REPORT ON A

HYDRAULIC MODEL STUDY OF THE BY-PASS
of the
CUMBAYA PROJECT
QUITO, ECUADOR

Prepared for

R. J. Tipton Associated Engineers, Inc.

by

S. Karaki and S. Ayoub

Colorado State University Research Foundation
Civil Engineering Section
Fort Collins, Colorado

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FOREWORD

Results of a hydraulic model study for the By-Pass of the Cumbaya Project, Ecuador, are presented in this report. The study was conducted in the Hydraulic Laboratory, Colorado State University, Fort Collins, Colorado, for the consulting engineering firm of R. J. Tipton Associated Engineers, Inc., Denver, Colorado. Direct technical supervision was given by M. L. Albertson, Director of the Colorado State University Research Foundation. The study was conducted under the general technical and administrative supervision of A. R. Chamberlain, Chief of the Civil Engineering Section.

The stilling basin design used in the By-Pass is a type developed by the Colorado State University Hydraulics Laboratory, in which the energy is dissipated by diffusion of submerged vertical jets. These jets are formed by changing the direction of approaching flow from horizontal to vertically upward by an inclined bottom of the stilling basin, which directs the water through a manifold--a horizontal row of openings formed by blocks. Because of the appearance of the structure, it is called the manifold-type stilling basin or more briefly, manifold stilling basin. Dimensions of the structure are governed by the quantity of flow and the amount of energy to be dissipated.

CONTENTS

I INTRODUCTION

Brief Description of Project

The Cumbaya Project is a hydroelectric power development project located in the Republic of Ecuador, South America. Fig. 1 is a general plan and profile of the Cumbaya Project as conceived at the time of the model study reported herein. The new power plant will be located on the Machangara River, approximately 7 kilometers east of Quito, and 2 kilometers north of Cumbaya. Water which flows through the turbines of the existing Guangopolo power plant will be diverted through an intake structure into a new concrete lined circular tunnel 3.5 meters in diameter and approximately 8.6 kilometers in length, thence to the plant on the Machangara River. Additional water to the tunnel will be diverted from the San Pedro River at the Guangopolo Plant by constructing a diversion dam across the river with appropriate headworks to divert water into the tunnel intake structure. At the outlet of the tunnel, an open channel will be constructed to connect with the regulation reservoir. At the lower end of the reservoir, an intake structure to the two-penstocks of the Machangara plant will be constructed. The penstocks are comprised of two sections, a 2.44-meter diameter circular concrete conduit and an 8.0-ft. diameter steel penstock. The concrete penstocks extend from the intake structure to the surge tanks, and the steel penstocks from the surge tanks to four 14000 H.P. Francis-type turbines in the power plant. Water discharges from the draft tubes of the turbines into a tailrace channel and is conveyed to the Machangara River.

To permit water to flow from the forebay of the Guangopolo power plant directly into the new tunnel without flowing through the existing turbines, a by-pass will be constructed, see Fig. 2. This by-pass consists of an intake structure, a steel pipe incased in masonry and a manifold stilling basin. The total length is approximately 219 meters with a total drop in water surface of 74 meters. This large hydraulic head must be dissipated in pipe friction and in the stilling basin.

The initial design given to the C. S. U. Hydraulics laboratory for testing may be described as follows: (Also refer to Fig. 2). The intake structure is a conventional type for pipe inlets. The by-pass consists of about 68 meters of 72-inch diameter steel pipe, 123 meters of 39-inch diameter steel pipe and approximately 20 meters of various transitions. There is also an 18-inch diameter air vent parallel to and above the main conduit, designed for the purpose of releasing air from the by-pass pipe. The manifold stilling basin is 10 meters long and 2.75 meters wide, discharging vertically into the invert of the main tunnel.

Scope of Investigation

The scope of this model study was to investigate the performance of the manifold stilling basin and air vent system as originally designed under various conditions of flow, and to test necessary modifications in the geometry of the system as guided by the test results and need to achieve improved hydraulic performance. It has also been considered within the scope of this report to recommend modifications in the by-pass pipe in so far as they might improve the performance of the manifold stilling basin.

II MODEL

Construction

To investigate the problem fully, and to insure that the flow in the model would faithfully reproduce conditions in the prototype, it was considered necessary to construct a model of the entire by-pass, from the intake structure adjacent to the forebay down to and including a portion of the 3.5 m diameter tunnel. Fig. 3 is a photograph and Fig. 4 is a schematic drawing of the complete model. In order to facilitate the model study, it was decided that a transparent plastic model would best serve the investigators. In addition to transparency, plastic had the advantage of being very smooth-walled, a condition especially desirable for the model conduit.

Consideration of laboratory space and facilities and material commercially available suggested the scale of 1:17. Accordingly, these relationships follow:

1. Linear Scale 1:17 ($L_p = 17L_m$)
2. Velocity Scale 1:4.12 ($V_p = 4.12V_m$)
3. Discharge Scale 1:1191 ($Q_p = 1191Q_m$)

These relationships are based on the Froude criterion which governs the similitude of the intake and the stilling basin. The conduit in between does not permit use of Froude similitude relationships because of predominating viscous forces at full pipe flow. It was necessary therefore, to develop similarity for the conduit by verification to original design, and the basis for the verification was the head loss within the pipe. That is, the head loss in the conduit of the model was made similar to the computed head loss in the prototype conduit. By this technique, it was possible to simulate operations of the entire by-pass.

Appurtenances

Water for the model was supplied from the laboratory circulating system; powered by an 8-inch high-head turbine pump. Discharge was measured by an orifice in the pipe and regulated by a gate-valve. A manually operated tail gate was utilized at the downstream end of the 3.5 m diameter tunnel so that the water surface level in the tunnel could be controlled. A water supply was also connected to the upstream end of the tunnel to simulate flow from either river diversion or diversion from the tailrace of the Guangopolo power plant. A total of 53 piezometers were installed along the invert of the by-pass pipe to obtain pressure readings. Fig. 4 illustrates the location of the piezometers. Four piezometers were also installed along the inside of the lower pipe bend.

III MODEL TESTS

Original Design

Test on the original design of the by-pass were made and observations and data on performance of the various features were recorded. Although it is not the intent of this study to make detailed analyses of all segments of the by-pass, a sufficiently thorough discussion is included herein in so far as it is considered to affect the performance of the manifold stilling basin.

The Air Vent The air vent pipeline as originally designed was intended to collect and discharge the air which would be initially entrained in the flow and then released in the by-pass pipe in areas of low pressure and velocity. However, because of the high velocity of flow in the 39-inch pipe, instead of being discharged, air was drawn into the by-pass through the vent which resulted in large quantities of air being entrained in the flow. The entrainment sufficiently reduced the capacity of the conduit so that it was not possible to convey a discharge of 18 m^3/sec through the pipe. There was also circulation of water through the lower portion of the vent pipe and risers. The circulation was not a stable phenomenon. Water, with considerable air entrainment, would rise through risers M and N. See Fig. 4, flow upstream in the vent pipe, discharge through risers L and K and flow through the main by-pass pipe back to the lower risers. Most often however, there was a vigorous circulation in the last two risers, rising through N and discharging through M. The reason for the variation in circulation was due in part to the water in the vent pipe above the circulation point moving downstream, or towards risers K and L. Also, the amount of air entrainment varied continuously, as did the flow in both the by-pass and vent pipes. Fig. 5 shows water in the vent pipe with considerable amount of air entrainment in the flow. The flow was the largest the system would convey which was about 12 m^3/sec. prototype. Considerable fluctuation existed because of the air entrainment just discussed.

When the air vent was closed to the atmosphere at the upper end, an increase in discharge through the by-pass pipe was noted. Flow conditions, however, were not improved. Even though air was not drawn in through the vent, there was circulation of flow through the lower risers and vent pipe. It was noted that this circulation set up turbulence and general flow disruption in the main conduit. The vent pipe was subsequently removed and each riser was plugged. With this condition, a flow of 18 m^3/sec was discharged through the by-pass conduit.

Flow Conditions in the By-Pass For partial discharges in the by-pass pipe, even without the air vent, it was not possible to prevent air entrainment in the flow. Quantitative measurements of air entrainment were not made in the model, but Figs. 6 to 13 give visual indications at various flows less than 18 m^3/sec. Fig. 7 shows a photograph of a hydraulic jump formed in the 72-inch pipe for a prototype flow of about 8 m^3/sec. The location of the hydraulic jump may vary from near the lower bend to a point well into the 72-inch diameter pipe above the transition to the 39-inch pipe, depending on the discharge through the conduit.

Attempts were made to eliminate the jump in the conduit for flow quantities of between 8 and 18 m^3/sec. that were normally expected in the prototype. An orifice was inserted in the line at various positions for several discharges in an effort to increase the total resistance in the pipe and to fill the conduit upstream from the orifice so that a jump could not occur. However, all attempts in this direction failed; because, although it is possible to get a constriction that would function adequately for any one particular discharge it would not function properly for any other discharge. The danger of applying this type of device to eliminate the hydraulic jump in the conduit, is that the capacity of the system would be reduced to such an extent that when the need arose the required flow could not be conveyed through the system. Since the discharge is proportional to the square root of the total head, a considerable increase in head would be necessary for any appreciable increase in discharge.

The transition from the 72-inch pipe to the 39-inch pipe was designed as a conical reducer. The inverts of the two pipes therefore, were not in the same plane, and at certain discharges the flow along the invert of the larger pipe turned upward at the reducer, forming fins along the walls of the smaller pipe which at times closed the pipe off completely. This resulted in slug flow and generally unstable flow conditions in the smaller pipe.

Stilling Basin Flow conditions above the stilling basin for discharges near 18 m^3/sec were not entirely satisfactory in the original design. Small positive pressures were developed in the tunnel above the stilling basin. However, for discharges near 9 m^3/sec, the water surface in the tunnel was free of the crown and the boil heights presented no problems.

Modified Design The original design of the by-pass pipe was modified in the model to achieve the desired flow conditions in the stilling basin. The desired flow condition was that which produced a satisfactory water surface level in the tunnel at maximum discharge of 18 m^3/ sec. The air vent was eliminated and the length of 2 1/4-inch (39-inch prototype) pipe was increased. See Fig. 14 for a schematic drawing of the modified model.

Intake At large discharges a vortex was formed at the inlet to the pipe and was sufficiently large that a decrease in quantity of flow resulted. In the model, this vortex was eliminated by using a floating board at the entrance. No vortex problems existed for small discharges because the inlet was not submerged.

By-Pass Pipe Flow in the by-pass for a discharge of 18 m^3/sec is possible. The flow is virtually without air entrainment and no disagreeable hydraulic jump or slug flow was evident in the conduit. However, pressure readings along the invert of the pipe indicated that negative pressures will be developed in the 39-inch pipe.

Model pressure data in terms of feet of water are listed in the table of the appendix to this report. It is to be noted that in this model the pressures do not have the same relationship to the prototype as linear dimensions because an exact dynamic similarity does not exist in the conduit portion of this model. An adjustment is therefore made to predict prototype values on the basis of the total head line determined in the model.

The calculated velocity head for the prototype subtracted from the total head line will then yield the hydraulic grade line. This procedure will be consistent only if the pipe roughness in the prototype is such that the head lost in pipe friction corresponds to the model. Because friction losses in models can not always be duplicated in the prototype, the difference must be made up in different lengths and sizes of pipe. This change will produce a different configuration in the total head line so that the negative head in the pipe may be reduced substantially when prototype values are calculated in this manner. The prediction of negative pressures therefore depends upon the final design of the pipe line. Assuming, however that the final design does not differ much from Fig. 6, negative pressures as high as 25 feet can be expected for flows near 18 m^3/sec. With a reduction in discharge to 12 m^3/sec, negative pressures will not be significant and for discharges smaller than 12 m^3/sec no negative pressures will exist.

A relatively stable hydraulic jump forms in the 72-inch conduit for a flow of 13.5 m^3/sec, with subsequent air entrainment. For flows of 9 m^3/sec and 4.5 m^3/sec, the hydraulic jump is somewhat unstable and as the volume of air entrainment varies so does the location of the jump. This instability is more a matter of interest than concern.

Stilling Basin Performance of the stilling basin for all discharges in the modified system were satisfactory. At 18 m^3/sec, the water surface in the tunnel was relatively smooth and the top of the boils just touched the crown of the tunnel, see Fig. 15. Boil heights are given for different discharges in the table of the appendix. At no time was the tunnel closed off to create positive pressures in the zone above the manifold stilling basin.

At discharges less than 18 m^3/sec, the entrained air was released in the transition approach to the stilling basin because of a decrease in velocity. The released air collect ed in pockets at the top of the conduit but because of the incline of the approach the pockets of air moved along with the flow and were released in the main tunnel. The flow was not impeded by the releasing of air.

Indications were that the last opening in the stilling basin was ineffective. This observation was made by injecting dye into the flow at the intake to trace the flow pattern in the stilling basin. Although air bubbles are not true traces because of the tendency to collect near the top of the conduit, Fig. 13 indicates photographically the distribution of flow in the stilling basin for a discharge of 9 m^3/sec. It seems reasonable then, in the final design, to shorten the basin by eliminating the last manifold opening.

Cavitation of the blocks in the manifold basin will not occur for the range of flows involved. For a discharge of 18 m^3/sec the effective opening amounts to about 0.24 m by 2.75 m. Nine of such openings provides a total area of 6.2 m^2. With the depth of water provided above the blocks and velocities of about 2.9 meters per second no cavitation should be expected.

IV RECOMMENDED DESIGN MODIFICATIONS

Intake and By-Pass Pipe

Results of model tests indicated that certain changes in the original design are desirable. In the intake structure, it is recommended that the design be altered to eliminate the vortex created at flows near 18 m^3/sec.

To develop sufficient frictional resistance in the pipeline, and to reduce the possibility of developing negative pressures in the smaller pipe at large flows, it is recommended that the alignment shown in Fig. 16 be changed to include a steeper pipe incline which will permit the hydraulic gradient to be above the pipeline. By such alignment, it would be possible to also reduce the danger of cavitation at the lower bend by developing greater positive pressures at the bend. It should be noted that the angle of intersection at the lower bend should not be much greater than 45^0, and that a large radius of bend be used. The vent pipe should be removed.

The length of transition from the 39-inch circular pipe to 2.75 m by 1.0 m rectangular section is satisfactory, but the 10 m section of the rectangular conduit following the transition can be reduced 5 m. It would improve flow conditions at partial discharges if the inverts of the two sizes of by-pass pipe were made to lie in the same plane.

Manifold Stilling Basin

The length of the stilling basin may be reduced from 10 meters to a length of 9 meters. The shortening of one meter must be made on the downstream end of the stilling basin with no change in the inclined bottom of the stilling basin.

APPENDIX

TABLE OF MODEL DATA

PIEZ. No.	Pressure in Feet of Water Q=0.54 c.f.s.	Q=0.41 c.f.s.	Q=0.27 c.f.s.	Q=0.13 c.f.s.	PIEZ No.	Pressure in Feet of Water Q=0.54 c.f.s.	Q=0.41 c.f.s.	Q=0.27 c.f.s.	Q=0.13 c.f.s.
1	0.15	0.20	0.18	0.10	30	0.42	1.67	1.42	0.62
2	0.12	0.13	0.14	0.08	31	0.03	1.12	1.02	0.44
3	0.88	0.08	0.12	0.08	32	-1.46	0.48	0.28	0.05
4	0.05	0.02	0.07	0.06	33	-2.21	0.14	0.30	0.05
5	0.24	0.01	0.04	0.04	34	-1.80	0.16	0.28	0.05
6	0.61	0.10	0.12	0.08	35	-1.26	0.18	0.29	0.05
7	0.89	0.08	0.18	0.08	36	-0.68	0.41	0.48	0.17
8	1.85	0.04	0.08	0.04	37	-0.74	0.42	0.47	0.16
9	2.88	0.05	0.08	0.06	38	-0.92	0.42	0.46	0.16
10	3.78	0.82	0.07	0.03	39	-1.13	0.36	0.50	0.15
12	4.19	0.22	0.19	0.18	40	-1.74	-0.02	0.54	0.14
13	3.98	0.10	0.18	0.07	41	-2.35	-0.48	0.58	0.16
14	3.33	0.09	0.13	0.28	42	-2.56	-0.92	0.57	0.50
15	2.06	-0.30	0.16	0.07	43	-0.95	-0.28	0.64	0.80
16	0.32	-0.02	0.08	0.18	44	0.52	0.13	0.54	1.02
17	-1.07	-0.32	0.02	0.03	45	0.91	0.47	0.47	1.03
18	-1.54	-0.65	0.32	0.09	46	1.47	0.99	1.12	1.02
19	-1.46	-0.62	0.32	0.12	47	1.33	1.02	0.46	0.95
20	-1.09	-0.67	0.32	0.09	48	1.32	1.06	0.46	0.90

REMARKS

Model Dimensions

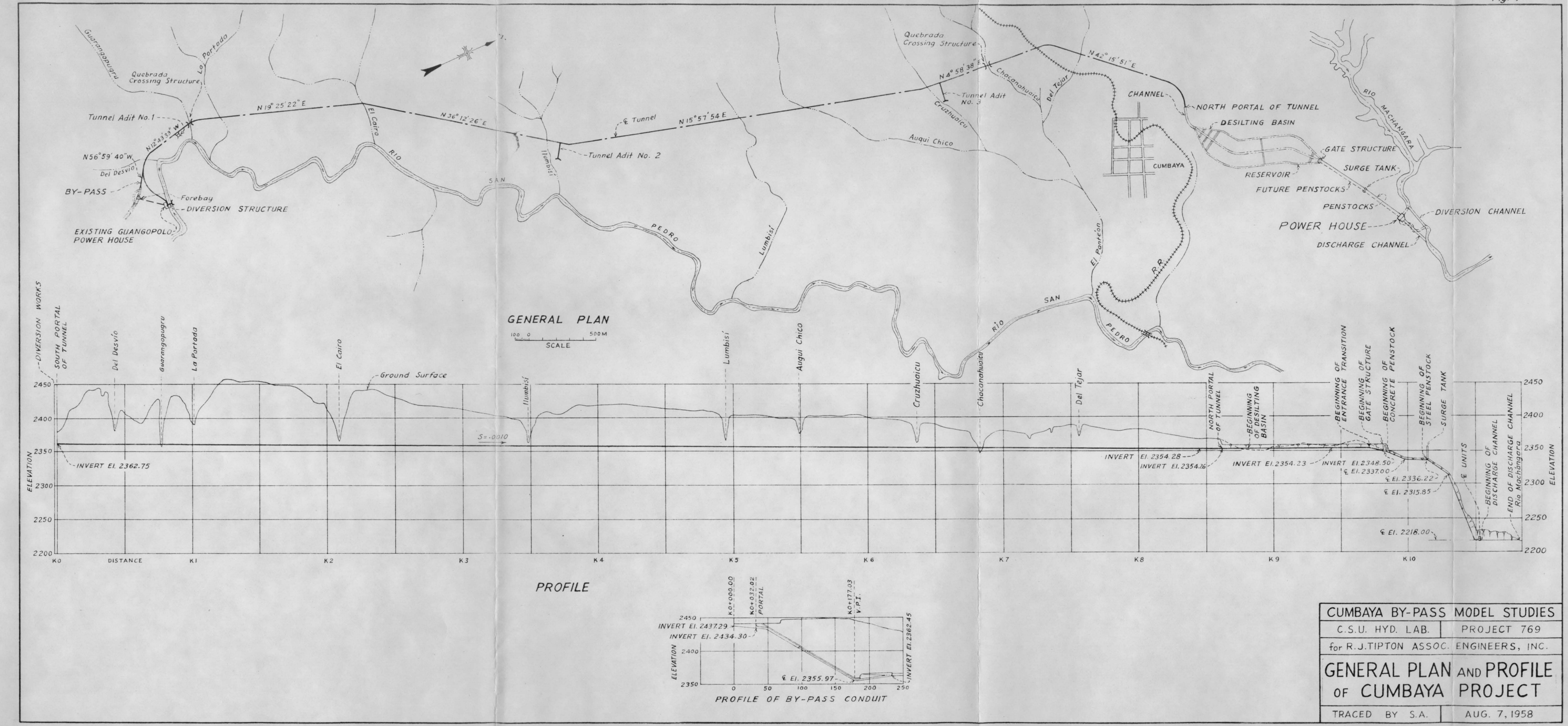
Pipe Length Ft.	Pipe Dia. In.	Friction Factor f.
10.73	4.25	.017
25.37	2.25	.013

Boil Heights

Discharge in c.f.s.	Distance from top of Boil to Crown of Tunnel in Proto. Meters.
0.54	Reaches Crown of Tunnel
0.41	0.5
0.27	1.0
0.13	1.5

TABLE OF MODEL DATA - Cont.

PIEZ No.	Pressure in Feet of Water				PIEZ No.	Pressure in Feet of Water				REMARKS
	Q=0.54 c.f.s.	Q=0.41 c.f.s.	Q=0.27 c.f.s.	Q=0.13 c.f.s.		Q=0.54 c.f.s.	Q=0.41 c.f.s.	Q=0.27 c.f.s.	Q=0.13 c.f.s.	
21	-0.78	-0.55	0.41	0.17	49	1.31	1.06	0.49	0.84	
22	-0.57	-0.37	0.37	0.12	50	1.26	1.02	0.58	0.82	
23	-0.48	-0.15	0.42	0.18	51	1.21	1.00	0.85	0.78	
24	-0.26	0.04	0.42	0.17	52	1.16	0.98	0.85	0.74	
25	-0.05	0.40	0.50	0.22	53	1.13	0.97	0.83	0.72	
26	-0.19	0.76	0.42	0.15	54	1.04	0.90	0.78	0.66	
27	-0.25	0.97	0.45	0.14	55	0.39	0.80	0.71	0.62	
28	-0.02	1.32	0.86	0.31	56	0.49	0.37	0.27	0.15	
29	0.36	1.75	1.46	0.64	57	0.75	0.67	0.57	0.48	



CUMBAYA BY-PASS MODEL STUDIES

C.S.U. HYD. LAB. | PROJECT 769

for R.J. TIPTON ASSOC. ENGINEERS, INC.

GENERAL PLAN AND PROFILE OF CUMBAYA PROJECT

TRACED BY S.A. | AUG. 7, 1958

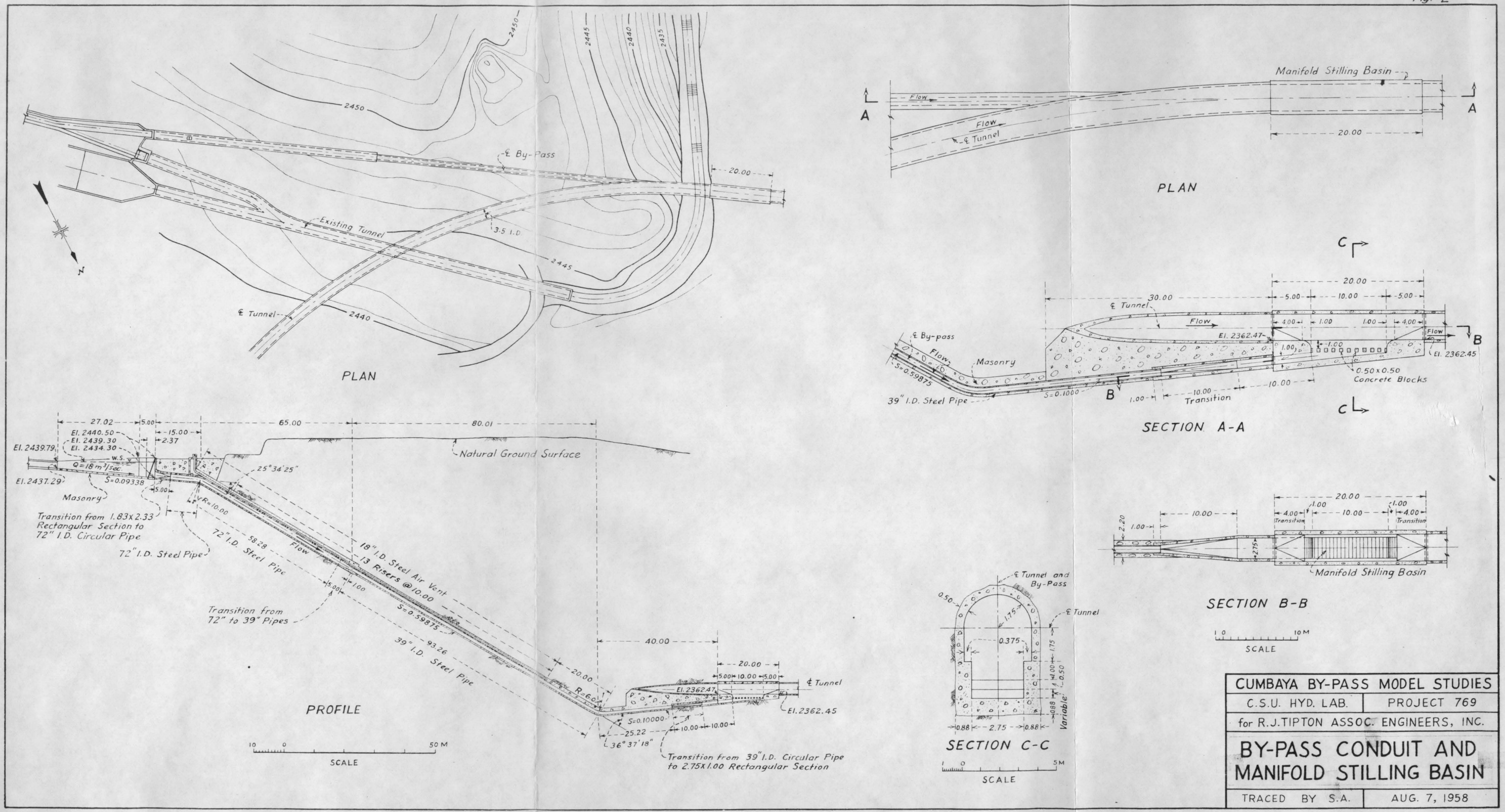

PLAN
℄ By-Pass
Existing Tunnel
℄ Tunnel
3.5 I.D.
20.00
2450
2445
2440
2435
PROFILE
Natural Ground Surface
El. 2439.79
El. 2440.50
El. 2439.30
El. 2434.30
El. 2437.29
Q=18 m³/sec
S=0.09338
Masonry
Transition from 1.83x2.33 Rectangular Section to 72" I.D. Circular Pipe
72" I.D. Steel Pipe
18" I.D. Steel Air Vent
13 Risers @10.00
25°34'25"
36°37'18"
Transition from 72" to 39" Pipes
39" I.D. Steel Pipe
S=0.59875
S=0.10000
El. 2362.47
El. 2362.45
Transition from 39" I.D. Circular Pipe to 2.75x1.00 Rectangular Section
SCALE
PLAN
Manifold Stilling Basin
Flow
℄ Tunnel
SECTION A-A
℄ By-pass
Masonry
39" I.D. Steel Pipe
S=0.59875
S=0.1000
Transition
0.50x0.50 Concrete Blocks
El. 2362.47
El. 2362.45
SECTION B-B
Manifold Stilling Basin
SECTION C-C
℄ Tunnel and By-Pass
℄ Tunnel
Variable
SCALE
CUMBAYA BY-PASS MODEL STUDIES
C.S.U. HYD. LAB.
PROJECT 769
for R.J.TIPTON ASSOC. ENGINEERS, INC.
BY-PASS CONDUIT AND MANIFOLD STILLING BASIN
TRACED BY S.A.
AUG. 7, 1958

Fig. 2

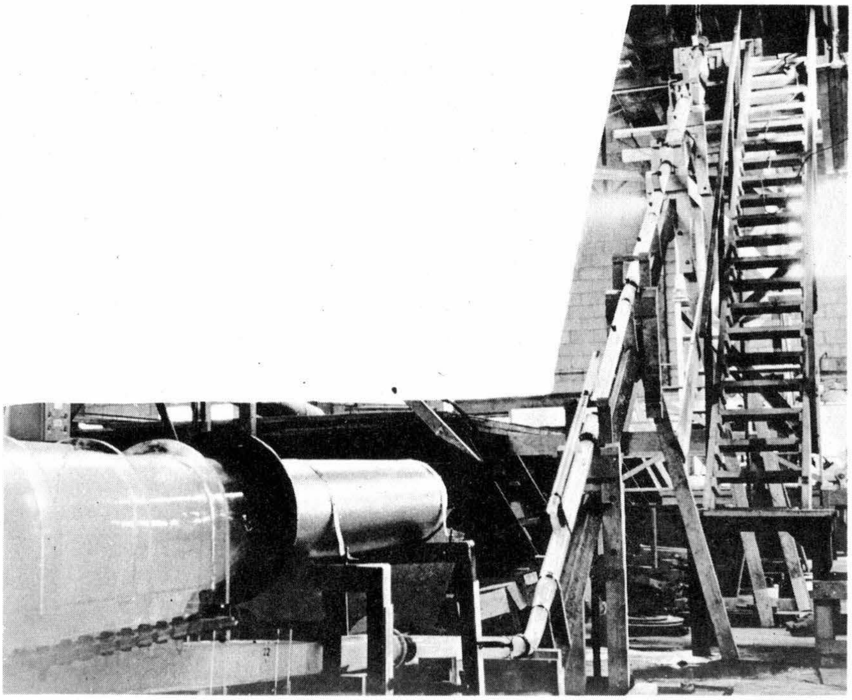


Fig. 3 Photograph of Cumbayá By-Pass Model

TRCD. T.Y.G.

CUMBAYA BY-PASS MODEL STUDIES	
C.S.U. HYD. LAB.	PROJECT 769
for R.J. TIPTON ASSOC. ENGINEERS, INC.	
MODEL OF ORIGINAL BY-PASS MODEL SCALE 1:17	
DWN. BY S.K. & S.A.	AUG. 7, 1958

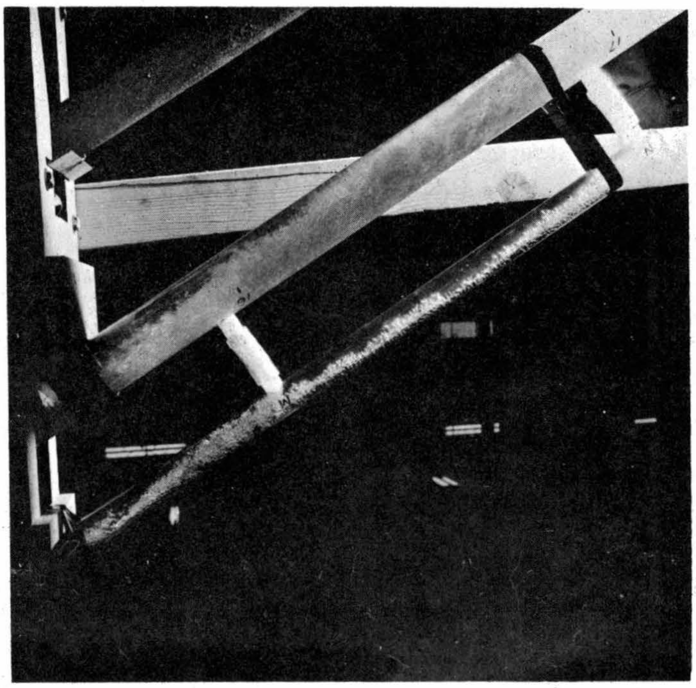


Fig. 5 Photograph Showing Water in the Vent Pipe With Considerable Amount of Air Entrainment.

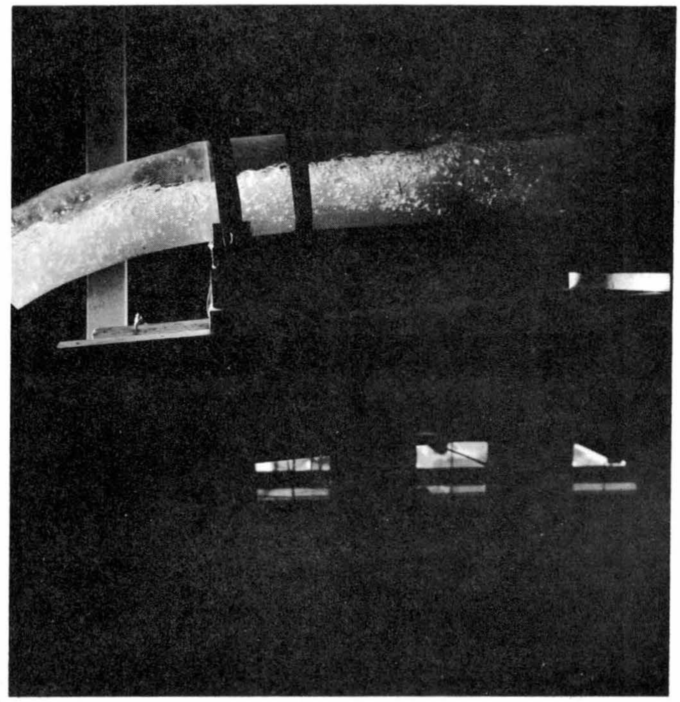


Fig. 6 Flow Conditions at Upper Bend for $Q = 8\ m^3/sec$ with No Air Vent.

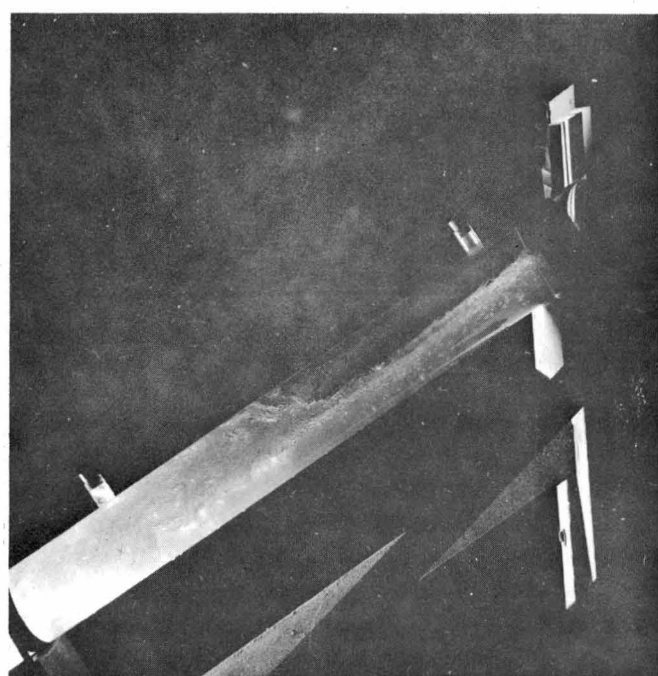


Fig. 7 Hydraulic Jump in Conduit for $Q = 8\ m^3/sec$.

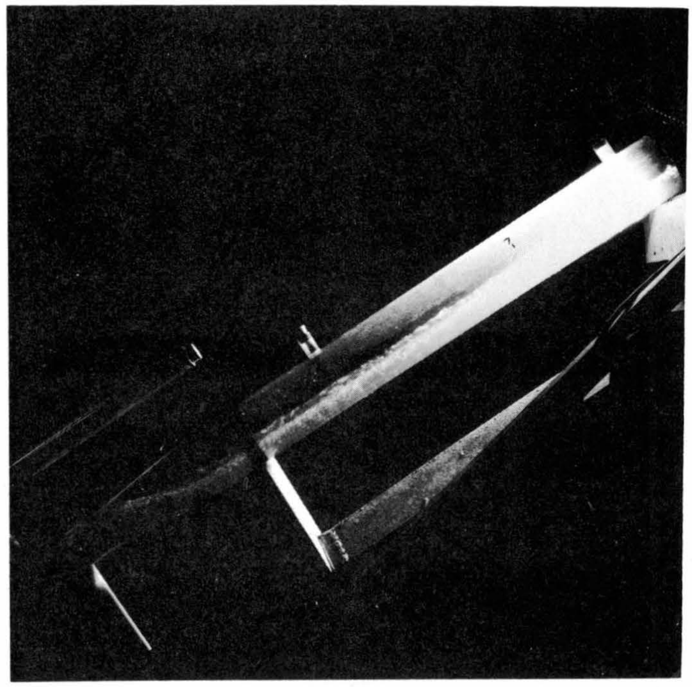


Fig. 8 Flow at Transition for Small Discharge: $Q < 3\ m^3/sec.$

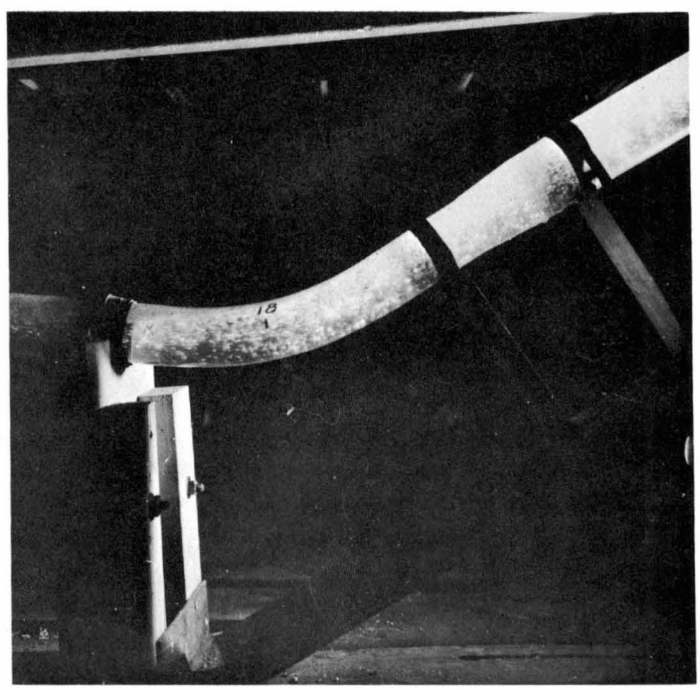


Fig. 9 Flow at Lower Bend $Q = 8\ m^3/sec.$

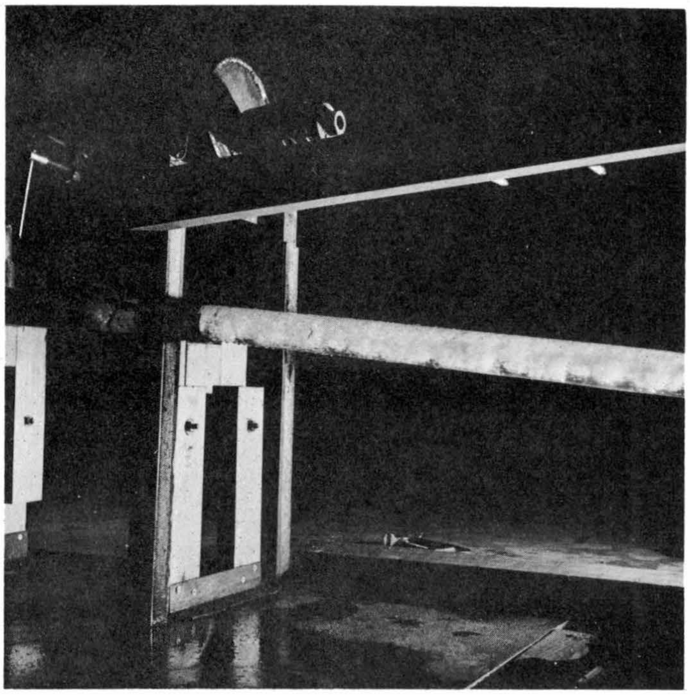


Fig. 10 Flow in Conduit Approach to Stilling Basin $Q = 8\ m^3/sec.$

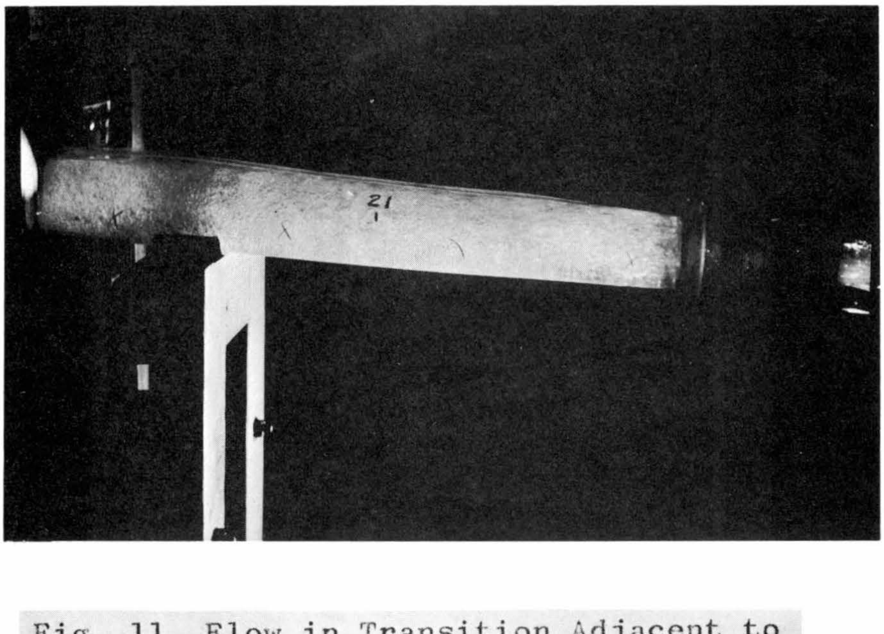


Fig. 11 Flow in Transition Adjacent to Stilling Basin $Q = 8\ m^3/sec.$

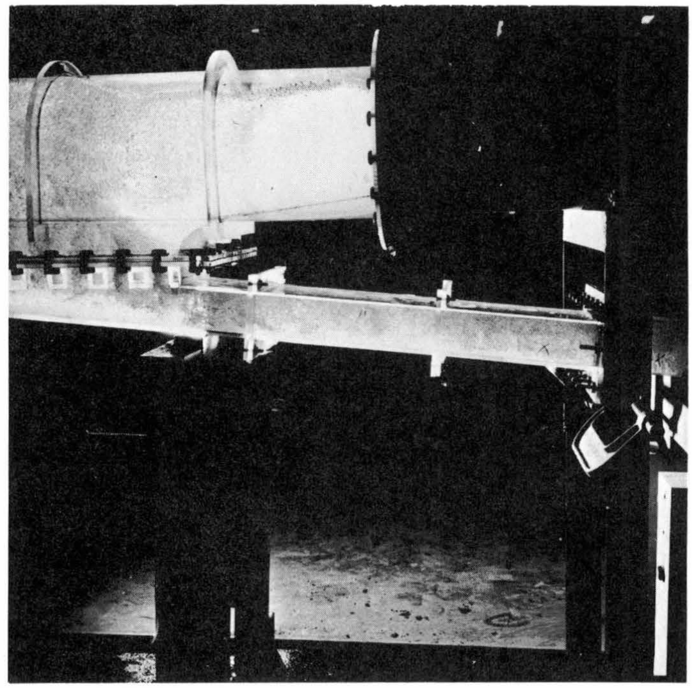


Fig. 12 Flow in Approach to Stilling Basin Q = 8 m^3/sec.

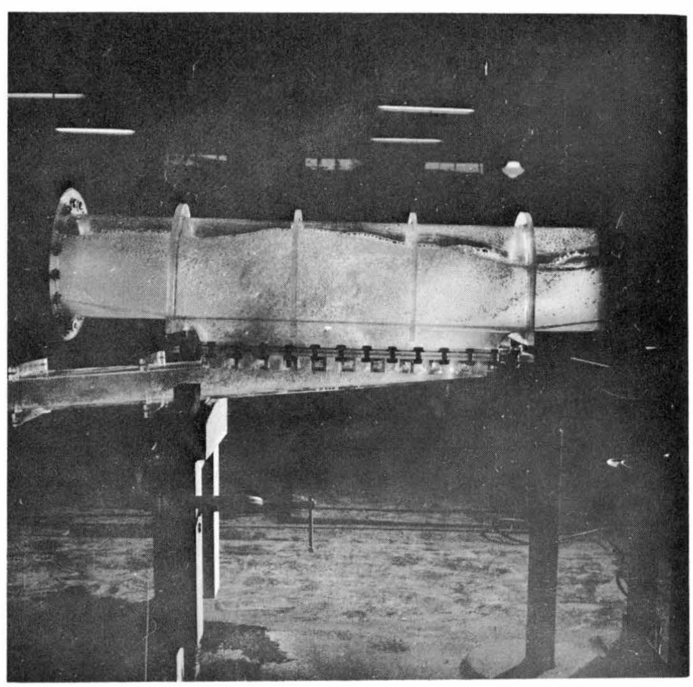


Fig. 13 Flow in Manifold Stilling Basin at Q = 8 m^3/sec.

NOTES

Model dimensions only are shown.
The hydraulic grade lines shown are model data and must be adjusted to predict prototype values.
See text of report.

CUMBAYA BY-PASS MODEL STUDIES	
C.S.U. HYD. LAB.	PROJECT 769
for R. J. TIPTON ASSOC. ENGINEERS, INC.	
MODEL OF MODIFIED BY-PASS MODEL SCALE 1 : 17	
DWN. BY S.K. & S.A.	AUG. 11, 1958

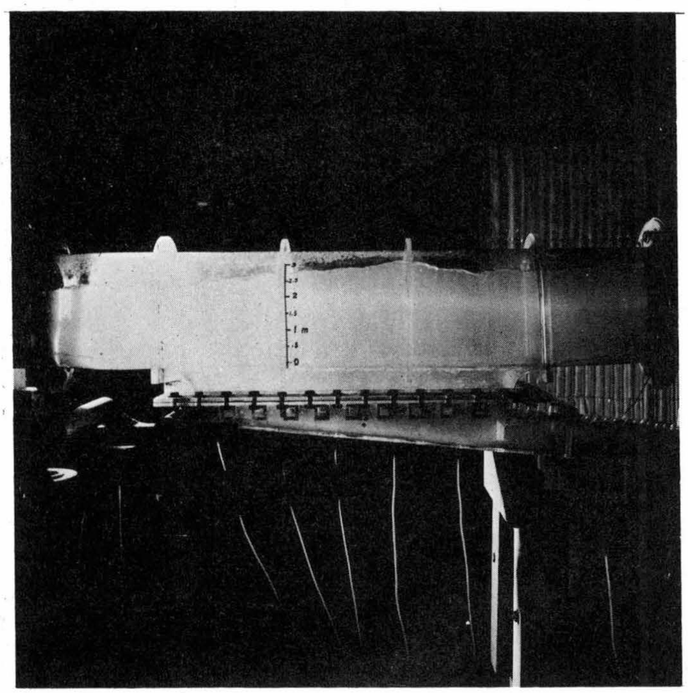


Fig. 15 Flow in Manifold Stilling Basin
Modified By-Pass $Q = 18\ m^3/sec.$