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HYDRAULIC MODEL STUDIES OF THE SANTA ROSA TURNOUT

TUCSON AQUEDUCT CENTRAL ARIZONA PROJECT

August 1990

U.S. DEPARTMENT OF THE INTERIOR
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16. ABSTRACT

This report describes a hydraulic model study performed by the Bureau of Reclamation on the Santa Rosa turnout on the Central Arizona Project, Arizona. Operation of two brands of flowmeters used on turnouts has provided satisfactory results by one model and inconsistent results by the other. The inconsistent results were initially attributed to the actual flow characteristics in the piping system. In order to address this question of performance, the Arizona Projects Office requested that a physical model study of the two barrels of the Santa Rosa turnout be undertaken. The purpose of the study was to confirm the actual flow conditions in the Santa Rosa turnout and to determine what modifications could be made to improve the flow conditions, if found to be necessary. A 1:7.385 scale model of two barrels of the turnout was constructed and tested in the Bureau of Reclamation's Denver Office laboratories. Results from the study showed there were no hydraulic reasons for the inconsistent performance of the flowmeters in the field. Even though there were fluctuations in point velocities due to turbulent flow, the discharge fluctuations were less than 1 percent. Results infer that there is some hardware or software problem with the flowmeters as they currently exist.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

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 CAP (Central Arizona Project) have experienced erratic readings on their permanently installed, four-path ultrasonic flowmeters. Large fluctuations in discharge (±40 percent) have been reported since the turnouts have been in service. Studies concentrated on verification of the large discharge fluctuations reported in the field.

INTRODUCTION

The Santa Rosa turnout is located on the Tucson Aqueduct, CAP, Arizona (fig. 1). The turnout features an intake structure off the main canal with seven individually gated discharge barrels (7-foot diameter). Each barrel is equipped with a permanently installed four-path-chordal acoustic flowmeter. The barrels enter a common weir chamber and exit into a distribution canal through seven short barrels (fig. 2). In addition to the Santa Rosa turnout, there are several other smaller turnout structures on the CAP with similar design features. Unreliable operation and output from the acoustic flowmeters have been concerns since the flowmeters were first installed and put into operation in 1985. Output from the flowmeters is responsible for tracking water deliveries and ultimately for billing purposes.

Flowmeters used on all CAP turnouts are manufactured by one of two companies. Operation of one of the models has provided satisfactory results. The other manufacturer contends that the inconsistent results of its meters are attributable to poor flow characteristics in the turnout.

CONCLUSIONS

- All operations at normal flow conditions yielded satisfactory hydraulic performance. Model results did not indicate the large discharge fluctuations that were reported by the installed acoustic flowmeters.

- Velocity profiles measured at the metering station in the model showed some skewness, mostly due to tailwater effects. However, the profiles were stable with time for a given flow condition.

- Discharge fluctuations were measured by monitoring storage in the model and inflow. Results indicated flows within ±0.6 percent of the set point.

- Operation of the sluice gate at very small openings resulted in noticeable secondary currents and flow reversal directly downstream from the gate. However, these effects were not measurable at the flowmetering station.

- Formation of an air cavity behind the sluice gate at small openings and high heads caused entrainment of air bubbles into the discharge barrels. The amount of air may be significant enough to effect the acoustic flowmeter readings on the upper path of the installed four-path-chordal system.

HYDRAULIC TESTS

The Model

The hydraulic tests were carried out in the Hydraulics Branch laboratory of the Research and Laboratory Services Division. Two barrels of the Santa Rosa turnout were modeled in a 1:7.385 Froude-based scale model. Froude numbers in the model and prototype were chosen to be equal:

$$\left[\frac{U^2}{gL}\right]_m = \left[\frac{U^2}{gL}\right]_p \qquad (1)$$

Where:

U	=	average velocity
g	=	gravitational constant
L	=	characteristic length
m,p	=	model and prototype, respectively

Satisfying this equation ensures dynamic similarity for a geometrically similar model due to the influence that the free surface (gravity) has on the hydraulic performance of the turnout. With a geometric or length scale of 1:7.385, the velocity ratio and discharge ratio are 1:2.718 and 1:148.21, respectively.

The model included a portion of the intake, the wall-mounted sluice gates, two discharge barrels, two bays of the common weir chamber, and gated exit conduits so that tailwater could be adjusted (fig. 3). Details of the model are shown on figures 4 through 8.

Test Procedure

The discharge and head levels (headwater and tailwater) were adjusted to desired values. Once a steady-state condition existed, measurements and observations were recorded. Table 1 is a synopsis of the test runs that were made. The first 12 runs were for normal operating conditions, while the second group was for an extremely high headwater condition (1 foot below 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 acoustic flowmetering station. The measurements were made with a pitot-static tube and differential pressure transducer (fig. 9). The transducer output was input to a Hewlett-Packard 3475A multimeter. A sample of 100 points was taken at 11 positions on each of 4 diametral traverses (fig. 10). The multimeter stored the data and computed 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 profiles.

Discharge fluctuations were measured by recording inflow to the model along with water surface elevations in the headbox. The inflows were recorded on a pressure transducer placed across the venturi meter. This transducer output is normally used as input to a PID (proportional integral differential) controller, used to maintain steady discharges to laboratory models (fig. 11). The water surface elevations in the headbox were measured with a capacitance-type wave probe (fig. 12). Combining the inflow and amount of storage in the model allowed the discharge fluctuations to be calculated.

TEST RESULTS

Velocity Profiles

Velocity profiles corresponding to test runs 1 through 12 are shown on figure 13 (a through l). These plots include absolute maximums, minimums, and the mean profile at each location. The basic profile shape is typical of turbulent pipe flow. The profiles measured at the flowmetering station indicated that the flow was not yet fully developed. However, when a theoretical profile based on the power law was compared to the measured profiles and corrections for the hydrostatic pressure distribution were made, they matched quite well (fig. 14). There was a maximum fluctuation in point velocities of approximately 15 percent, which is acceptable for turbulent pipe flows. On the average, the velocity profiles were very stable.

Discharge Fluctuations

The velocity profile data did not account for large discharge fluctuations which had been measured in the field. The actual discharge fluctuations were measured in the model by measuring variations in the headbox water surface elevation and monitoring the inflow to the model simultaneously. The discharge through the control gate was evaluated by:

$$Q = C_d A_g \sqrt{2g\Delta H} \qquad (2)$$

Where

C_d = coefficient of discharge
A_g = area of the gate opening
ΔH = head drop across the gate

In this equation for a given gate opening, the variation in head can be translated into a fluctuation in discharge. However, the variation in the flow rate delivered to the model through the venturi meter had a larger error than that attributable to the head variation in the model. Table 2 shows the test conditions where discharge fluctuation data were collected, the values, and an estimate of the measurement uncertainty.

DISCUSSION

The consistent and accurate measurements of discharge by acoustic flowmeters can be affected by many factors: The acoustic flowmeter is a complex electronic instrument. Most units are microprocessor based and include some type of software or firmware to convert measured transit times to flow rates for a particular site. In addition, conditions at the site to be measured are very important, since many times the flow profile shape and angular orientation of the flow are partially assumed and can induce large errors if the assumptions are not valid. A simplified explanation of the operation of a typical chordal acoustic flowmeter can help in understanding the relative importance of different aspects of the operation. The flowmeter essentially solves the equation:

$$Q = \iint v dx dy \tag{3}$$

Where:

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

The inside integral, vdx, is solved by making a time measurement with high-frequency acoustic transducers. A pair of transducers, one upstream (No. 1) and one downstream (No. 2), are used to make the transit time measurement. A pulse of acoustic energy is sent from transducer No. 1 to transducer No. 2. When the signal has been received, a pulse is returned from transducer No. 2 to transducer No. 1. The difference in time between the two transmitted pulses is related to the velocity by:

$$v = \frac{L_p \Delta T}{2\, T_{1-2}(T_{1-2} + \Delta T)\cos\phi} \tag{4}$$

Where:

L_p	=	path length
T_{1-2}	=	traveltime of a pulse from upstream to downstream transducer
ΔT	=	difference in traveltimes between the two directional pulses
ϕ	=	angle of path to pipe axis.

Many flowmeters have multiple pairs of transducers, or paths. Chordal-type meters typically have four paths, generally spaced vertically along the pipe diameter. Through appropriate spacing, different integration techniques (Gaussian Quadrature, for example) can be used to compute the discharge reading. Equation 5 demonstrates the Gaussian Quadrature approach to integration:

$$Q = \iint v dx dy = \int (v_p L_p \tan\phi)\, dy = D \sum_{n=1}^{4} W_n v_{pn} L_{pn} \tan\phi_n \tag{5}$$

Where:

W_n	=	Gaussian weights
n	=	path number
v_p	=	average pipe diameter

Normally, multiple samples of upstream and downstream transit times are collected and used to compute the average discharge, Q, over some fairly short period of time.

In this discussion, the chordal path meter was used as an example. However, there is also a family of acoustic flowmeters known as diametral path meters. These meters typically use strap-on transducers (one or two pairs). Due to the location of the average velocity measurement (center of the pipe), these meters are extremely sensitive to flow profile shape. The integration technique

Gate Effects

Operation of an acoustic flowmeter directly downstream from a gate or valve can affect the performance greatly due to the modified velocity profile. The wall-mounted sluice gates used for control at Santa Rosa turnout typically operate at partial openings. The combination of a square gate leaf on a circular conduit creates strong secondary currents in the form of longitudinal swirl. This swirl begins at the intersection of the gate leaf and the circular conduit (fig. 15). There can also be separation and flow reversal directly downstream from the gate. However, measurements taken at the flowmetering station showed little evidence of either of these effects.

Air Entrainment

The discharge of an air-water mixture cannot be accurately measured with an acoustic flowmeter due to the large differences in the sonic velocity between air and water. The gate configuration at Santa Rosa has an air vent pipe directly downstream from the wall-mounted sluice gate. This air vent can be a source for air bubbles in the water. The large scale model used in this study allowed for good representation of the air entrainment which takes place due to gate operation. At normal operating levels, no air was observed entering the discharge barrels. However, at high heads (1 foot below top of lining), an air cavity formed behind the gate at partial openings. Air was supplied to this cavity by the air vent pipe and air bubbles were continually breaking free from the cavity and passing downstream. The air bubbles remained near the top of the pipe due to their size and relative velocity of flow in the barrel. There was a sufficient amount of air that readings on the upper path of the presently installed acoustic flowmeters might be affected.

Table 1. - Summary of test runs - May 2 to June 10, 1988.

Run No.	Q (ft^3/s)	U.S. canal elevation (ft)	Elevation 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
6	100	1538.83	5
7	225	1538.83	5
8	300	1538.83	5
9	50	1538.83	10
10	100	1538.83	10
11	225	1538.83	10
12	300	1538.83	10
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
18	100	1547.83	5
19	225	1547.83	5
20	300	1547.83	5
21	50	1547.83	10
22	100	1547.83	10
23	225	1547.83	10
24	300	1547.83	10

Table 2. - Discharge fluctuation summary.

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 flow rate

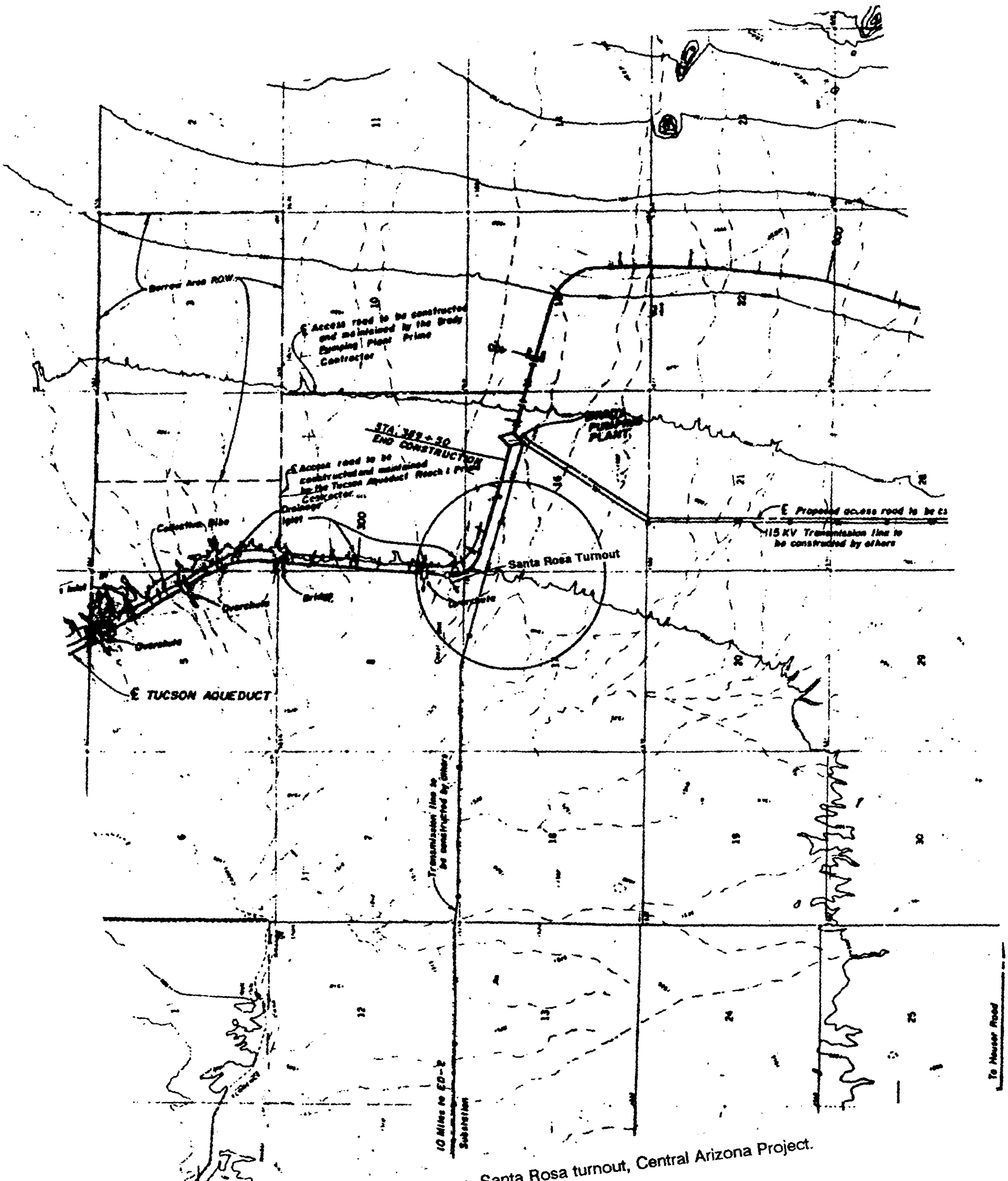

Figure 1. - Location map, Santa Rosa turnout, Central Arizona Project.

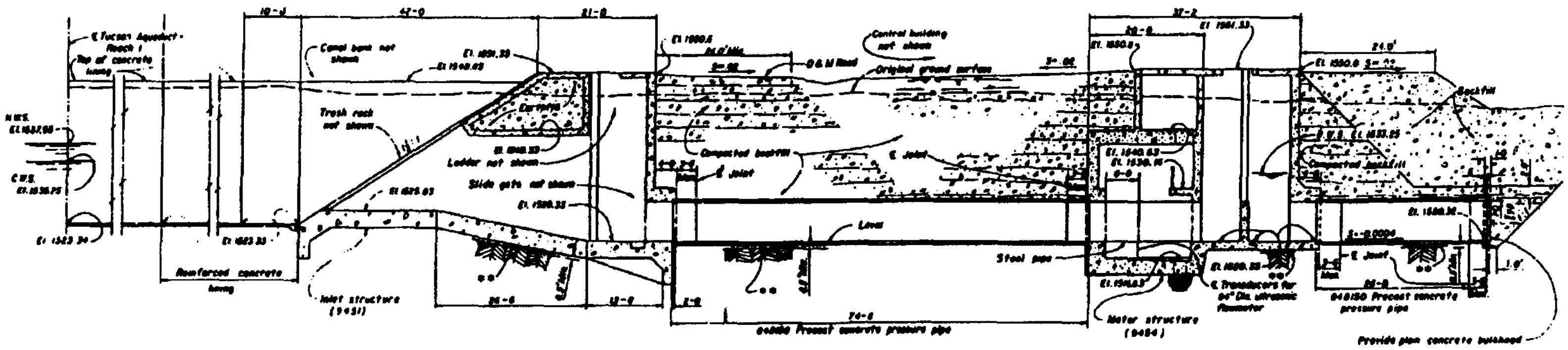

Figure 2. - Elevation of Santa Rosa turnout.

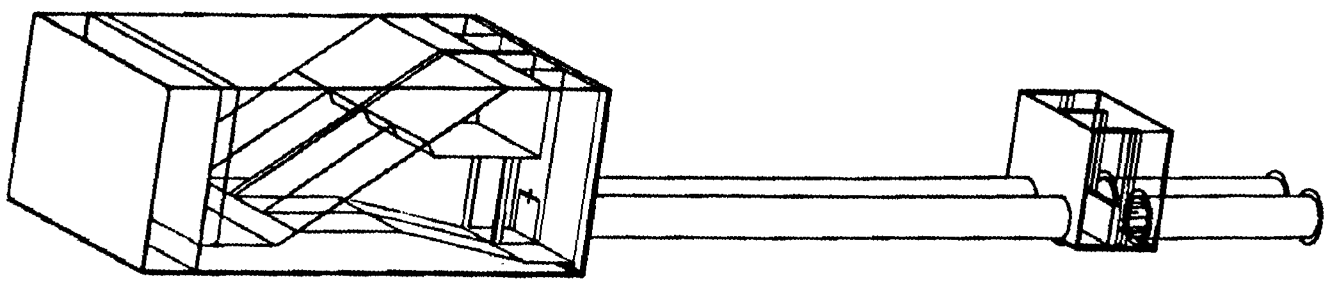

Figure 3. - Sketch of the hydraulic model.

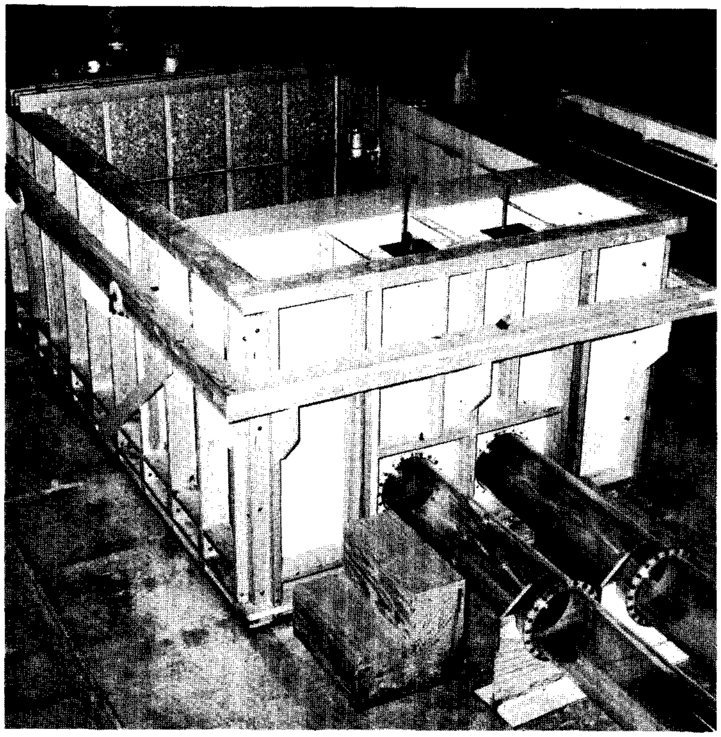

Figure 4. - Model headbox.

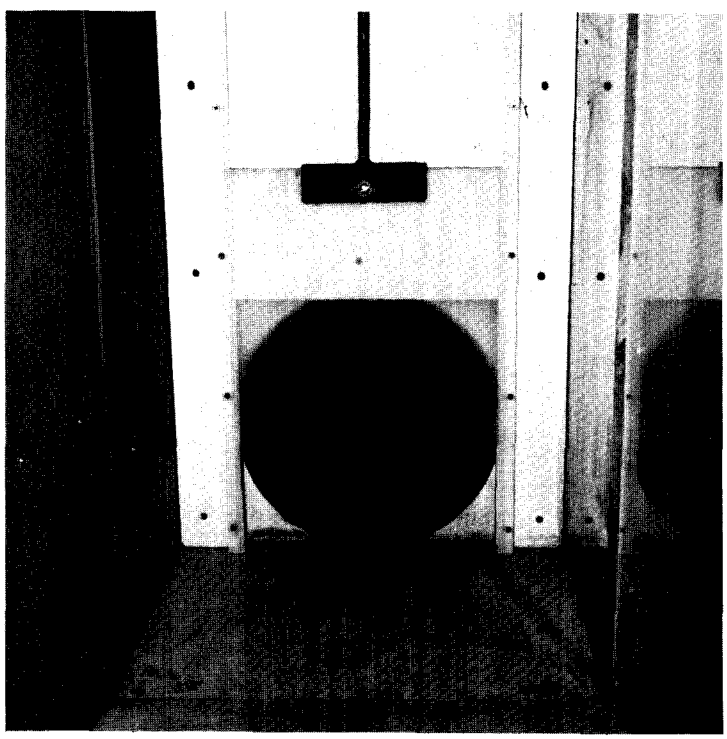

Figure 5. - Wall-mounted sluice gate (note square gate on circular barrel).

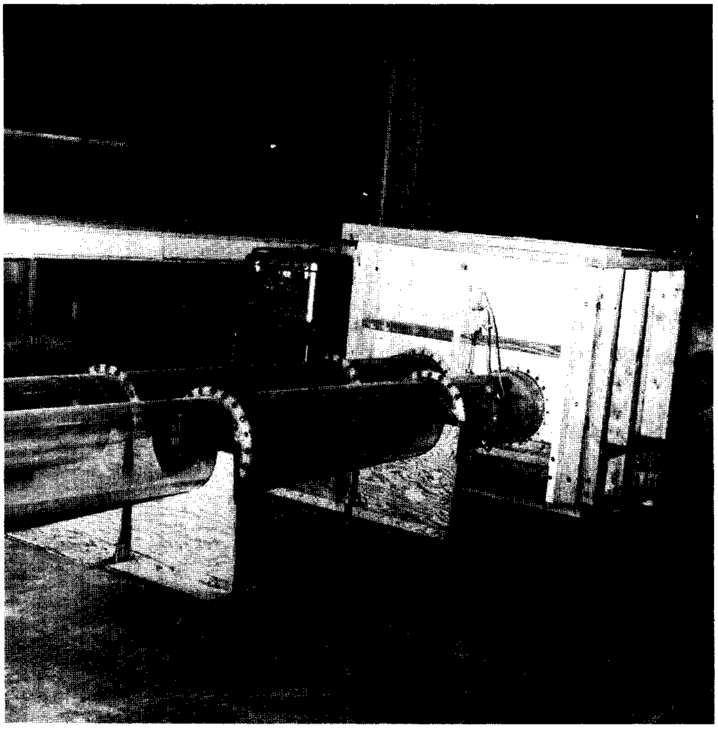

Figure 6. - Acrylic plastic pipe simulating two barrels of the turnout.

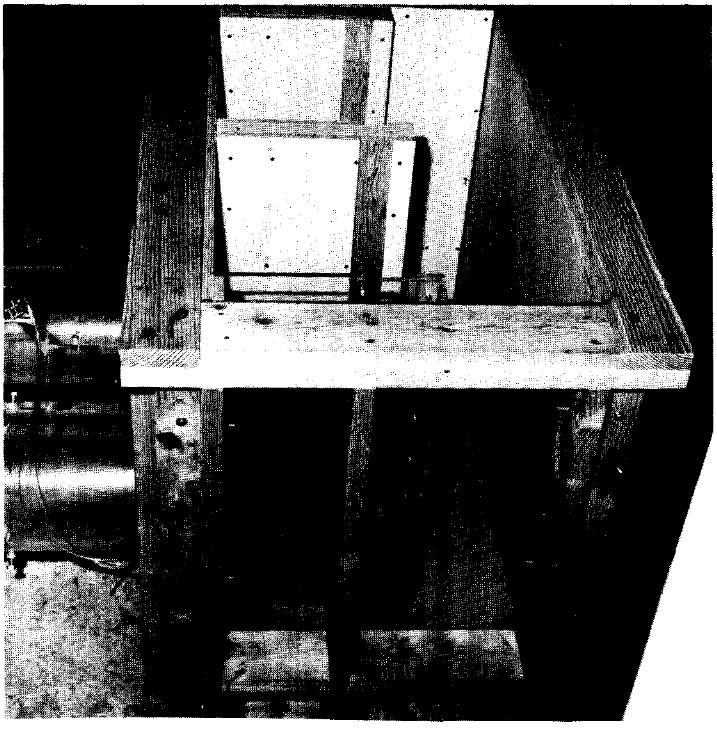

Figure 7. - Two bays of the common weir chamber which keeps barrels watered up.

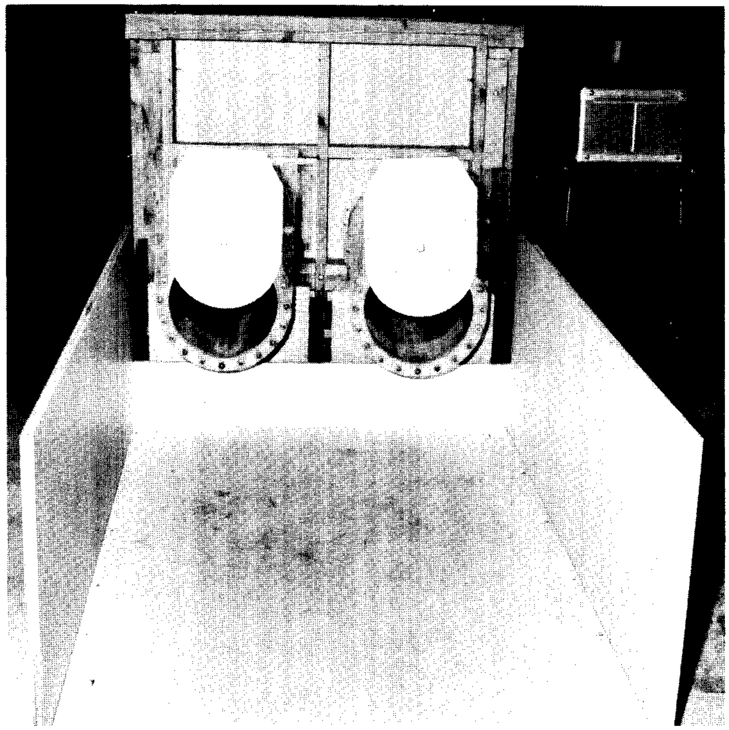

Figure 8. - Slide gates used to control tailwater levels.

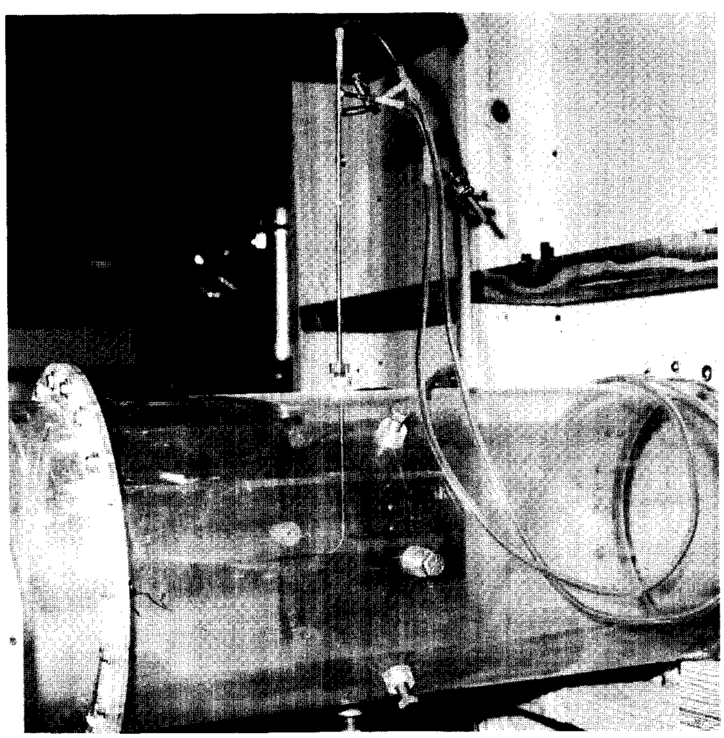

Figure 9. - Pitot-static tube used to measure velocity profiles.

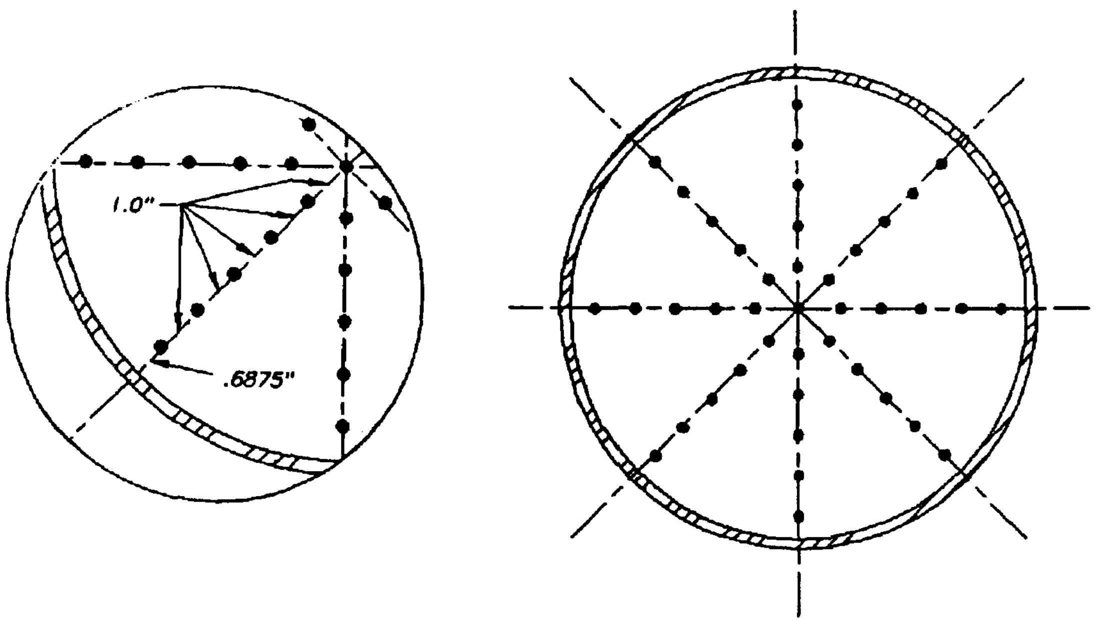

Figure 10. - Locations for velocity profile measurements.

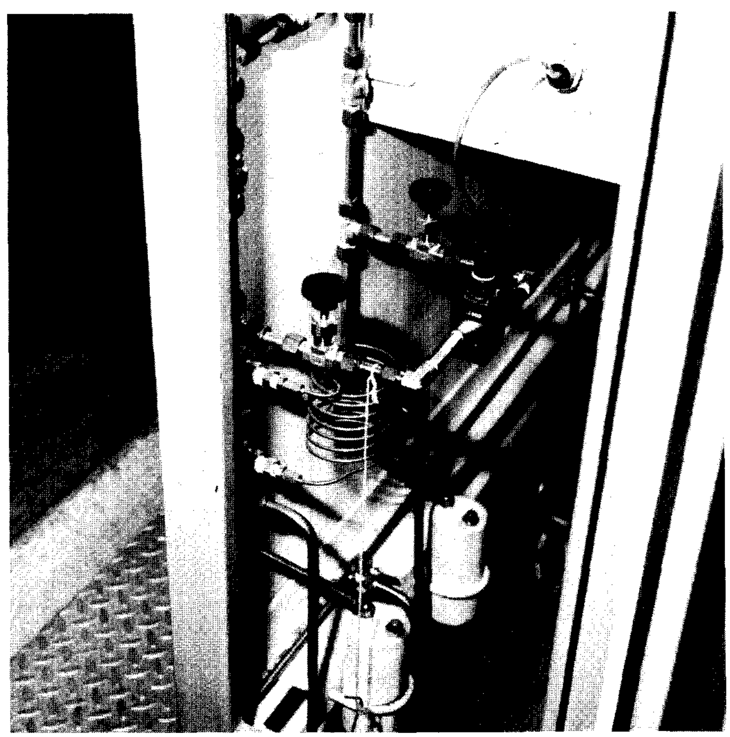

Figure 11. - Pressure transducer used to sense venturi meter differential.

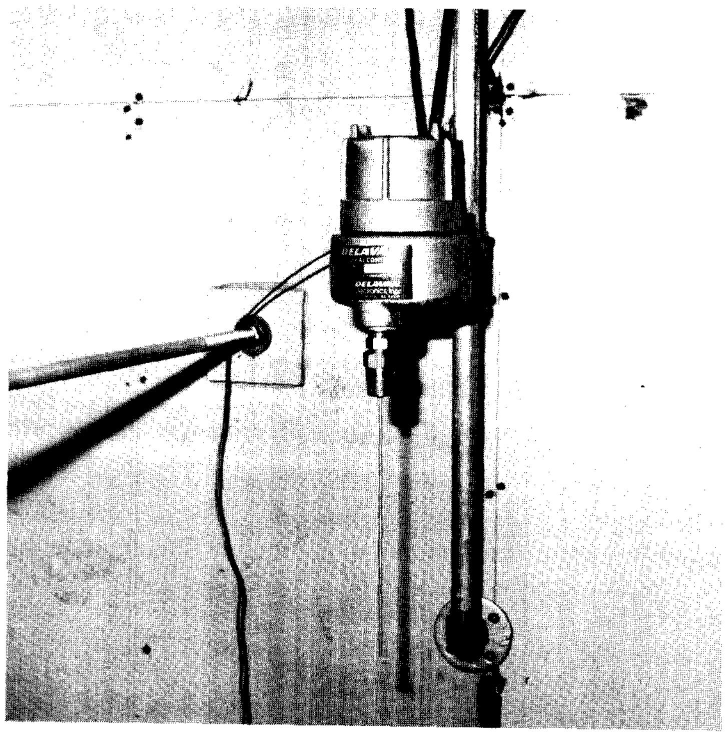

Figure 12. - Capacitance-type wave probe used to monitor water level.

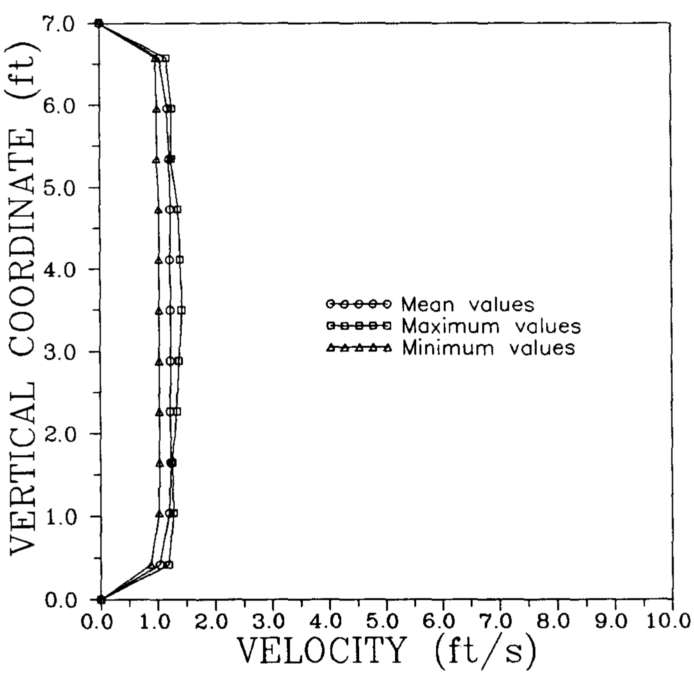

Figure 13a. - Profile for test run 1, Q = 50 ft^2/s, HW = 1538.83, free flow.

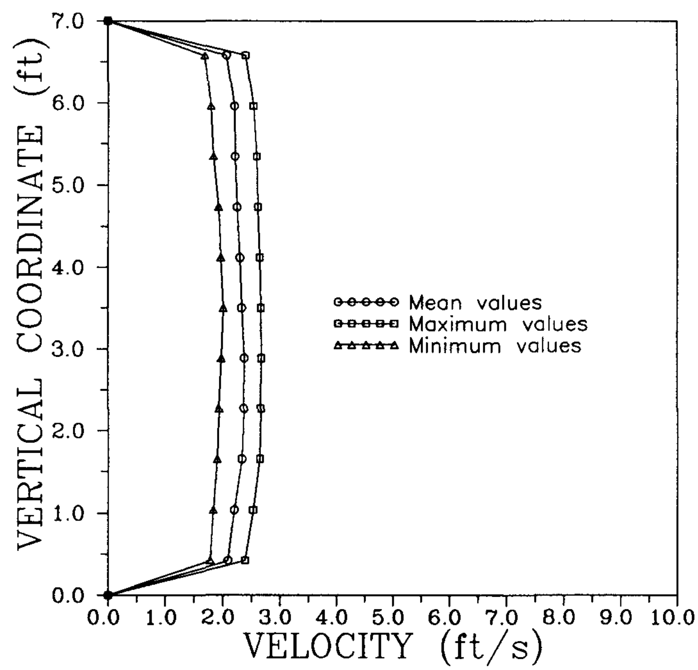

Figure 13b. - Profile for test run 2, Q = 100 ft^3/s, HW = 1538.83, free flow.

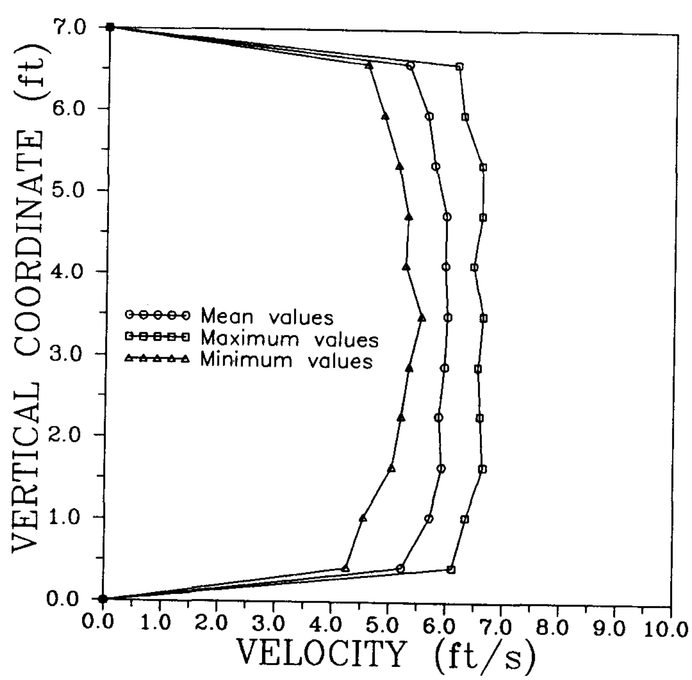

Figure 13c. - Profile for test run 3, Q = 225 ft^3/s, HW = 1538.83, free flow.

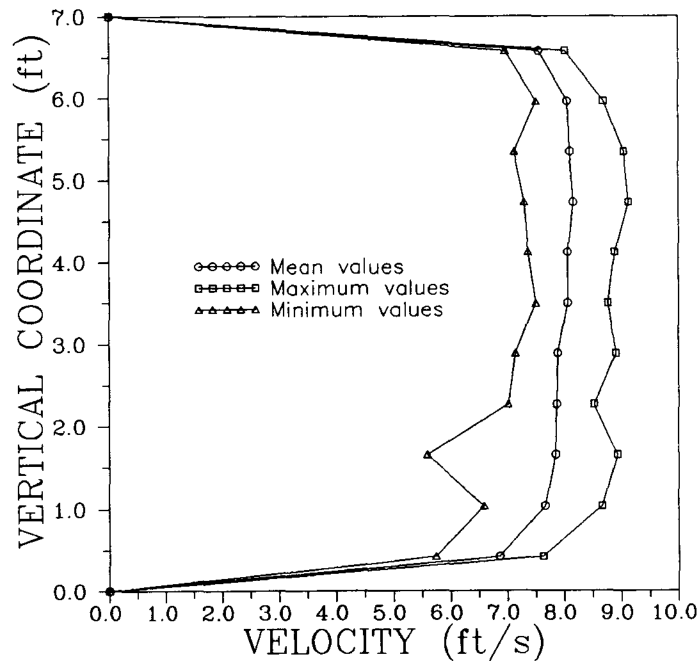

Figure 13d. Profile for test run 4, Q = 300 ft^3/s, HW = 1538.83, free flow.

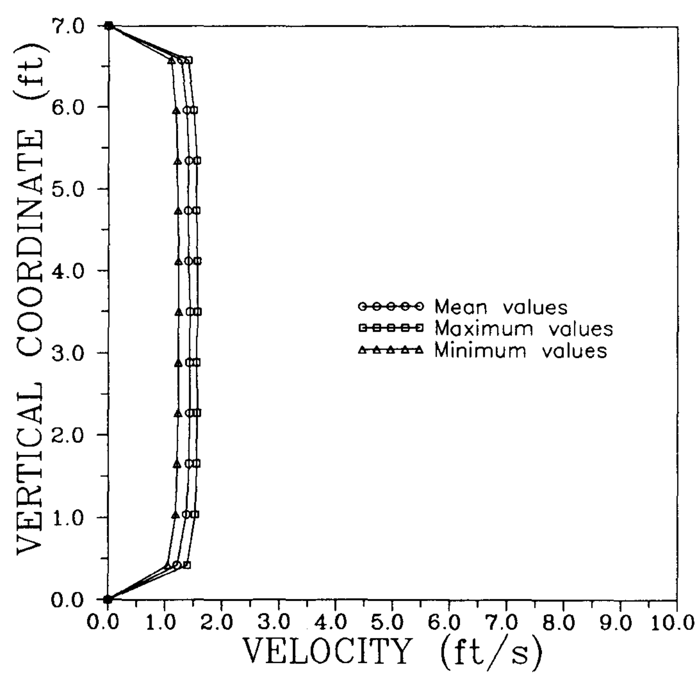

Figure 13e. Profile for test run 5, Q = 50 ft^3/s, HW = 1538.83, 5 feet over weir.

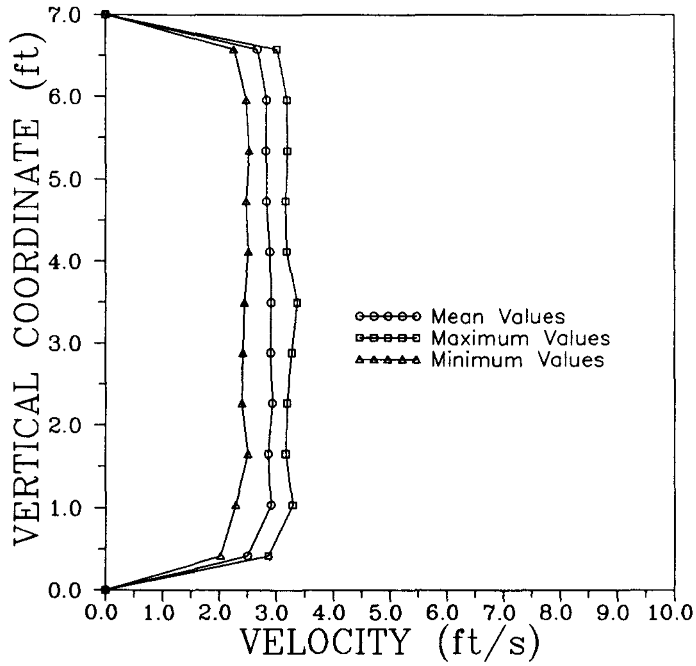

Figure 13f. Profile for test run 6, Q = 100 ft^3/s, HW = 1538.83, 5 feet over weir.

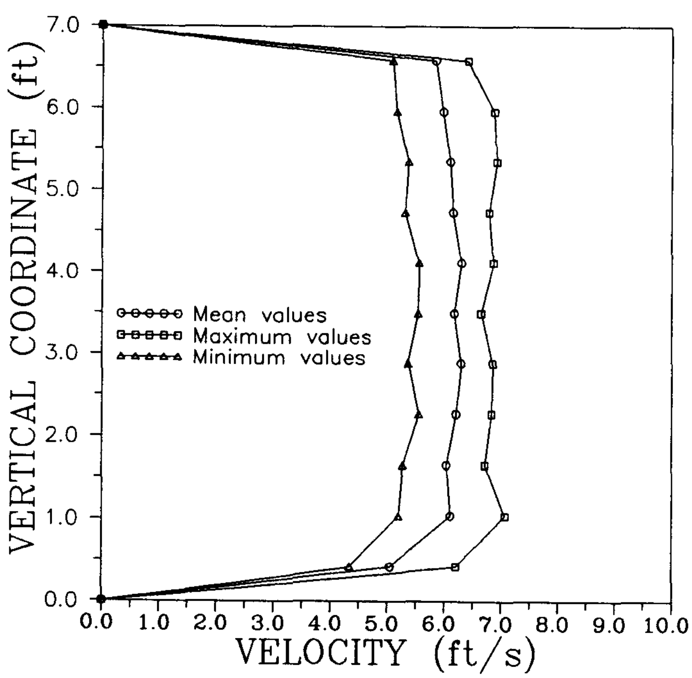

Figure 13g. Profile for test run 7, Q = 225 ft^3/s, HW = 1538.83, 5 feet over weir.

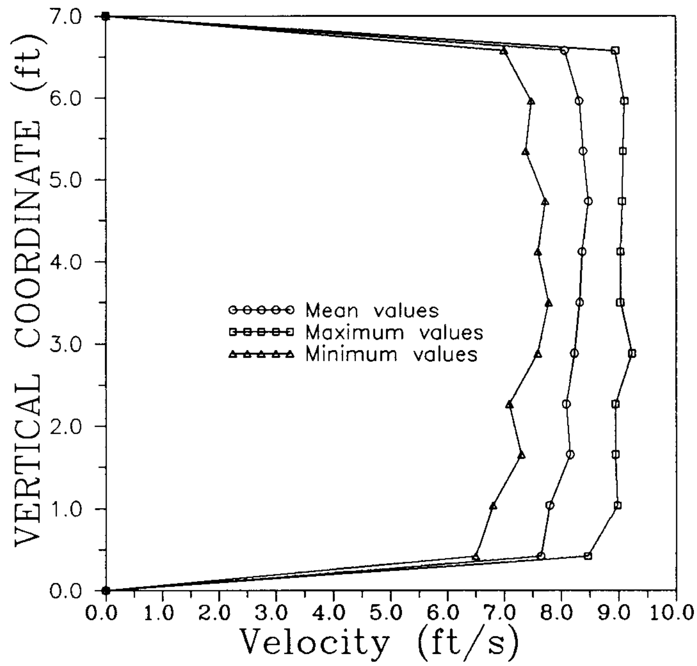

Figure 13h. Profile for test run 8, Q = 300 ft^3/s, HW = 1538.83, 5 feet over weir.

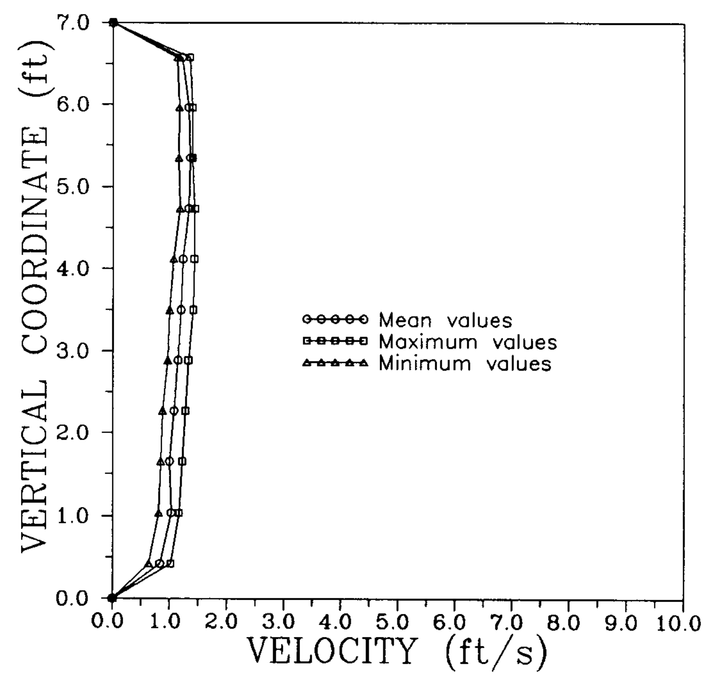

Figure 13i. Profile for test run 9, Q = 50 ft^3/s, HW = 1538.83, 10 feet over weir.

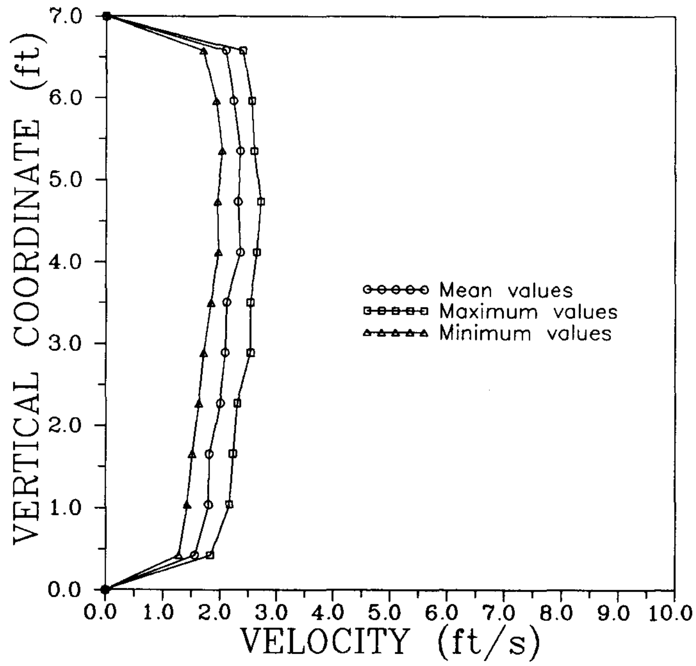

Figure 13j. Profile for test run 10, Q = 100 ft^3/s, HW = 1538.83, 10 feet over weir.

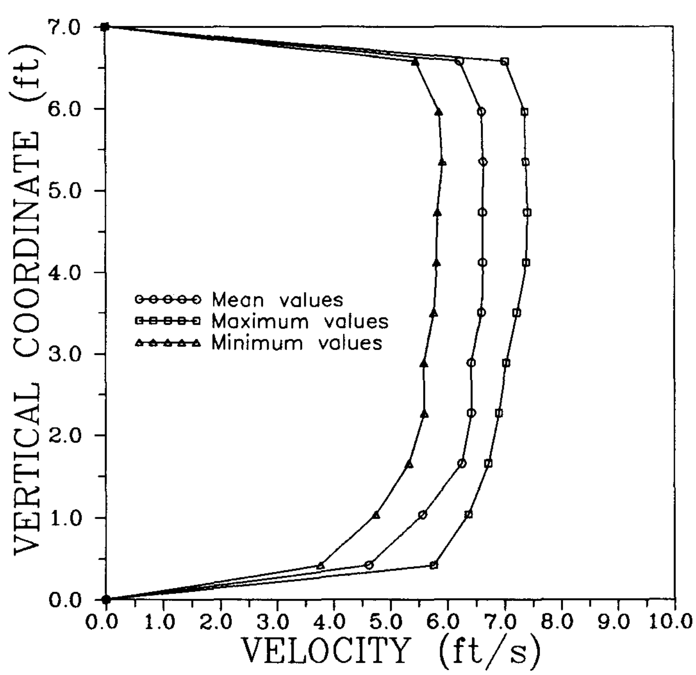

Figure 13k. Profile for test run 11, Q = 225 ft^3/s, HW = 1538.83, 10 feet over weir.

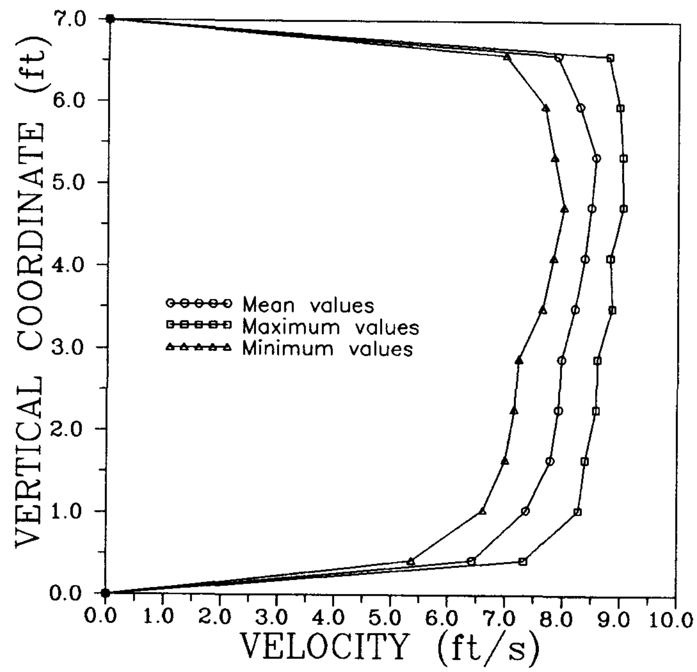

Figure 13l. Profile for test run 12, Q = 300 ft^3/s, HW = 1538.83, 10 feet over weir.

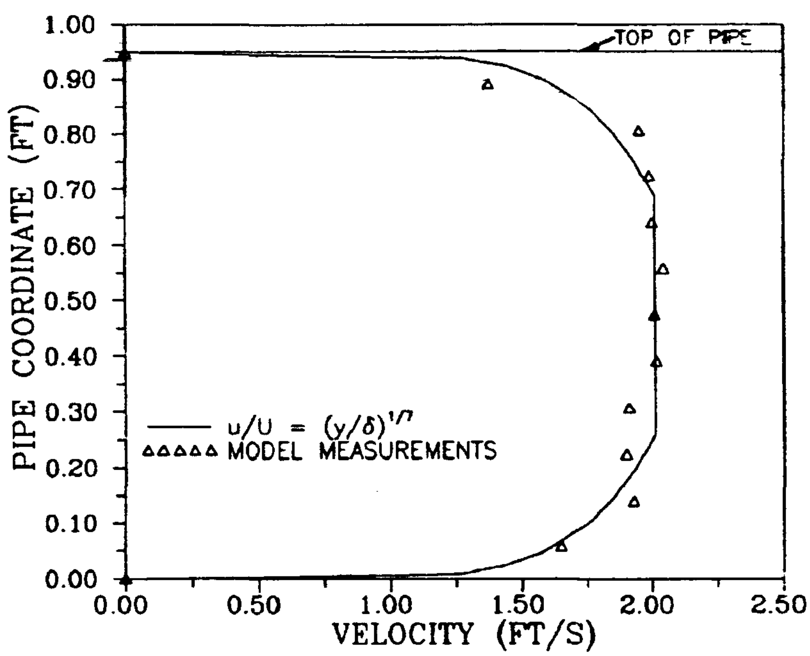

Figure 14. - Comparison of measured and theoretical velocity profiles.

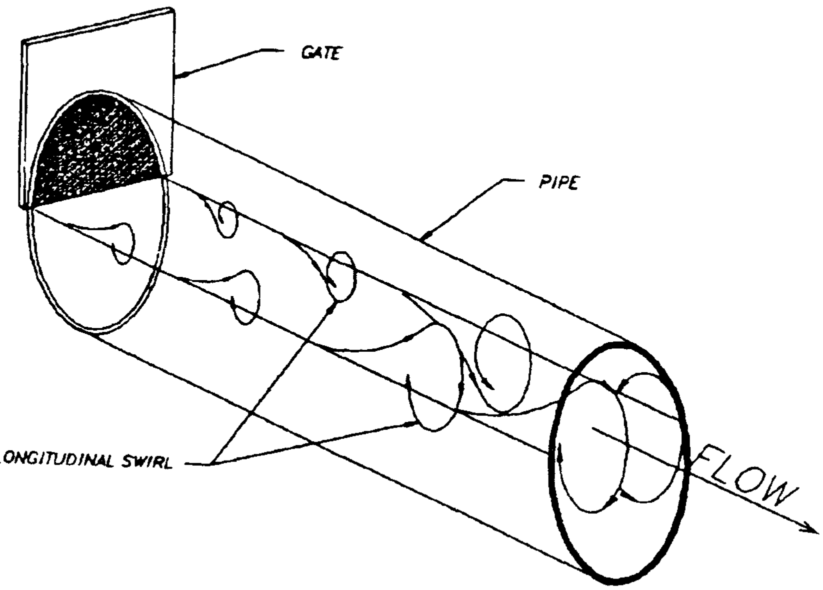

Figure 15. - Sketch of longitudinal swirl (secondary current) caused by gate control.

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