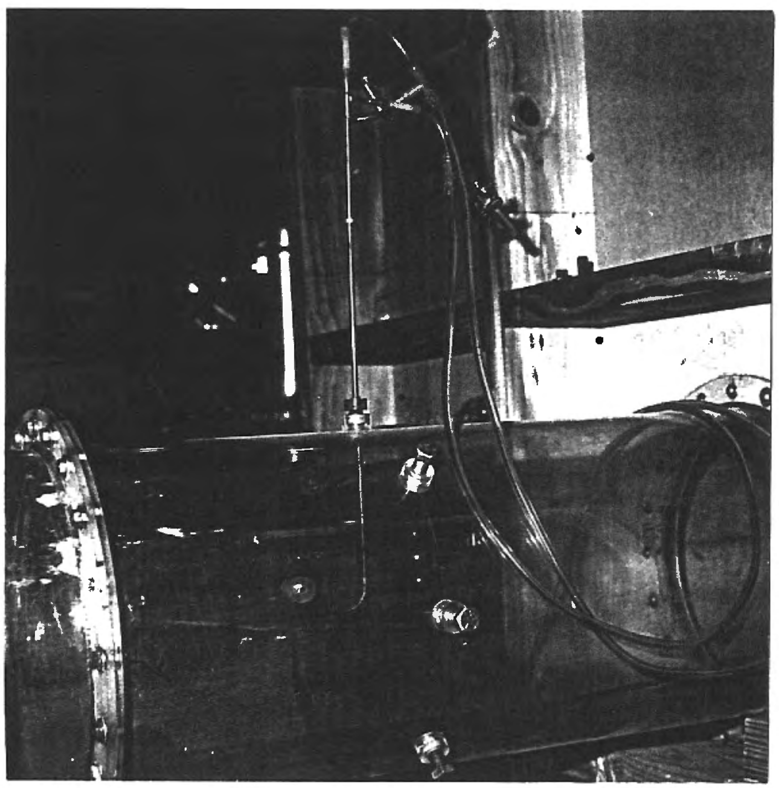


Figure 9: Pitot-static tube used to measure velocity profiles.

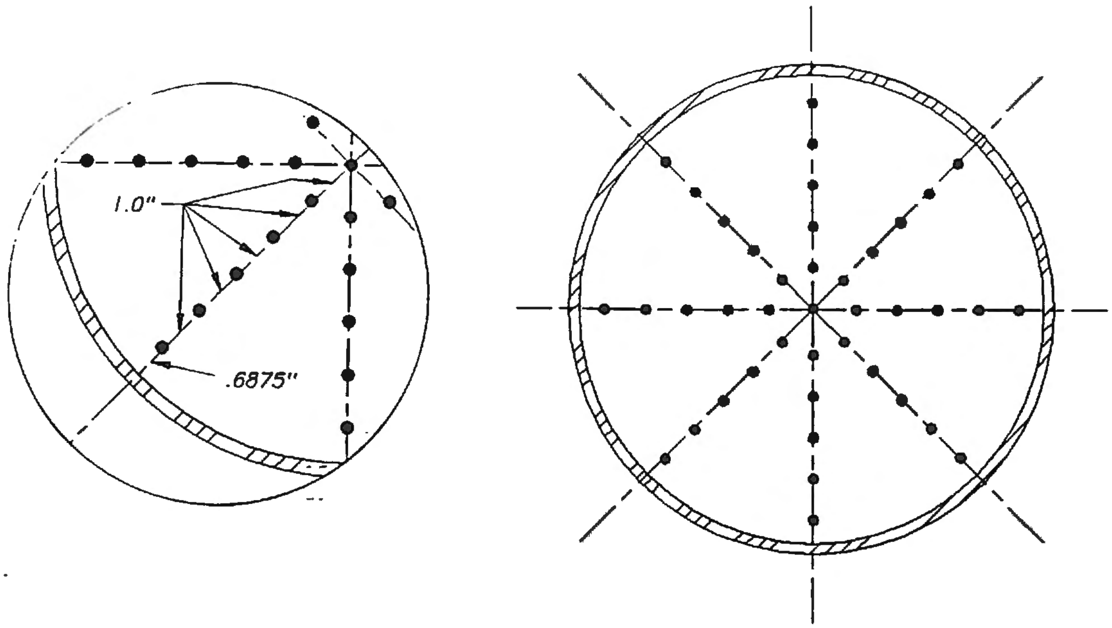


Figure 10: Cross section of barrel showing locations of velocity profile measurements.

Figure 11: Flow reversal at 2.5 diameters downstream of control gate.

Figure 12: Pressure transducer used as input to PID controller.

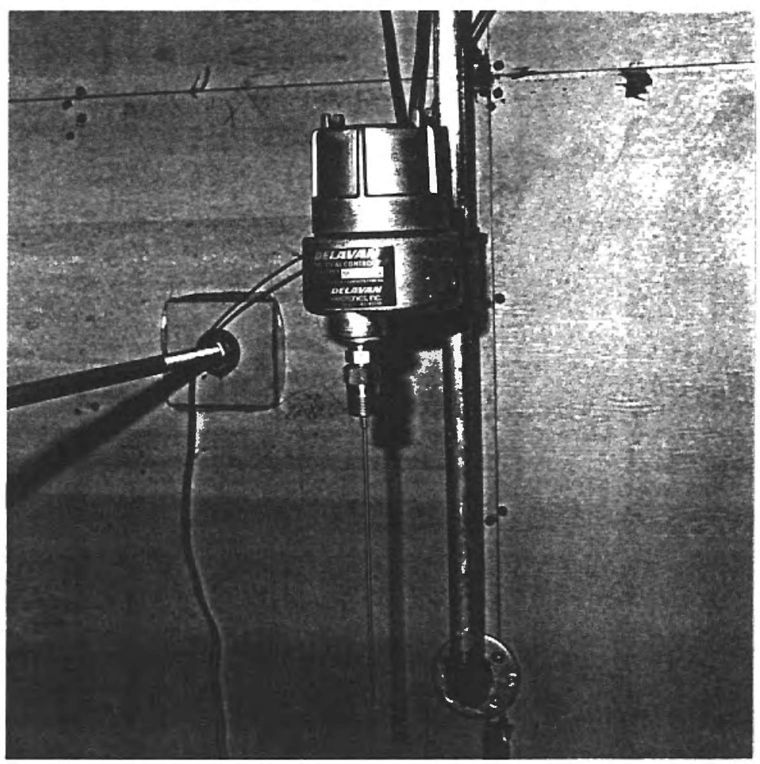
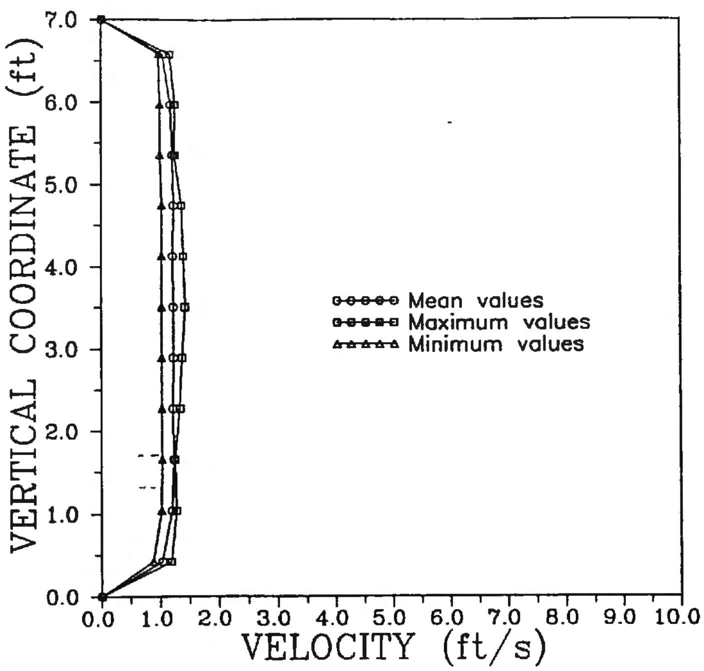
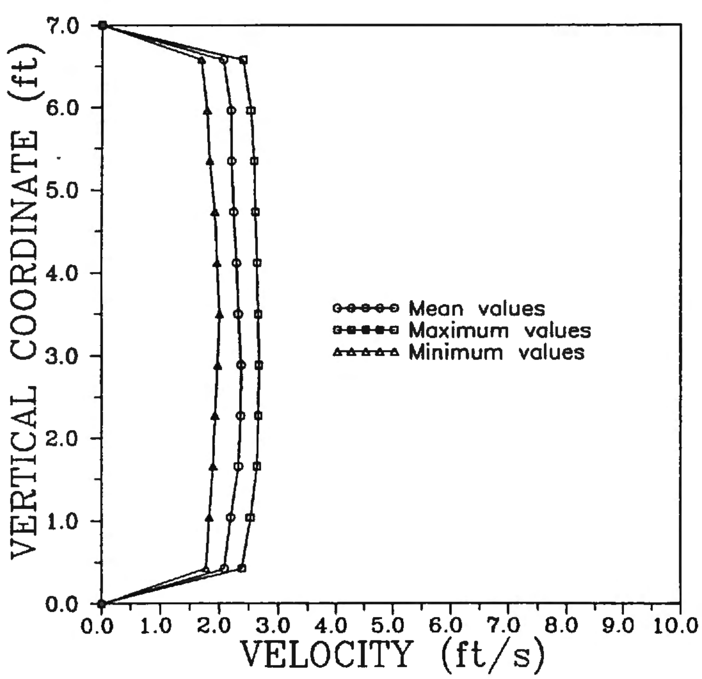


Figure 13: Capacitance-type wave probe used to measure head fluctuations.

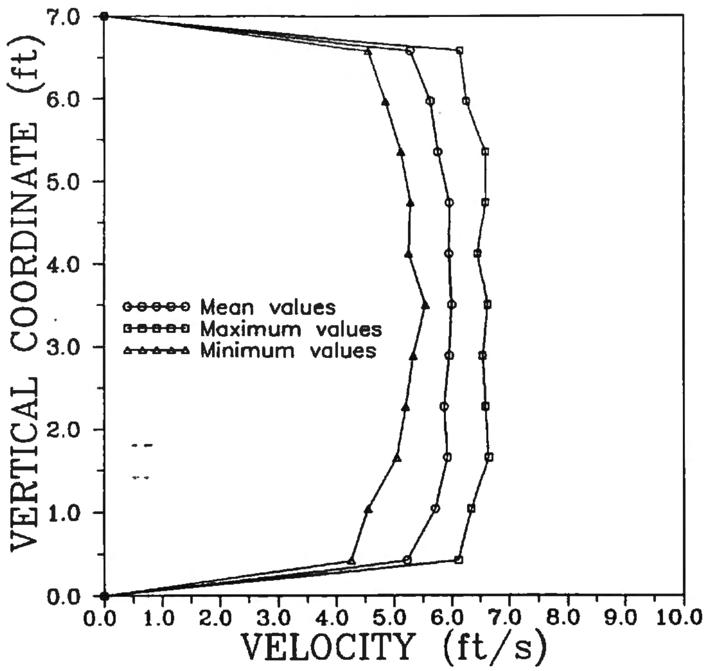


a. Profile for test 1, Q=50 ft^3/s, H.W.=1538.83, free flow.

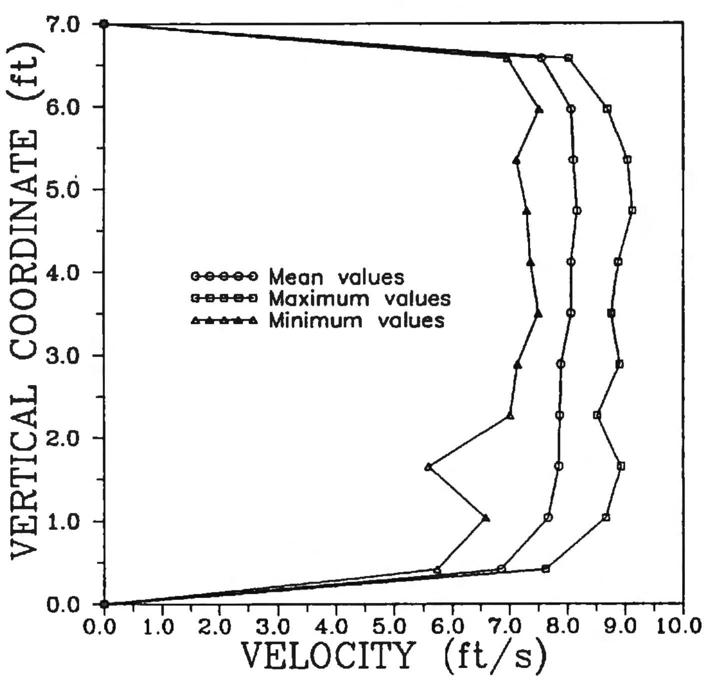


b. Profile for test 2, Q=100 ft^3/s, H.W.=1538.83, free flow.

Figure 14: Profiles along the vertical section of barrel 1.

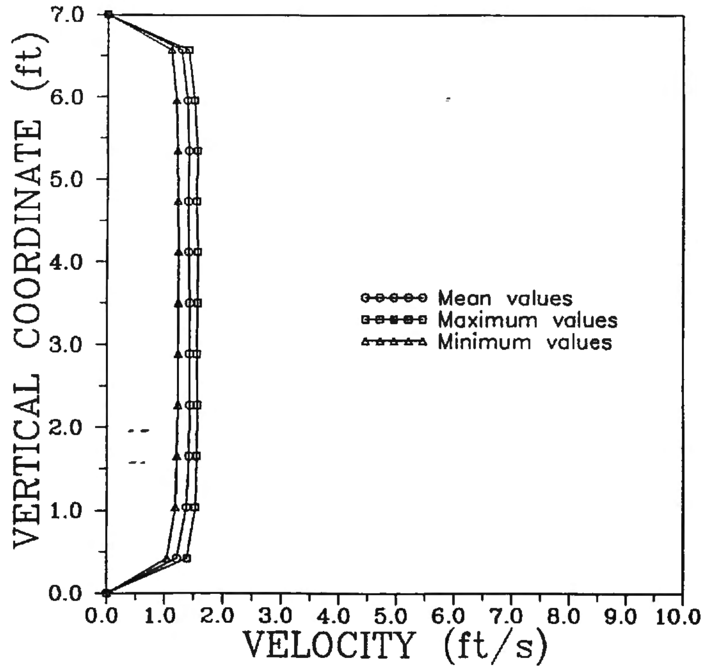


c. Profile for test 3, Q=225 ft³/s, H.W.=1538.83, free flow.

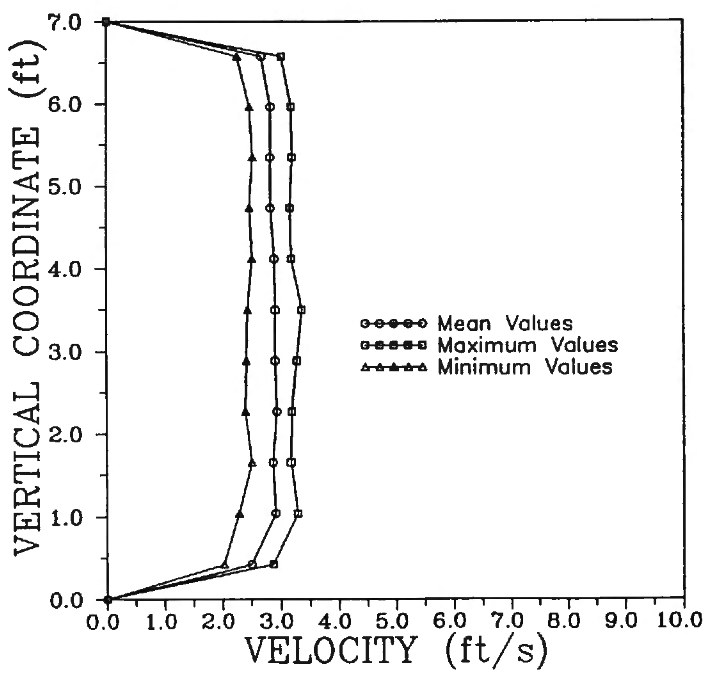


d. Profile for test 4, Q=300 ft³/s, H.W.=1538.83, free flow.

Figure 14: cont.

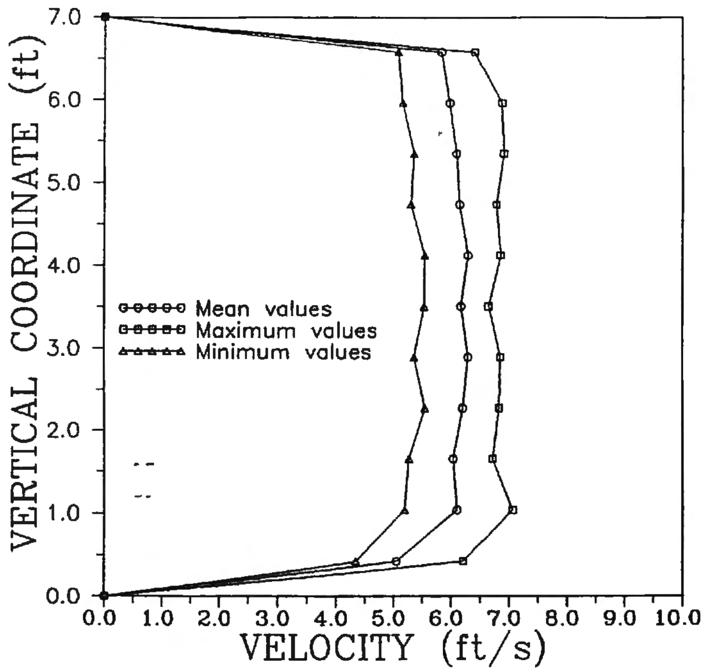


e. Profile for test 5, Q=50 ft^3/s, H.W.=1538.83, 5 ft over weir.

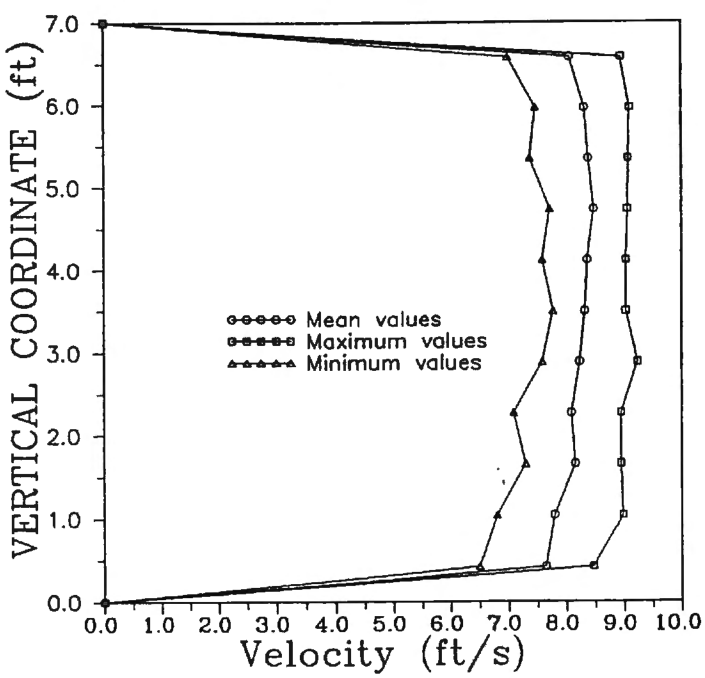


f. Profile for test 6, Q=100 ft^3/s, H.W.=1538.83, 5 ft over weir.

Figure 14: cont.

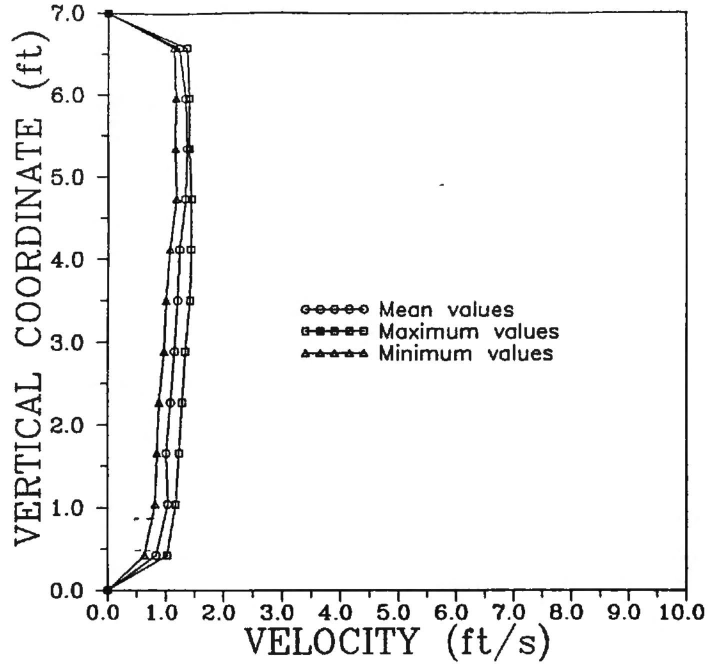


g. Profile for test 7, Q=225 ft^3/s, H.W.=1538.83, 5 ft over weir.

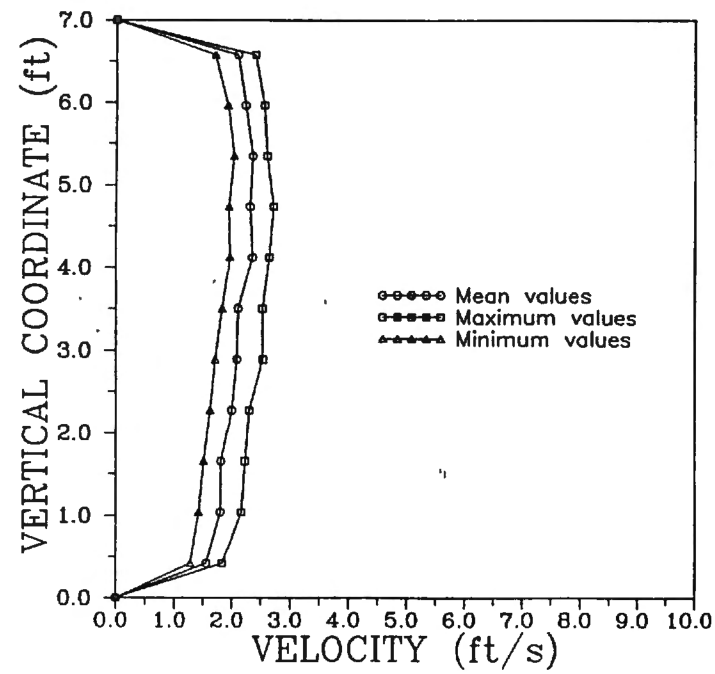


h. Profile for test 8, Q=300 ft^3/s, H.W.=1538.83, 5 ft over weir.

Figure 14: cont

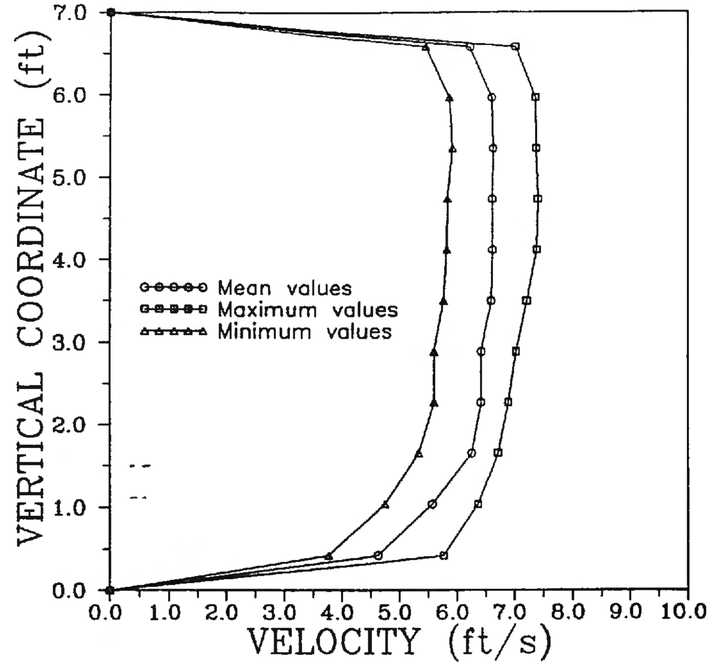


i. Profile for test 9, Q=50 ft³/s, H.W.=1538.83, 10 ft over weir.

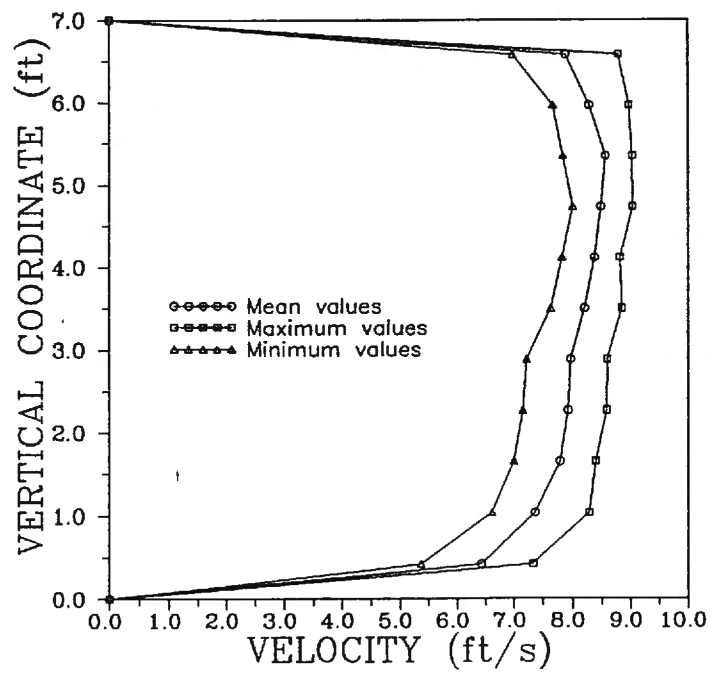


j. Profile for test 10, Q=100 ft³/s, H.W.=1538.83, 10 ft over weir.

Figure 14: cont.



k. Profile for test 11, Q=225 ft^3/s, H.W.=1538.83, 10 ft over weir.



l. Profile for test 12, Q=300 ft^3/s, H.W.=1538.83, 10 ft over weir.

Figure 14: cont.

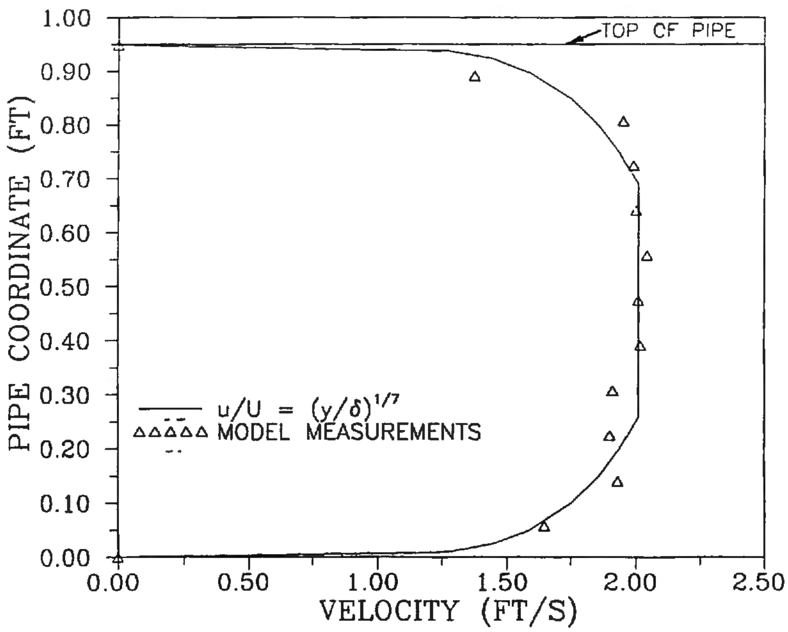


Figure 15: Comparison of measured and theoretical velocity profiles.

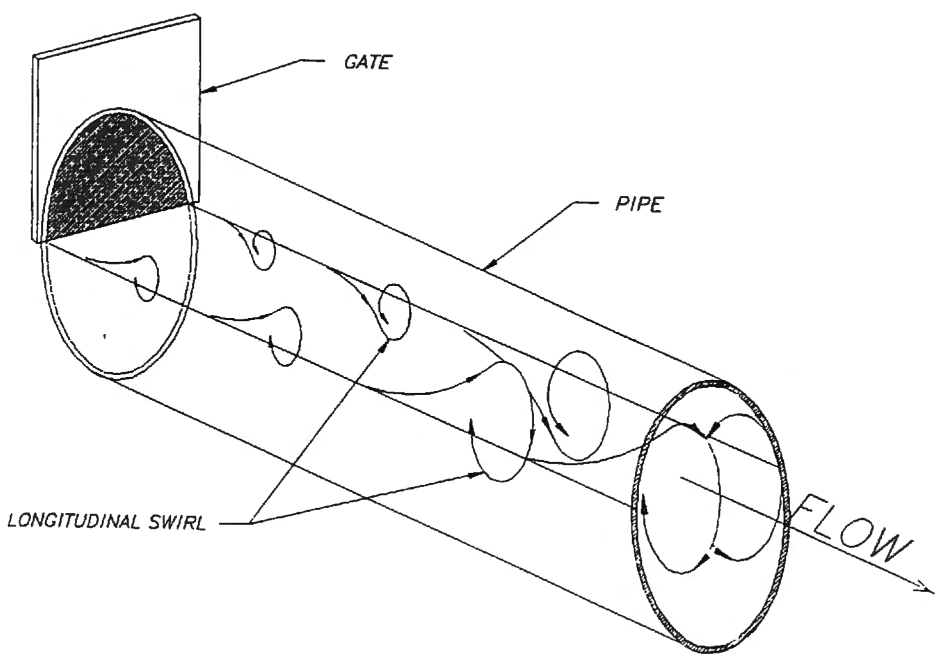


Figure 16: Sketch of longitudinal swirl (secondary current) caused by gate control.

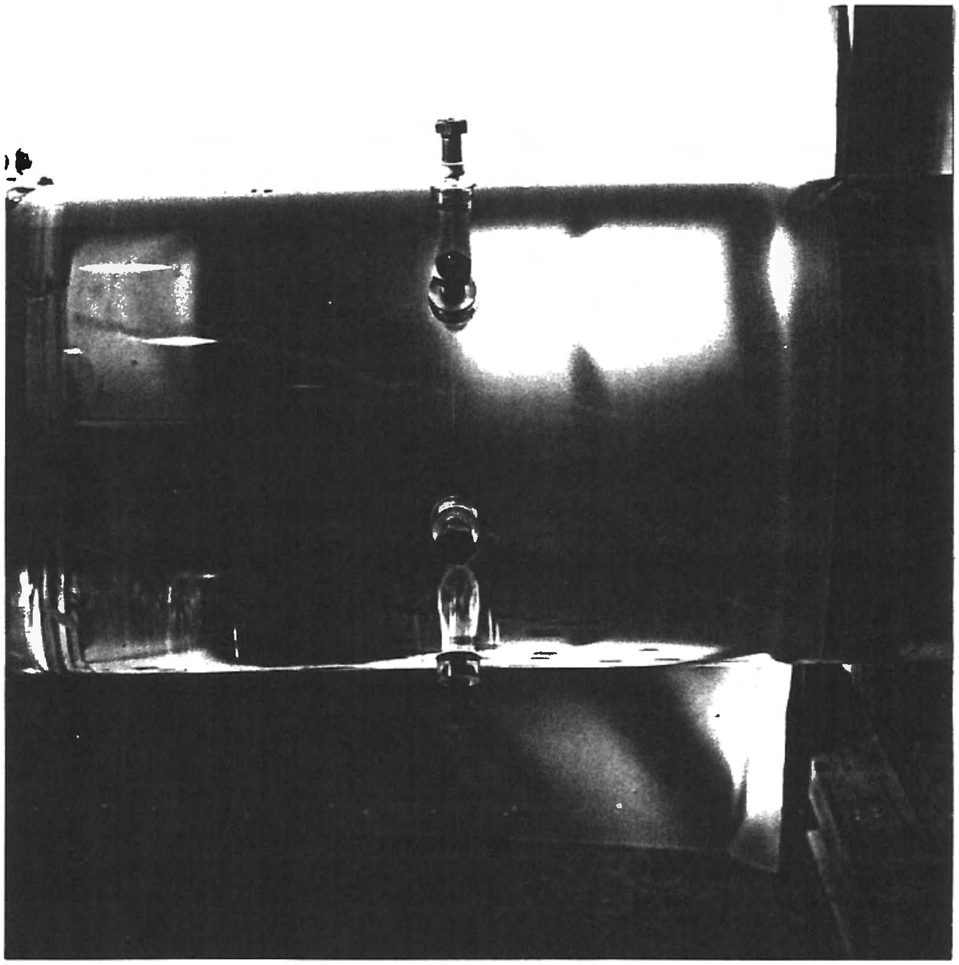


Figure 17: Smooth streaklines at the ultrasonic flowmeter measuring station.

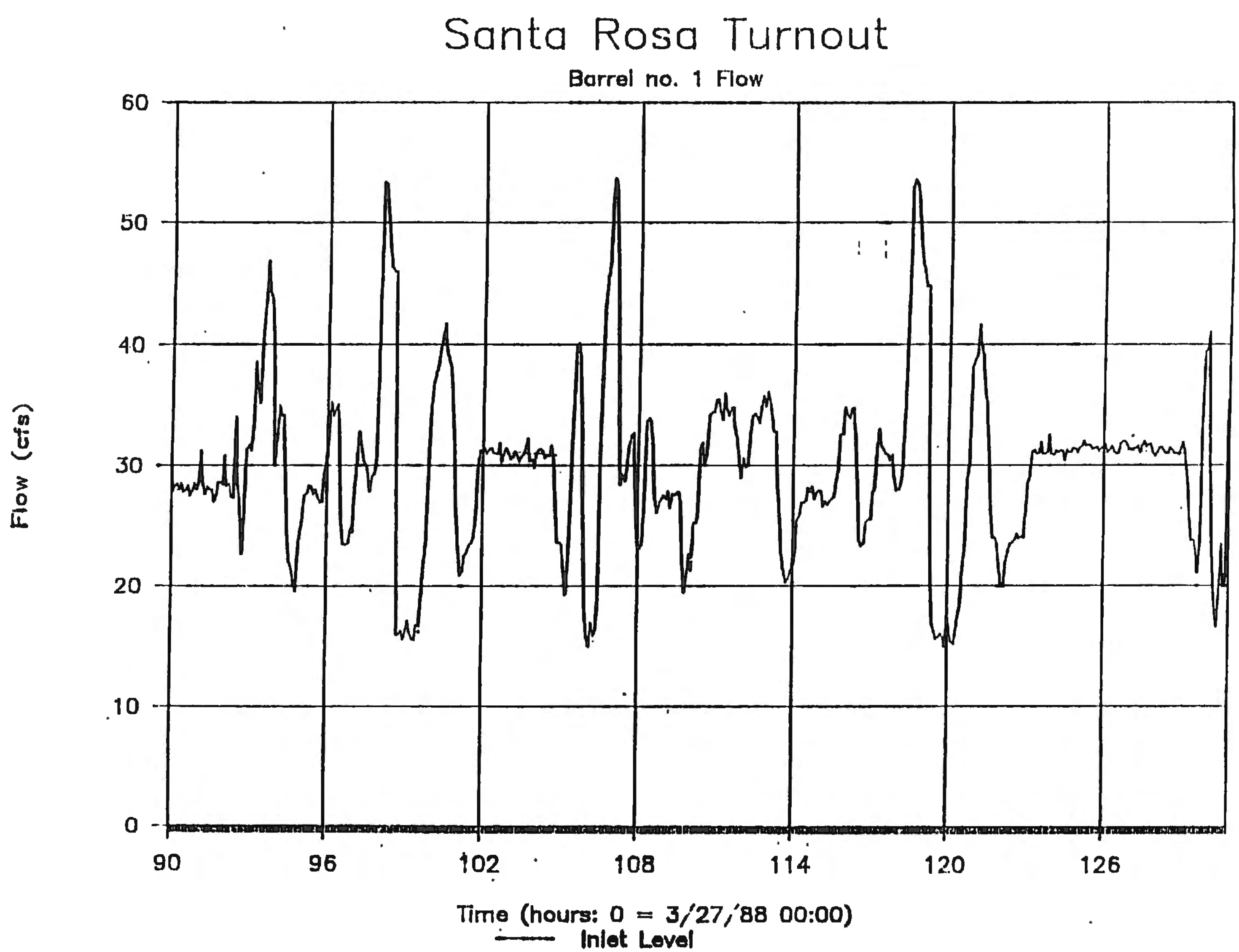


Figure 18: Typical turnout flow, Santa Rosa Barrel No. 1, $Q=30\ ft^3/s$, 3/30/88.