HYDRAULIC MODEL STUDY

CONROE DAM SPILLWAY

SAN JACINTO RIVER AUTHORITY
TEXAS

CIVIL ENGINEERING DEPARTMENT

ENGINEERING RESEARCH CENTER
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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FINAL REPORT

OF

HYDRAULIC MODEL STUDIES

CONROE DAM SPILLWAY

SAN JACINTO RIVER AUTHORITY

TEXAS

Prepared for
Freese, Nichols and Endress
Fort Worth, Texas

by

J. F. Ruff and S. Karaki

Colorado State University
Engineering Research Center
Civil Engineering Department
Fort Collins, Colorado
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PREFACE

The Engineering Research Center at Colorado State University is located between two lakes, Horsetooth Reservoir of the Colorado Big Thompson Project, and College Lake. The laboratories of the Center were strategically placed to utilize the high head, 250 feet, available from the reservoir and the storage capacity of the lake. The Center is the focal point for research and graduate education.

There are four principal parts to the Center; the offices for staff and graduate students, the hydraulics laboratory, the fluid dynamics laboratory, and the outdoor hydraulics - hydrology laboratory. The research activities of the Center are fluid mechanics, hydraulics, hydrology, ground-water, soil mechanics, hydro-biology, geomorphology and environmental engineering.

The hydraulics laboratory includes 50, 000 square feet of floor space in which basic and applied research activities are undertaken. The floor of the laboratory is constructed over a large sump system, having one-acre foot capacity, which permits recirculation of water through the various research facilities. Generally, pumps are used for recirculation but the high head and large flow capacity from the reservoir can also be utilized.

The Center includes well equipped machine and woodwork shops. All research facilities of the Center are constructed on site and in the case of this model study, necessary metal work, carpentry, and nearly all the plastic work was done by personnel in the shops. The shop personnel are particularly well experienced in the art and skill of model construction.

Grateful acknowledgement is hereby expressed by the writers to Mr. W. L. Eeds of Freese, Nichols and Endress for his cooperation during the conduct of this study, to personnel of the machine shops for their ingeneous contributions in solving model construction problems, particularly in the plastic works and to others contributing to the model study and the preparation of this report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

SUMMARY

This report describes a hydraulic model study of the morning glory spillway for Conroe Dam. Specific studies of the morning glory spillway, vertical bend, and stilling basin, indicated that the morning glory spillway was satisfactory as designed for all discharges and symmetrical combination of open gates. Discharge rating curves for the spillway for different gate combinations are provided in Fig. 22. The spillway structure was modified to include an air vent and a deflector above the vent at the P. C. of the vertical bend, to eliminate detrimental negative pressures along the inside radius of the bend.

The original stilling basin floor level was raised 5 feet and 3 additional feet were recommended to be added to the top of the walls for freeboard. Immediately downstream of the conduit portal, fillets should be included to form a transition from a circular to rectangular section, to prevent negative pressures from developing at the boundaries.

Graded rip rap of 39 to 42-in. maximum size, five feet thick should be provided for a distance of 200 ft downstream of the basin to prevent scouring of the earth channel. A layer of gravel should underlie the rip rap. An earth channel 200 feet wide and 6.5 feet deep with an overbank flow width of at least 700 ft wide at elevation 142 feet should be provided to accommodate the flow. The model construction, tests, and conclusions and recommendations are described in this report.

INTRODUCTION

General Description of the Project

Conroe Dam is a proposed earth-fill dam to be constructed by the San Jacinto River Authority at a site approximately 7 miles northwest of the town of Conroe, Texas, across the West Fork of the San Jacinto River. The length of the dam at the crest is approximately 12, 000 ft. The crest elevation is at 220. 0 ft.[1] The upstream face of the dam is sloped at 3:1 (horizontal to vertical) from the base to an 85 foot wide berm at elevation 160. 0. The 3:1 slope continues from the berm to the maximum normal water level at 201. 0 and is 2:1 from there to the crest. The downstream slope is 3:1 from the crest to a berm at elevation 175. 0. The 3:1 slope continues from the berm to the base. The width of the dam crest is 20 feet. A general plan of the dam and appurtenant works is shown in Fig. 1.

The project is conceived as a water storage and flood control project. The reservoir capacity will be approximately 430, 000 acre-feet. The proposed reservoir spillway is a morning glory type to be capable of passing floods up to 22, 000 cfs. The crest of the morning glory is at elevation 189. 0 and is 60 ft in diameter. It will be gated with 12 vertical fixed wheel gates to permit controlled outflow through the spillway.

Description of the Spillway

The location of the spillway relative to the dam is shown in Fig. 1. Detail plan and profile of the spillway is given in Fig. 2. The spillway consists of three principal features: the morning glory crest structure, the circular conduit and the hydraulic jump stilling basin. Details of these features are shown in Fig. 3.

The morning glory crest is at elevation 189. 0 where the diameter is 56. 0 ft which narrows to 23. 5 ft diameter at elevation 153. 0, 63 ft below the crest. There the 23. 5 ft circular conduit enters into a 90-degree vertical bend with a radius of 35. 25 ft to the centerline of the conduit. Because of the small radius of curvature relative to the diameter of the conduit it was particularly important to investigate boundary pressures and flow conditions in the bend. Twelve equally spaced piers are located around the circumference of the spillway which extends from the base at elevation 101. 5, 118. 5 feet to the top at elevation 220. 0.

A circular conduit 23. 5 feet in diameter extends from the end of the vertical bend 495. 86 ft downstream to a stilling basin. Approximately 300 feet of the initial length is inclined upward at a slope of 0. 090 which levels out at an invert elevation of 137. 50. The purpose for the upward inclination is to keep part of the conduit flowing full at all times and to keep the portal of the tunnel above the influence of the backwater in the downstream channel.

The stilling basin consists of a flared chute approach to the basin 131. 0 ft long and a hydraulic jump basin 93. 75 ft long. Chute and floor blocks are provided in the basin to assist formation and stabilization of the jump. The basin is 55. 0 ft wide and the floor elevation is at 112. 0. The stepped end sill at the end of the basin is 8 ft in height. Downstream of the basin a rip rapped transition section will be required to join with the channel.

Scope of the Model Study

The purpose of the model study was to investigate the hydraulic performance of the morning glory spillway, the hydraulic conditions within the elbow and conduit, and the performance of the chute and stilling basin for the expected range of head water levels, discharges and tailwater levels. The specific objectives sought in the model study are listed below:

1. Determine through visual observation, photographs, and pressure data the flow characteristics through the morning glory spillway, the vertical bend, the conduit, and the stilling basin for all expected discharges.

2. Observe flow through the spillway and pressures on the crest for various numbers and combinations of open gates; 1, 2, 3, 4, 6 and 12, at several reservoir levels. The bottom of the gate in all instances to be above the water surface.

3. Determine the existence and magnitude of negative pressures on the boundaries and the necessity of aeration to relieve the negative pressures.

4. Study the performance of the stilling basin for the full range of discharges with the tailwater at the expected minimum elevation 142. 0 and the expected maximum elevation 150. 5.

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[1] All elevations or levels expressed in numbers will be understood to have dimensions in feet whether or not it is explicitly stated.

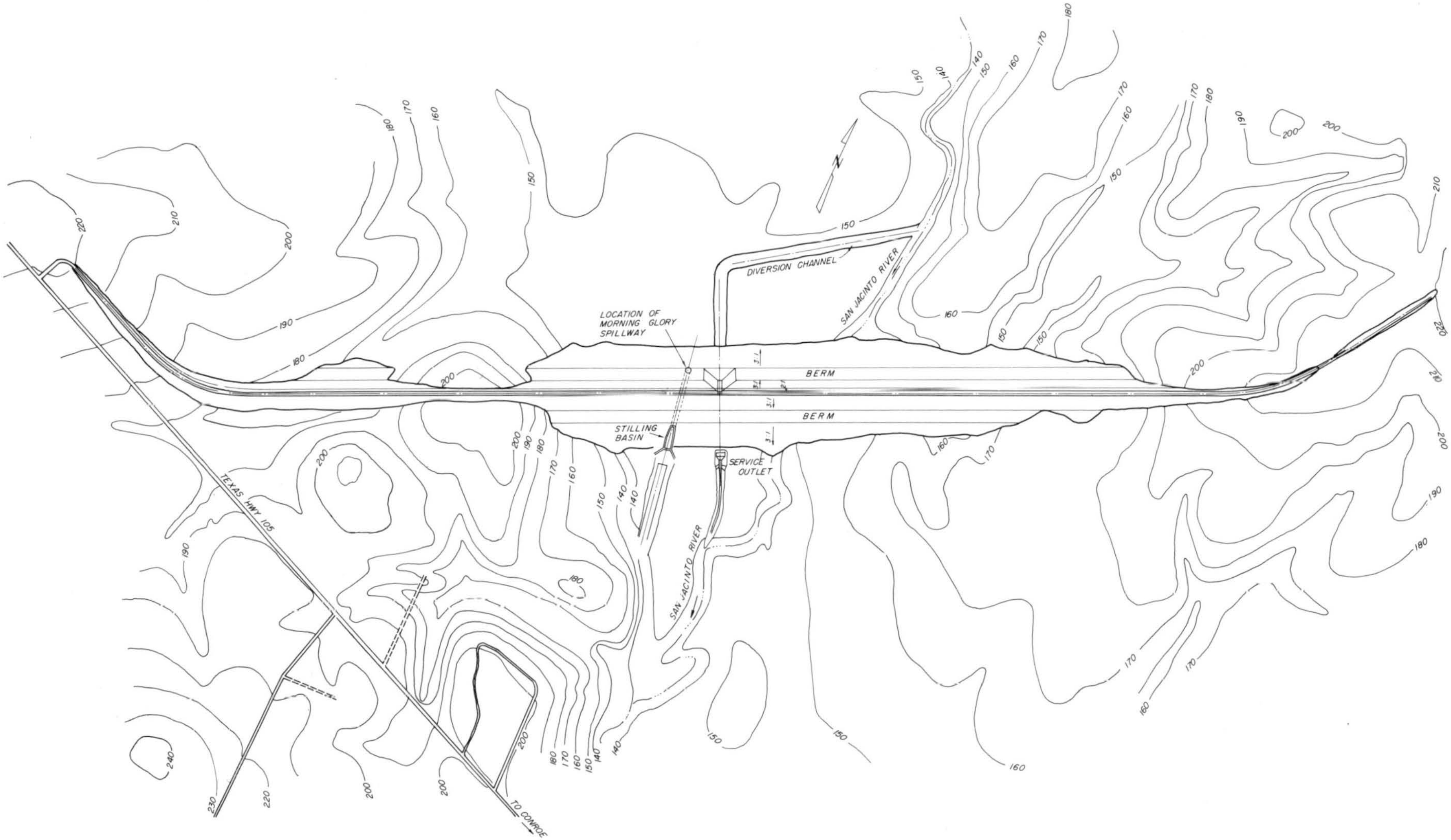


FIGURE I GENERAL PLAN OF CONROE DAM

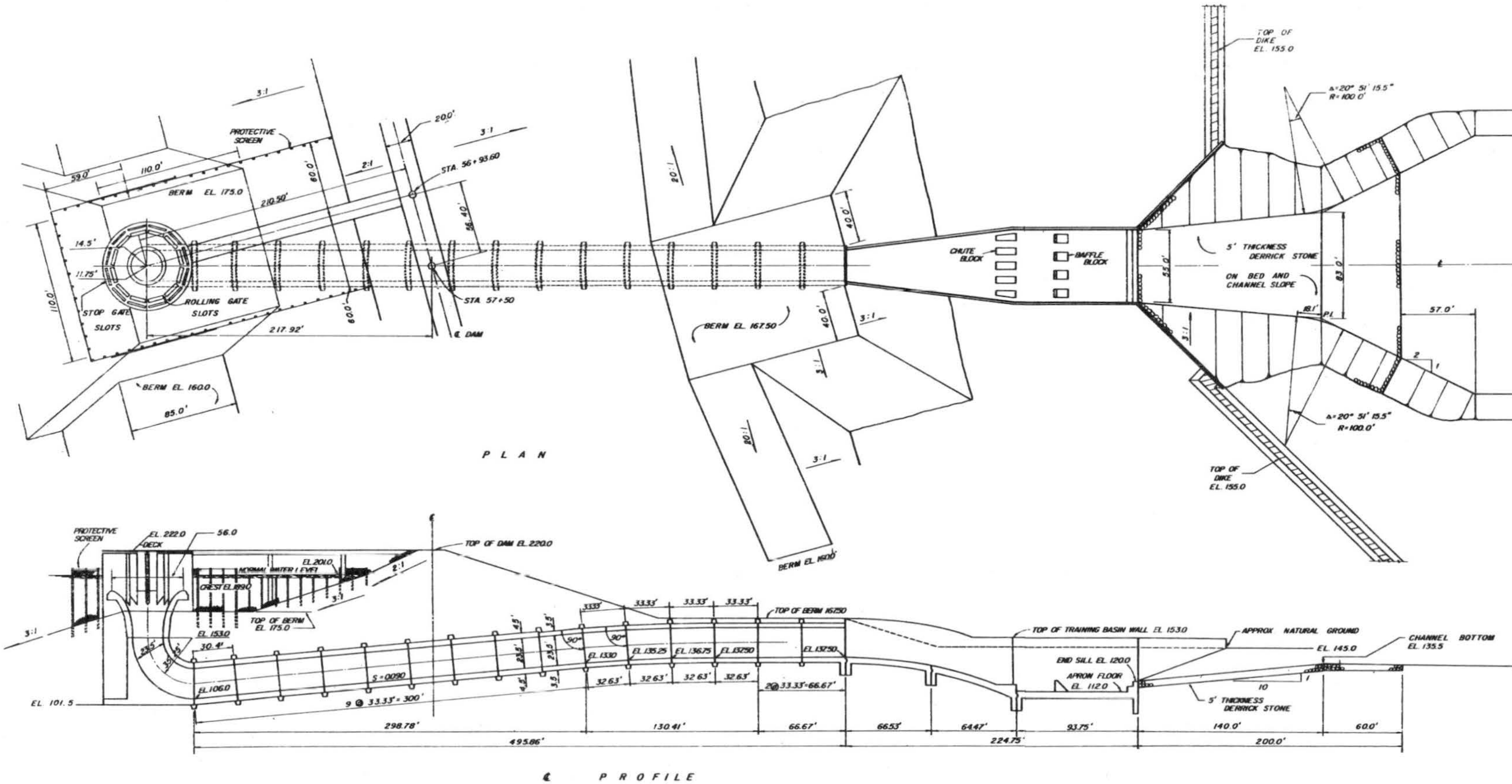
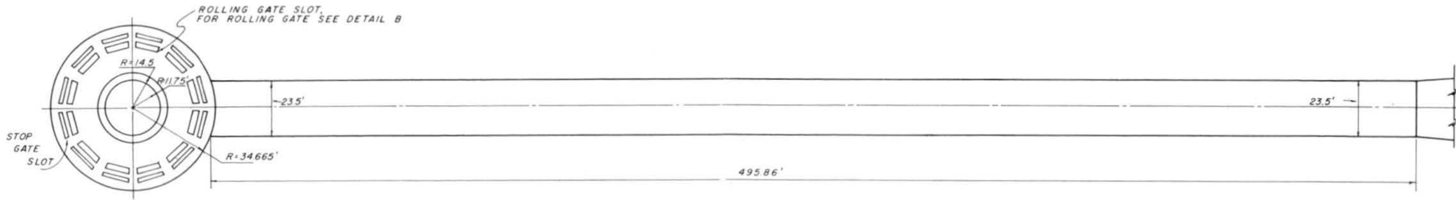
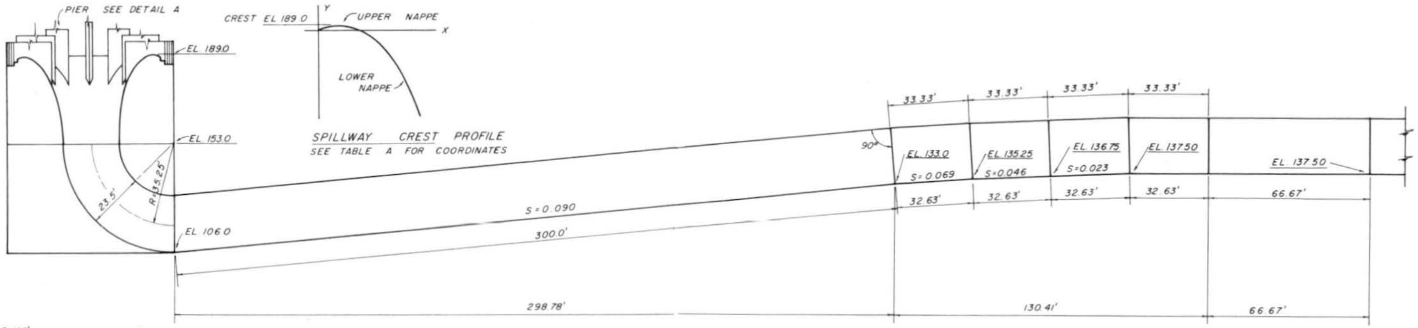


FIGURE 2 CONROE DAM FLOOD SPILLWAY



PLAN

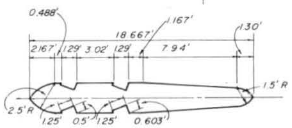


PROFILE

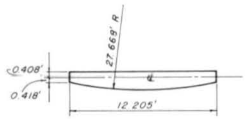
TABLE A

COORDINATES OF SPILLWAY CREST

UPPER NAPPE COORDINATES X FEET	UPPER NAPPE COORDINATES Y FEET	LOWER NAPPE COORDINATES X FEET	LOWER NAPPE COORDINATES -Y FEET
0.000	0.000	5.268	0.000
0.128	0.156	5.776	0.255
0.255	0.287	6.212	0.510
0.383	0.393	6.620	0.765
0.510	0.481	7.003	1.020
0.638	0.556	7.360	1.276
0.765	0.624	8.176	1.913
0.893	0.685	8.904	2.551
1.020	0.737	9.567	3.189
1.148	0.782	10.166	3.827
1.276	0.819	11.225	5.102
1.531	0.871	12.131	6.378
1.786	0.899	12.909	7.654
2.041	0.906	14.185	10.205
2.296	0.899	15.167	12.756
2.551	0.878	15.919	15.307
3.189	0.760	16.494	17.858
3.827	0.569	16.965	20.410
4.465	0.357	17.323	22.961
5.102	0.077	17.616	25.512
		17.862	27.090
		18.188	32.090
		18.250	35.090



PLAN



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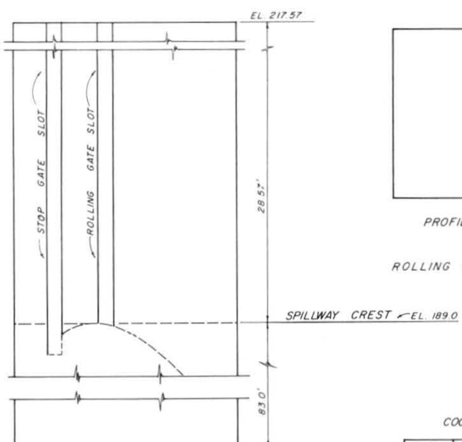
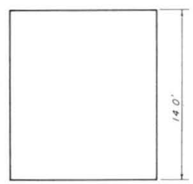


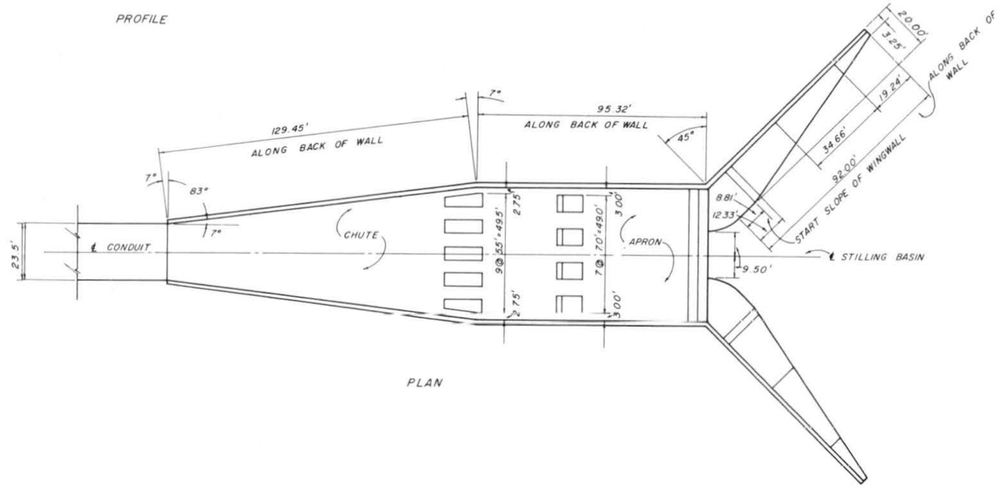
PROFILE

PIER DETAIL "A"

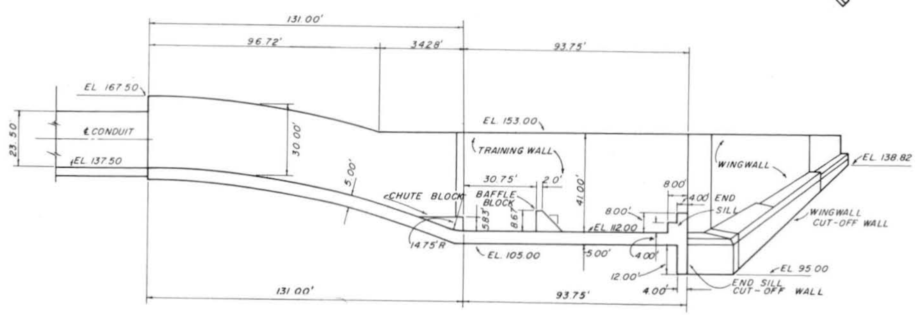


PROFILE

ROLLING GATE DETAIL "B"



PLAN



℄ PROFILE

TABLE B

COORDINATES OF CHUTE

X FEET	-Y FEET	X FEET	-Y FEET
0.00	0.00	65.00	6.55
5.00	0.04	70.00	7.60
10.00	0.16	75.00	8.72
15.00	0.35	80.00	9.92
20.00	0.62	85.00	11.20
25.00	0.97	90.00	12.56
30.00	1.40	95.00	13.99
35.00	1.90	100.00	15.50
40.00	2.48	105.00	17.09
45.00	3.14	110.00	18.76
50.00	3.88	115.00	20.50
55.00	4.69	120.00	22.32
60.00	5.58	125.32	24.22

CHUTE PROFILE

FIGURE 3 DETAILS OF STRUCTURE

5. Recommend rip rap sizes in the transition from the stilling basin to the channel and recommend a channel size downstream from stilling basin.

Selection of Model Scale and Model Criteria

The objective of a hydraulic model is to develop dynamically and kinematically similar flows as the prototype. This requires that geometrical similitude be maintained. Dimensional analysis will show that both the Froude and Reynolds numbers are important for the objectives of this study. For instance, the free overflow into the morning glory spillway, the hydraulic jump in the stilling basin and the open channel flow are dependent upon gravity predominantly, hence the Froude criterion prevails, whereas, for the closed conduit flow where viscous effects are dominant, the Reynolds number is important. Because in this study the open channel flow aspects dominate, the Froude criterion was chosen to determine the geometric scale.

A model-prototype relationship of about 1:30 was determined to be most feasible from an analysis of scale ratios based upon model size required for accurate measurements, flow conditions, available laboratory space and facilities, and economy of cost. The actual geometric scale used was 1:31.333 which was determined by the available sizes of commercially manufactured cast acrylic resin tubes used to represent the conduit. Table I contains a list of some of the characteristic model-prototype ratios based upon the selected scale.

TABLE I

MODEL PROTOTYPE SCALE RATIOS

Parameter	Scale Ratio		Absolute Magnitude	
	Function of the length	Numerical Ratio	Prototype	Model
Length	L_r	1:31.333	1 ft	0.383 in.
Area	$(L_r)^2$	1:981.757	1000 ft^2	1.019 ft^2
Velocity	$(L_r)^{1/2}$	1:5.598	1 fps	0.179 fps
Discharge	$(L_r)^{5/2}$	1:549.86	10000 cfs	1.820 cfs
Time	$(L_r)^{1/2}$	1:5.598	1 min	10.718 sec

THE MODEL

Model Construction

The general limits of the model are shown in Fig. 4. Dimensions of the model facilities and actual arrangement are given in Fig. 5 with a photograph of the completed model shown in Fig. 6.

The head box and tail box were constructed of plywood and waterproofed with a fiberglas lining. The inside dimensions of the head box were 10 ft wide by 12 ft long by 3 ft deep. The tail box was constructed to the size indicated in Fig. 5. The areal extent of the tail box was considered sufficient to provide control of the tailwater level, by a hinged gate at the downstream end of the tail box.

Water to the head box was supplied by a 14-inch turbine pump. The discharge was regulated by a control valve in the pipe line near the head box. A rock baffle was used to distribute the flow uniformly in the approach to the spillway. The approach velocity in the head box was designed to be small enough to assure that model effects would not influence the results of the study. The topography of the upstream face of the dam was included in the model to represent the approach conditions in the prototype. Discharge measurements were made with a calibrated orifice in the supply line.

The morning glory spillway was constructed by forming a wood mold in the lathe to the exact inside dimension of the spillway and then covering this mold with fiberglas as shown in Fig. 7. Four lines of piezometers were installed in the spillway to measure pressures on the face of the crest. The position and and orientation, with respect to the conduit, of the piezometers are shown in Fig. 8. To provide a continuous line of piezometers along the crest of the spillway, the vertical bend, and the crown and invert of the conduit, the piers in the model were rotated 7.5^{0} with respect to those in the prototype. This rotation of the piers did not affect the performance or flow conditions of the spillway nor the results of the tests.

The piers were milled from solid sheets of plexiglass and oriented on the spillway as noted above. Figure 9 shows how the piers were installed on the morning glory spillway, and Fig. 10 shows the morning glory installed in the head box. The fixed wheel roller gates were made from wood and coated with fiberglas for waterproofing. A rubber seal was glued to the edge of the gates.

The 90^{0} vertical bend was molded with epoxy resin. The mold used in construction is shown in Fig. 11. Four lines of piezometers were installed to measure the pressures at the boundaries, located as shown in Fig. 8.

A 9-inch inside diameter cast acrylic resin tube was used to model the 23.5 ft diameter conduit. Piezometers located along the crown and invert of the conduit are shown in Fig. 12.

The stilling basin was constructed from fiberglas coated plywood and plexiglass. Plywood formed the chute, basin floor, and left[2] wall. Plexiglass was used for the right wall to facilitate visual observation of the flow conditions and water surface profile within the stilling basin. Piezometers were located in the original stilling basin (hereinafter referred to as stilling basin I) as shown in Fig. 13. Piezometers were located only in the center chute block as shown in Fig. 14. The baffle block just to the right of the stilling basin center line had piezometers located as shown in Fig. 14. The chute and baffle blocks containing the piezometers were cut from blocks of plexiglass. The other chute and baffle blocks were wood blocks waterproofed with a fiberglas coating.

During testing of the model, stilling basin I was modified by raising the basin floor 5 feet from elevation 112.0 to 117.0. The modified stilling basin shall hereafter be referred to as stilling basin II. Details of stilling basin II and the location of piezometers are shown in Fig. 15. A modified baffle block (referred to as baffle block A) was tested in stilling basin II and the details of block A and piezometers located on it are shown in Fig. 14.

Piezometers

All piezometers were attached to manometer boards with flexible polyethylene tubing. Where negative pressures existed, measurements were made with a U-tube manometer.

[2] Left and right as used in this report refer to the observer's left and right looking downstream.

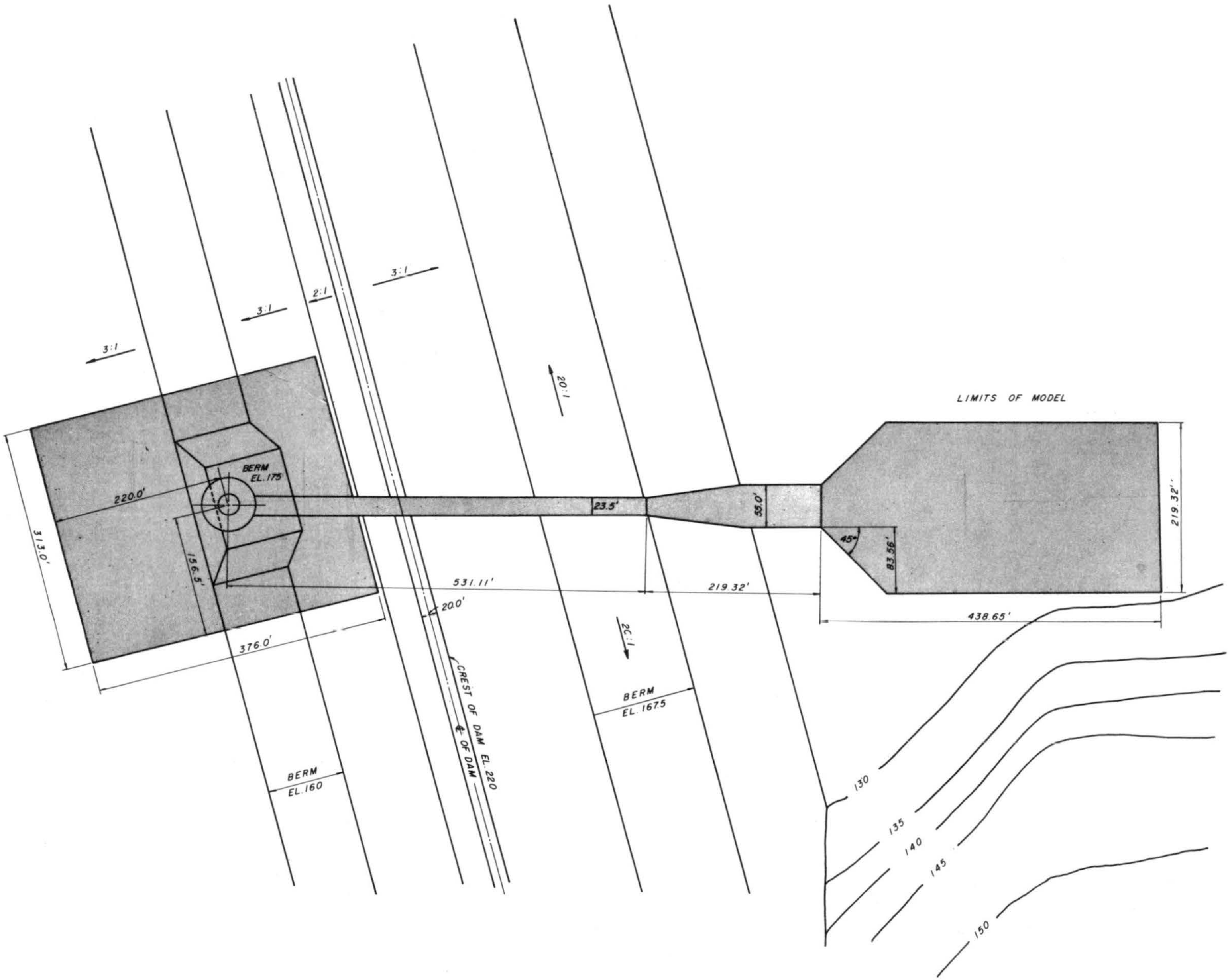


FIGURE 4 GENERAL LIMITS OF MODEL

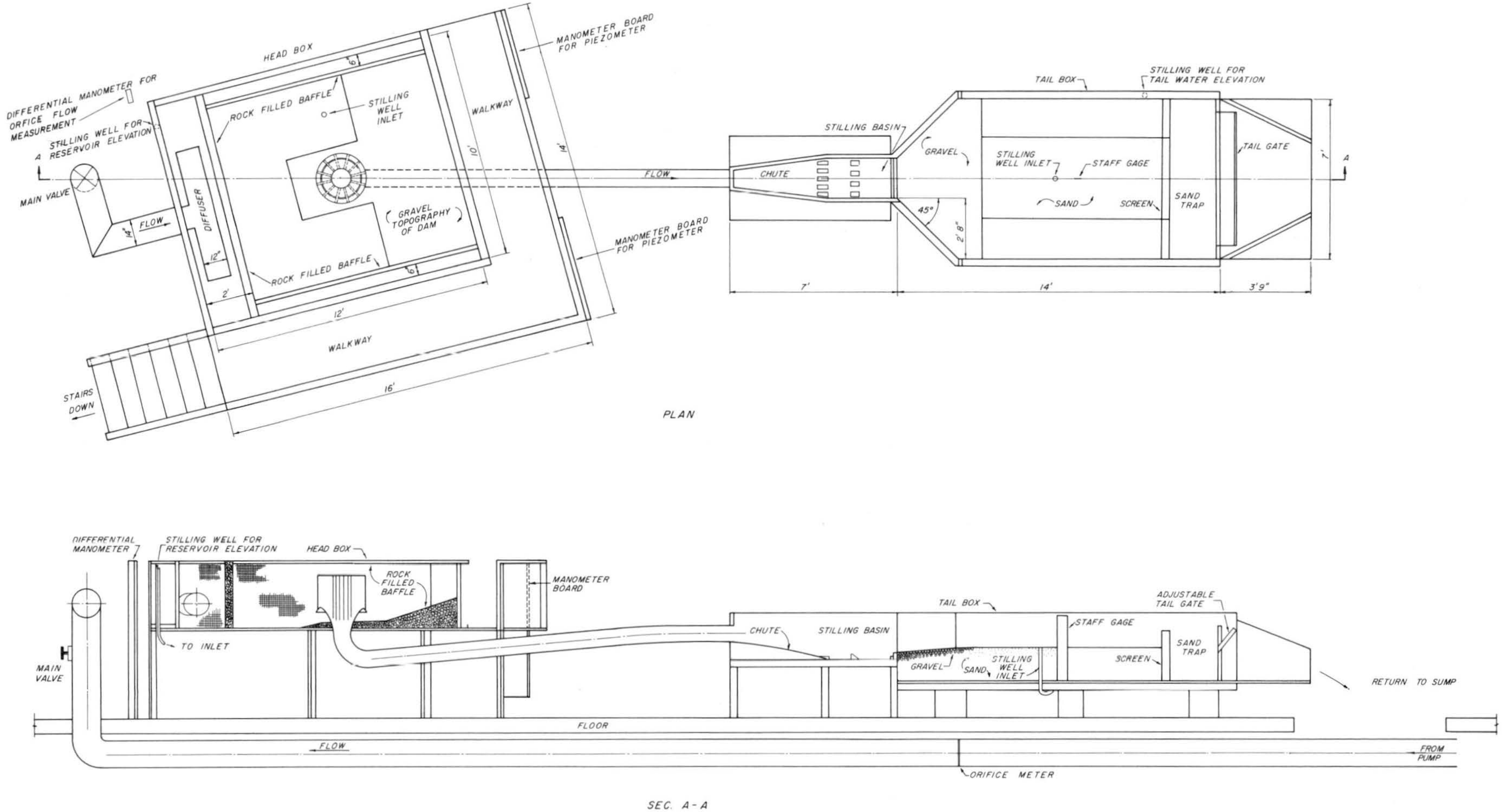
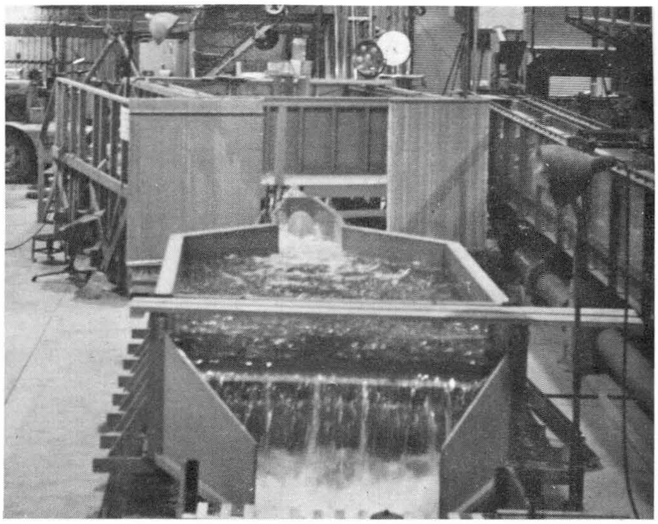


FIGURE 5 SCHEMATIC DRAWING OF MODEL



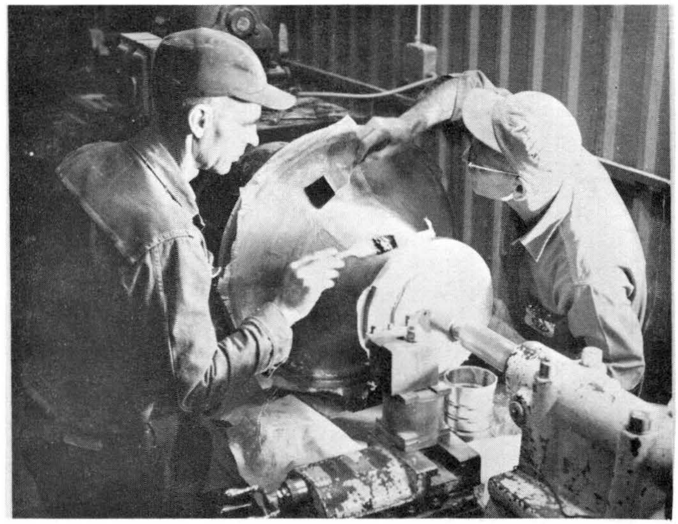
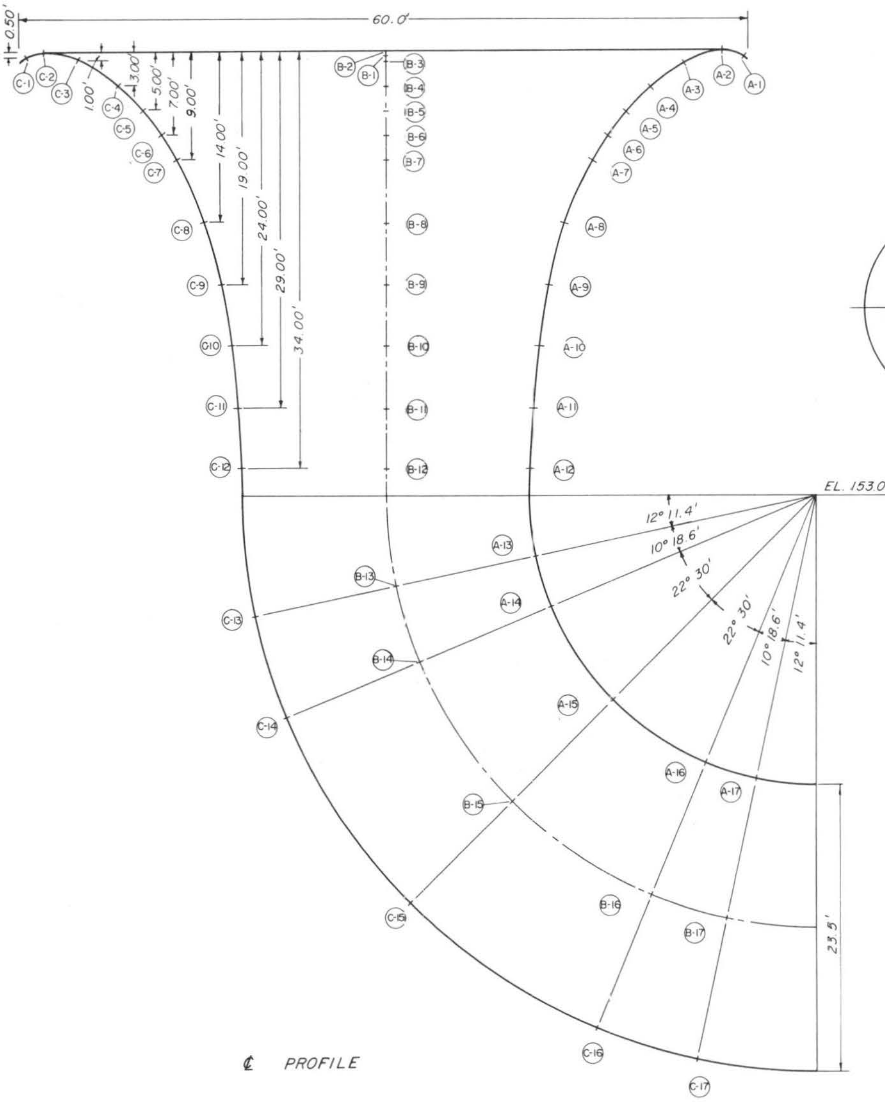
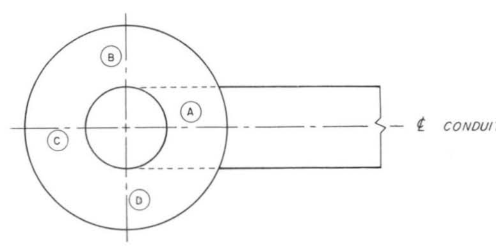


Fig. 6. Photograph of completed model.

Fig. 7. Morning glory spillway mold being covered with fiberglas.



ORIENTATION OF PIEZOMETERS



PIEZOMETER ELEVATIONS

PIEZO. NO.	ELEV. IN FT.
A,B,C,D – 1	188.5
A,B,C,D – 2	189.0
A,B,C,D – 3	188.0
A,B,C,D – 4	186.0
A,B,C,D – 5	184.0
A,B,C,D – 6	182.0
A,B,C,D – 7	180.0
A,B,C,D – 8	175.0
A,B,C,D – 9	170.0
A,B,C,D -10	165.0
A,B,C,D -11	160.0
A,B,C,D -12	155.0
A-13	148.0
A-14	144.0
A-15	136.5
A-16	131.5
A-17	130.0
B,D-13	145.5
B,D-14	139.5
B,D-15	128.0
B,D-16	120.5
B,D-17	118.5
C-13	143.0
C-14	135.0
C-15	120.0
C-16	109.5
C-17	107.0

FIGURE 8 MORNING GLORY SPILLWAY AND VERTICAL BEND PIEZOMETER LOCATIONS

Fig. 9. Installation of piers on the morning glory spillway crest.

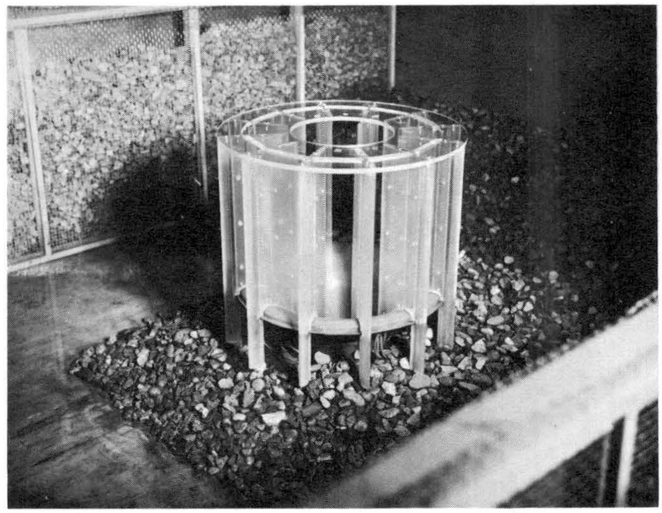


Fig. 10. Installation of the morning glory spillway and piers inside the head box.

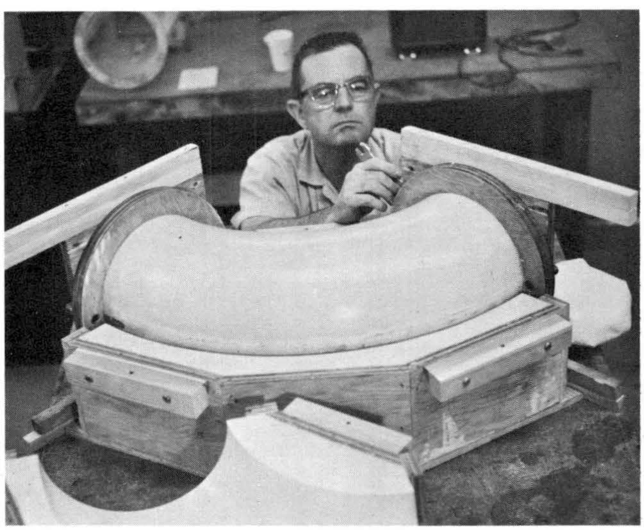
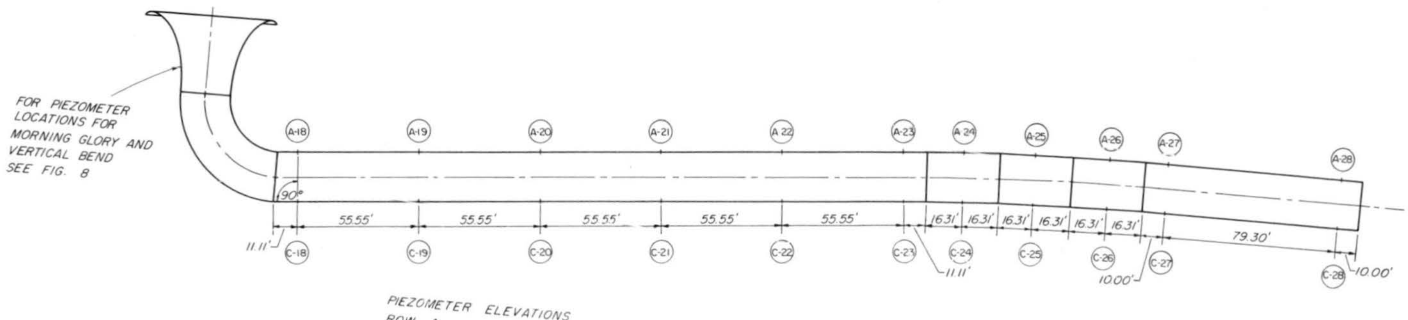


Fig. 11. Construction of the vertical bend mold.



PIEZOMETER ELEVATIONS
ROW A

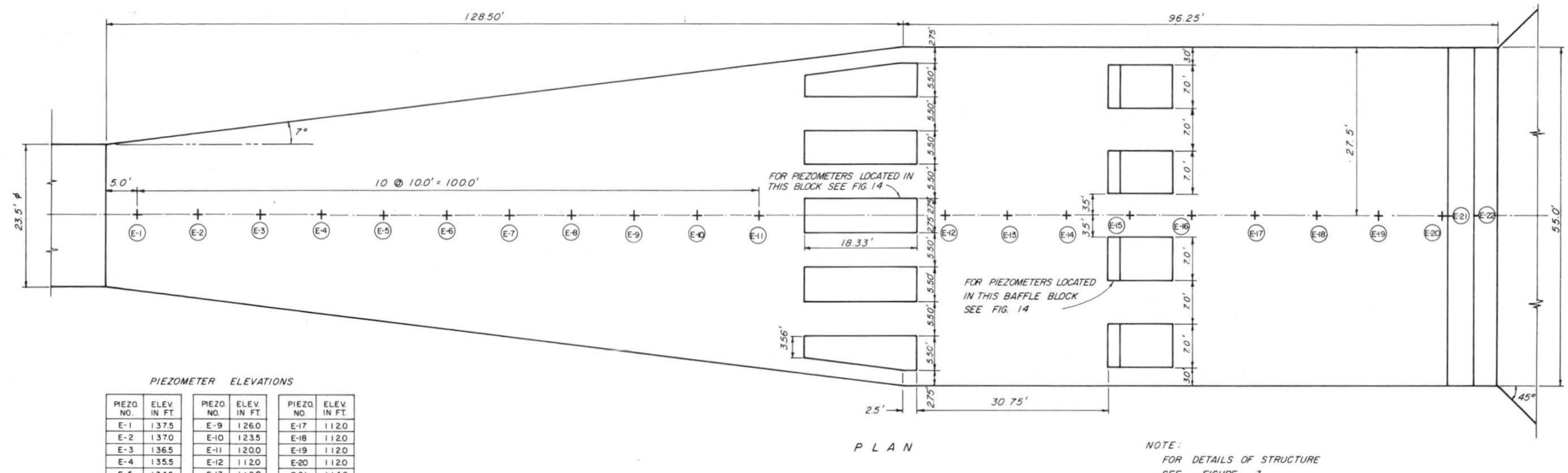
Piezo. No.	Elev. In Ft.
18	130.5
19	135.5
20	140.5
21	145.5
22	150.5
23	155.5
24	157.5
25	159.5
26	160.5
27	161.0
28	161.0

PIEZOMETER ELEVATIONS
ROW C

Piezo. No.	Elev. In Ft.
18	107.0
19	112.0
20	117.0
21	122.0
22	127.0
23	132.0
24	134.0
25	136.0
26	137.0
27	137.5
28	137.5

NOTE: PIEZOMETER LINES B AND D TERMINATE AT THE END OF VERTICAL BEND

FIGURE 12 CONDUIT PIEZOMETER LOCATIONS



PIEZOMETER ELEVATIONS

PIEZO. NO.	ELEV. IN FT.	PIEZO. NO.	ELEV. IN FT.	PIEZO. NO.	ELEV. IN FT.
E-1	137.5	E-9	126.0	E-17	112.0
E-2	137.0	E-10	123.5	E-18	112.0
E-3	136.5	E-11	120.0	E-19	112.0
E-4	135.5	E-12	112.0	E-20	112.0
E-5	134.5	E-13	112.0	E-21	114.0
E-6	133.0	E-14	112.0	E-22	118.0
E-7	131.0	E-15	112.0		
E-8	129.0	E-16	112.0		

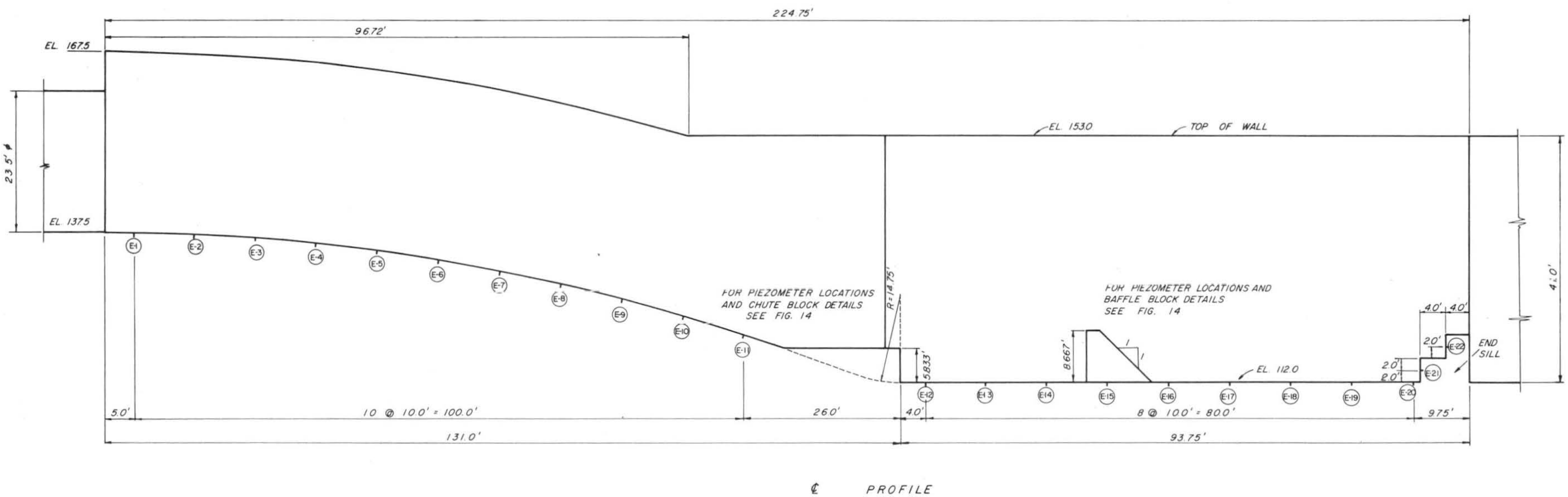
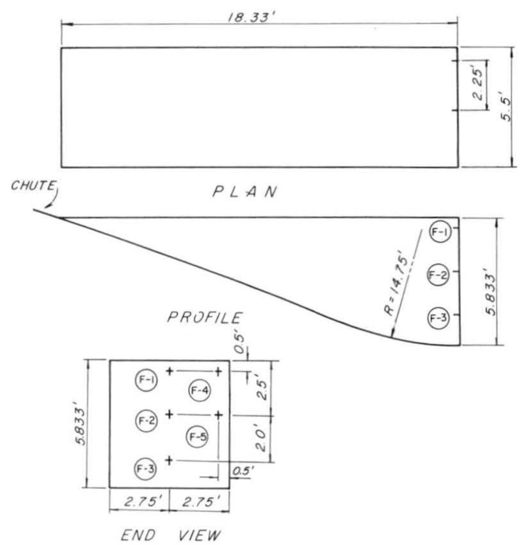
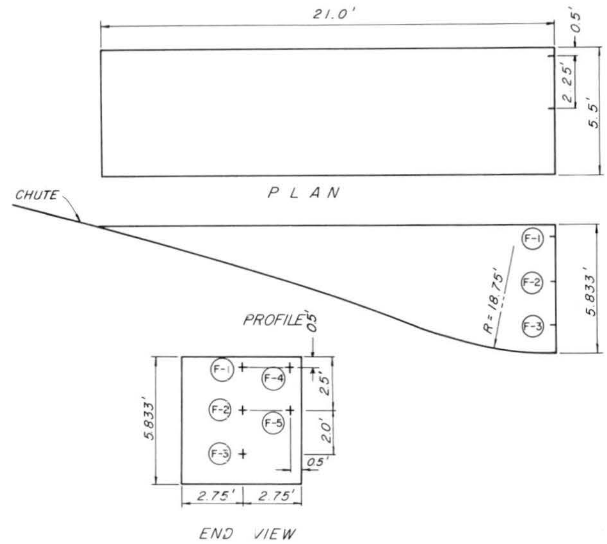


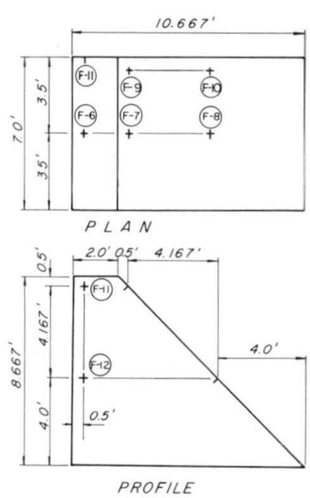
FIGURE 13 STILLING BASIN I PIEZOMETER LOCATIONS



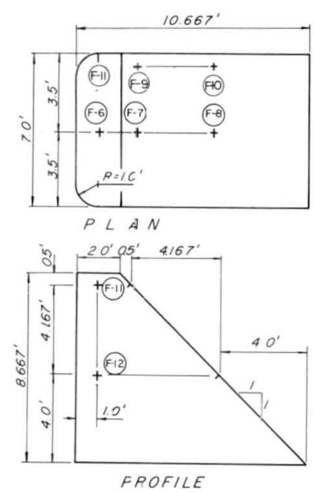
CHUTE BLOCK — STILLING BASIN I



CHUTE BLOCK — STILLING BASIN II



BAFFLE BLOCK



BAFFLE BLOCK A

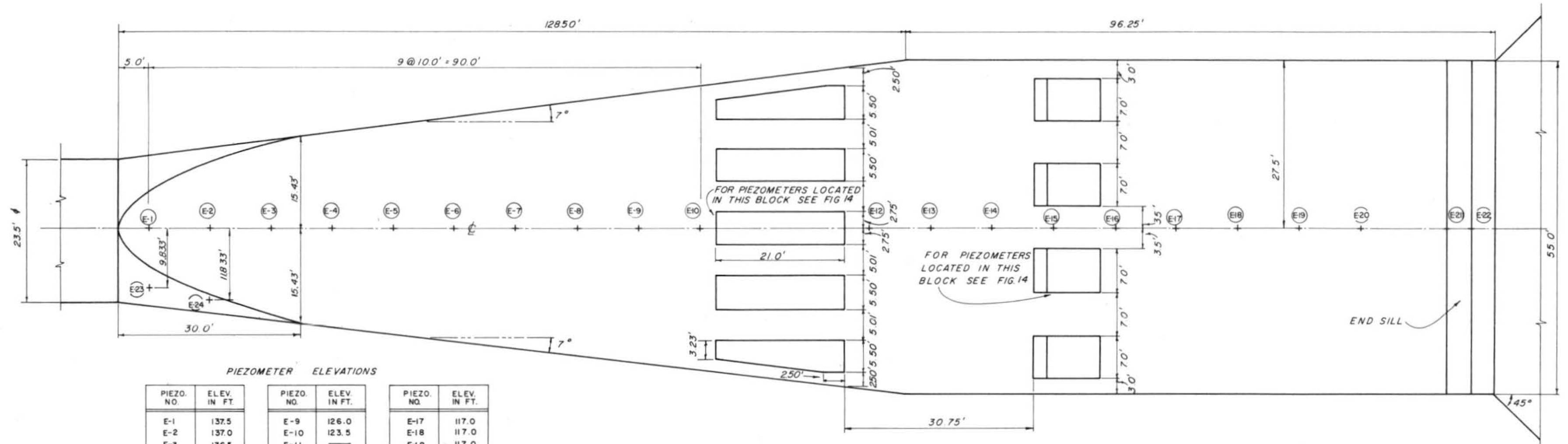
CHUTE BLOCKS PIEZOMETER LOCATIONS

PIEZO NO.	ELEV. IN FT. STILLING BASIN I	ELEV. IN FT. STILLING BASIN II
F-1	117.0	122.0
F-2	115.0	120.0
F-3	113.0	118.0
F-4	117.0	122.0
F-5	115.0	120.0

BAFFLE BLOCKS PIEZOMETER LOCATIONS

PIEZO NO.	ELEV. IN FT. STILLING BASIN I	ELEV. IN FT. STILLING BASIN II
F-6	120.5	125.5
F-7	120.0	125.0
F-8	116.0	121.0
F-9	120.0	125.0
F-10	116.0	121.0
F-11	120.0	125.0
F-12	116.0	121.0

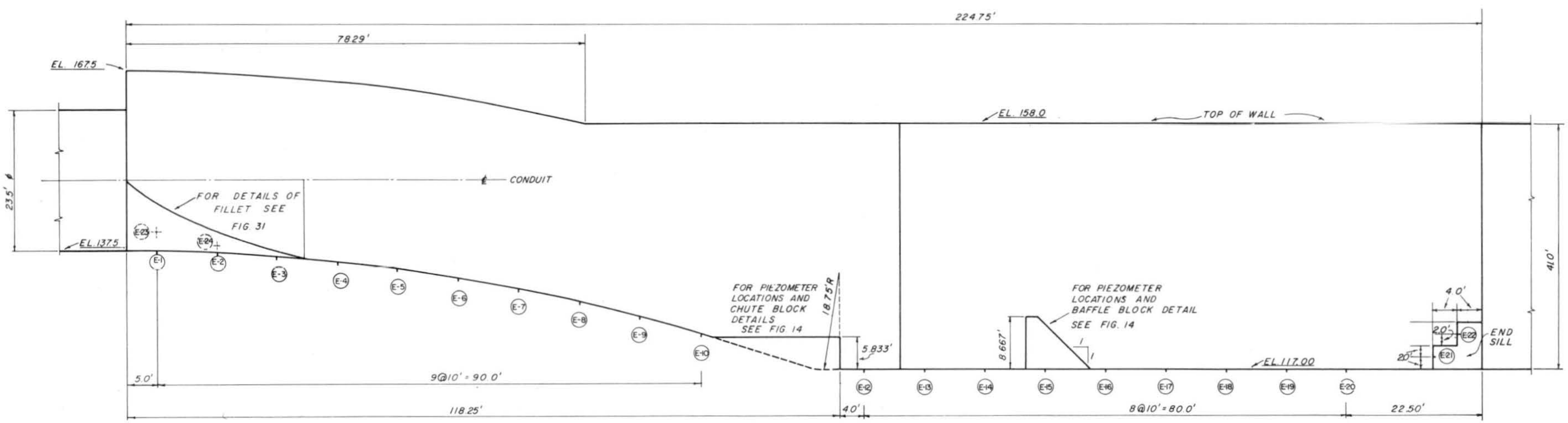
FIGURE 14 CHUTE AND BAFFLE BLOCK PIZOMETER LOCATIONS



PIEZOMETER ELEVATIONS

PIEZO. NO.	ELEV. IN FT.	PIEZO. NO.	ELEV. IN FT.	PIEZO. NO.	ELEV. IN FT.
E-1	137.5	E-9	126.0	E-17	117.0
E-2	137.0	E-10	123.5	E-18	117.0
E-3	136.5	E-11	——	E-19	117.0
E-4	135.5	E-12	117.0	E-20	117.0
E-5	134.5	E-13	117.0	E-21	119.0
E-6	133.0	E-14	117.0	E-22	123.0
E-7	131.0	E-15	117.0	E-23	140.5
E-8	129.0	E-16	117.0	E-24	138.5

PLAN



℄ PROFILE

FIGURE 15 STILLING BASIN II — PIEZOMETER LOCATIONS

Chronology of Tests

Initial tests of the model were made to determine the location and magnitude of negative pressures throughout the spillway for all crest gates open. When adverse negative pressures were observed, as along the inside radius of the elbow, modifications necessary to reduce or eliminate these negative pressures were tested. Then the performance of the morning glory spillway under different heads and various numbers of open gates along with flow conditions through the vertical bend and conduit were studied in detail. The performance of the stilling basin under varying conditions of discharge and tailwater depth was the final phase of testing.

Initial Tests

The discharge rating curve for the model without modifications and with all gates open is shown in Fig. 16. The curve is included here so that the reader may relate discharge to reservoir elevation or vice versa when only one quantity is mentioned in the following discussion.

For reservoir elevations below 199.0 some negative pressures were observed. Pressure data for these tests are given in table A-1 of Appendix A. As the reservoir rose from 189.0 to 201.0 adverse negative pressures were measured along the inside radius of the elbow. The lowest pressure was measured at piezometer A13 which indicated a pressure head of -12 feet of water at reservoir elevation 201.0 (see Fig. 8 for piezometer locations). This was considered to be excessive and cavitation could result if this magnitude of negative pressure persisted.

First Modification

A constriction at the portal was first attempted to eliminate negative pressures within the conduit. The constriction consisted of a wedge with a maximum thickness of 3 ft installed along the crown of

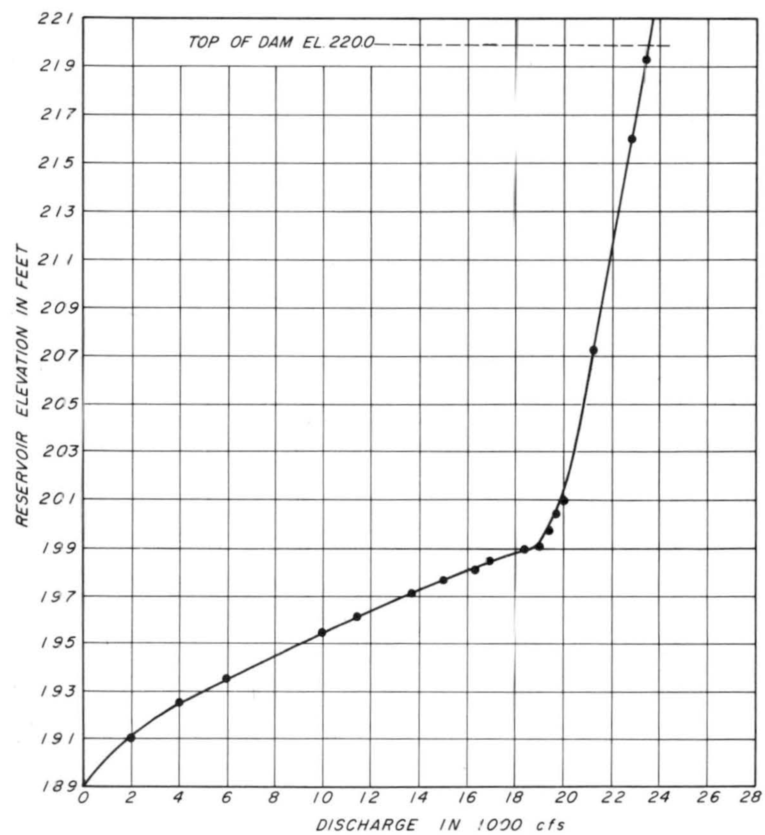


FIGURE 16 MODEL DISCHARGE RATING CURVE

the conduit. The constriction increased the hydraulic gradient throughout the tunnel upstream of the portal, which increased the pressure within the conduit, but which also reduced the discharge. A proper balance between pressure increase and maximum discharge could not be maintained by use of the constriction. That is, if the pressure within the conduit was acceptable, maximum discharge was too small, and if the maximum discharge was increased at maximum reservoir level by reducing the size of the wedge, the negative pressures were too large in magnitude.

Second Modification

Local negative pressures can be eliminated by aerating the conduit, that is, allowing air to be drawn into the zone of the negative pressures and by causing the flow to be physically separated from the tunnel boundary. Two 1/4-in air vents were installed near the point of curvature of the vertical bend. The centers of the vents were located at elevation 149.5 and symmetrically placed about the vertical center line as shown in Fig. 17. A small wedge was placed directly above the air vents to create separation of the flow and to prevent the flow of water from impacting on the downstream lip of the air vent opening and causing erosion of the concrete there. By aerating, a slight reduction in the discharge occurred as the discharge rating curves show in Fig. 18. A discharge of 19,000 cfs at reservoir elevation 201.0 was considered acceptable. Aeration resulted in increased pressures at piezometer A13 from -12 to -0.5 feet of water at reservoir elevation 201.0. For pressure data resulting from aeration of the vertical bend see table A-2 of Appendix A.

Morning Glory Spillway

After the adverse pressures in the vertical bend were eliminated, a detailed study of the overall performance of the spillway was made. Photographs of the approach flow lines in the reservoir to the morning glory spillway are shown in the photographs of Fig. 19 for reservoir elevations of 195 and 201 and discharges of 9000 cfs and 19000 cfs respectively. As the reservoir rises, the surface velocities of the approaching flow increase until they reach a maximum at a reservoir level of 200.0. As the reservoir level increases above elevation 200.0, the surface velocities decrease. This is because the conduit controls the discharge above 18,500 cfs and discharge per unit area of approach decreases with rising reservoir levels. The magnitude and orientation of the surface velocities for two reservoir levels are shown in Fig. 20.

Uniform discharge through each bay existed for all reservoir levels as determined by the uniformity of pressure readings between the four lines of piezometers located in the spillway crest. Pressure data on the crest surface are given in table A-2 of Appendix A.

Flow conditions over the spillway crest are illustrated in the photographs of Fig. 21 for discharge of 4,000, 19,000 and 21,500 cfs. There was a slight draw down of the water surface near the piers. Standing waves about 0.5 feet high were observed between the piers for discharges between 14,000 cfs and 20,000 cfs. These standing waves were not objectionable as they did not interfere with the flow.

When the reservoir level was near elevation 199, an oscillation of the water surface in the throat of the morning glory was noted. This oscillation was quite regular. The "boil" of water in the throat rose to submerge the morning glory and then dropped and completely swept out of the throat. As long as the free over-fall on the spillway exists, the discharge is proportional to the head on the crest to the three halves' power ($Q = CLH^{3/2}$). However, when the morning glory becomes submerged, the throat diameter controls and in effect it becomes an orifice and the discharge becomes proportional to the one-half power of the head above the orifice ($Q = KH^{1/2}$). By referring to the discharge rating curve of the spillway (Fig. 18), the two regions of operation, (free overflow and orifice flow) are clearly distinguished. In the region where the two curves intersect, instability of discharge occurs which results in oscillation of the water surface within the throat as described above. A considerable amount of turbulence and alternate entrainment and release of air was observed in the model at the morning glory crest. Due to the periodicity of the oscillation, some detrimental vibrations could be set up in the prototype if the reservoir level remained near 199 for any length of time. Discharge at this reservoir level with all gates open should, therefore be avoided.

The oscillatory condition did not occur when only 2, 3, 4 or 6 gates were open. The transition zone between the free overflow and orifice flow was "smoothed out" as can be seen from the rating curves with various combinations of open gates shown in Fig. 22. A "boil" similar to those shown in the photographs of Fig. 23 remained above the throat of the morning glory when 2, 3, 4 or 6 gates were open. As the reservoir level rose, the "boil" also rose, until the conduit controlled the discharge, whereupon the "boil" became submerged and was not significantly evident.

Pressures on the surface of the spillway crest were satisfactorily positive for all reservoir levels for all symmetrical combinations of open gates. Pressure data from the tests are given in Appendix B.

With only one gate open the jet impacting on the opposite side of the morning glory could erode the concrete at that point. Detrimental vibrations due to the impacting jet could be set up. It is not recommended that only one gate be used to release water from the reservoir. Symmetrical gate openings should be included in the operating procedure.

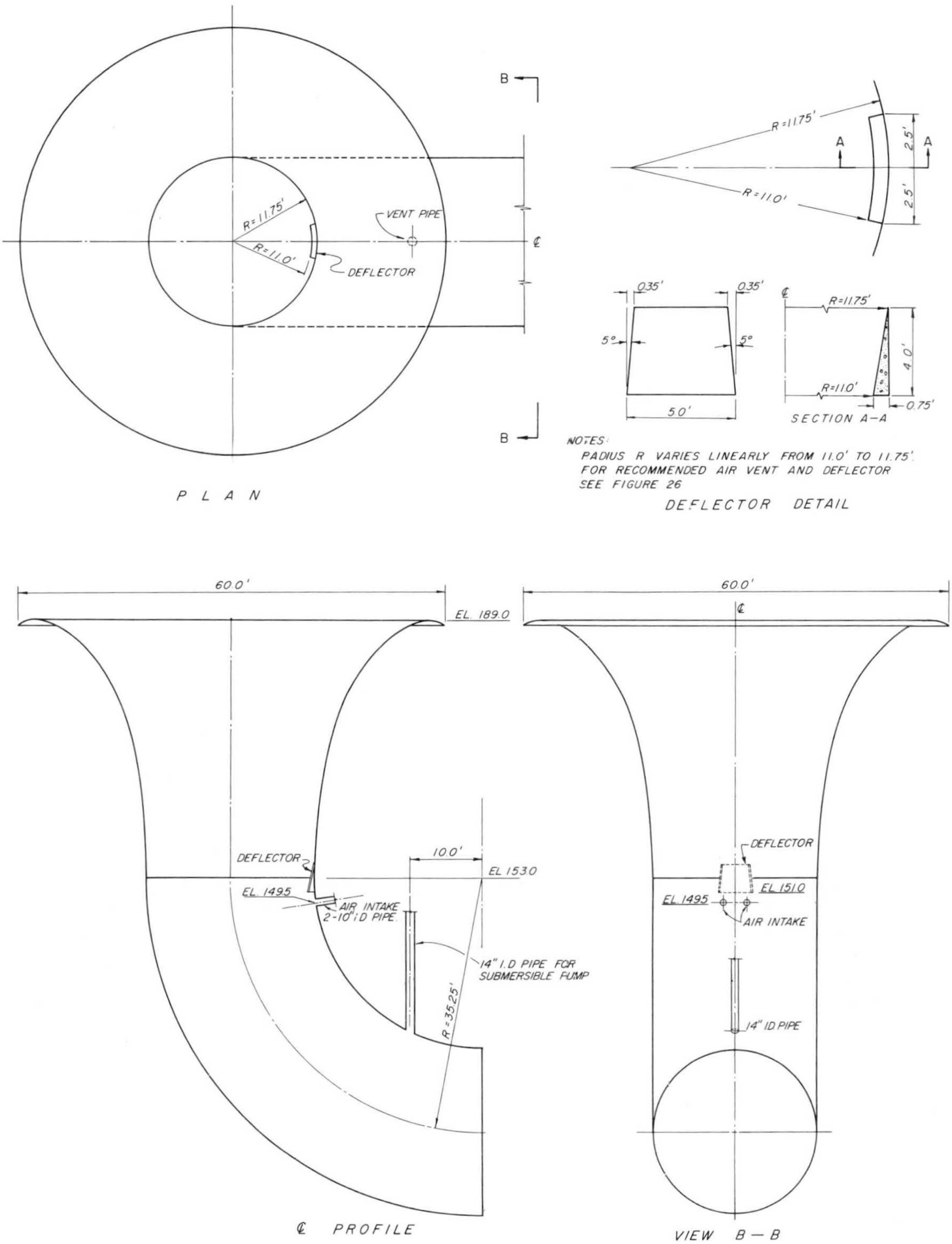


FIGURE 17 AIR VENT AND DEFLECTOR

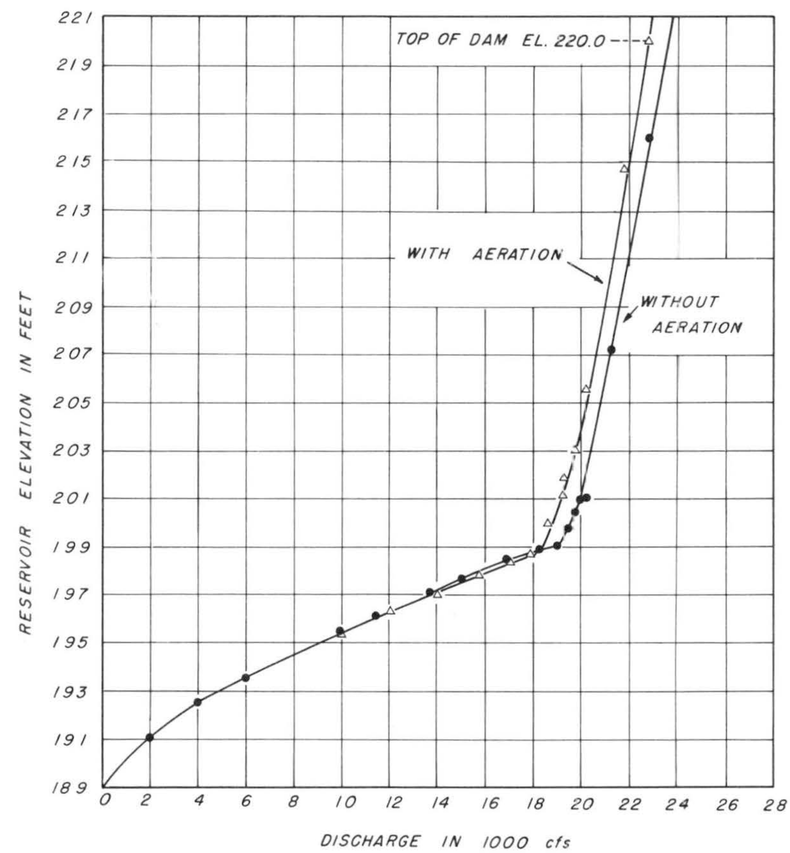


FIGURE 18 DISCHARGE RATING CURVES FOR MODEL WITH AND WITHOUT AERATION

Fig. 19(a). Flow lines into the morning glory spillway from the reservoir with water level at 201.0.

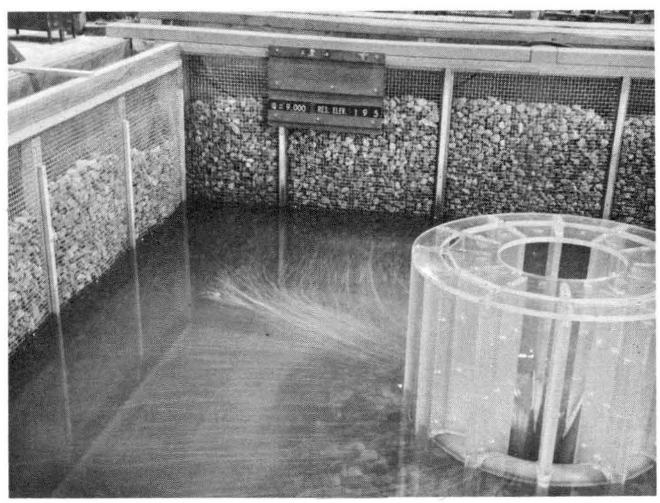


Fig. 19(b). Flow lines into the morning glory spillway from the reservoir with water level at 195.0.

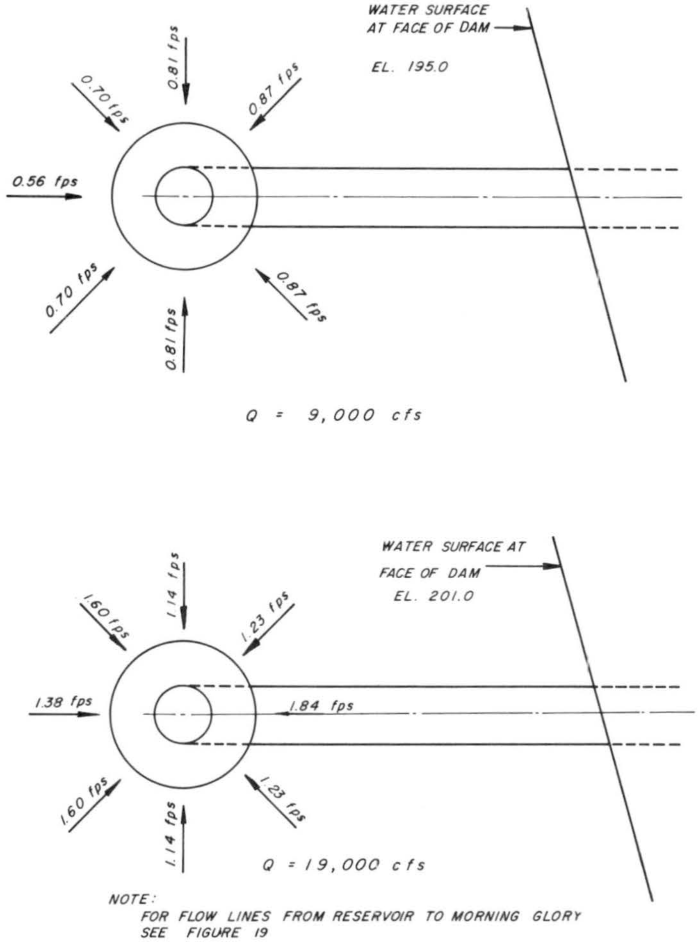


FIGURE 20 MODEL SURFACE VELOCITIES

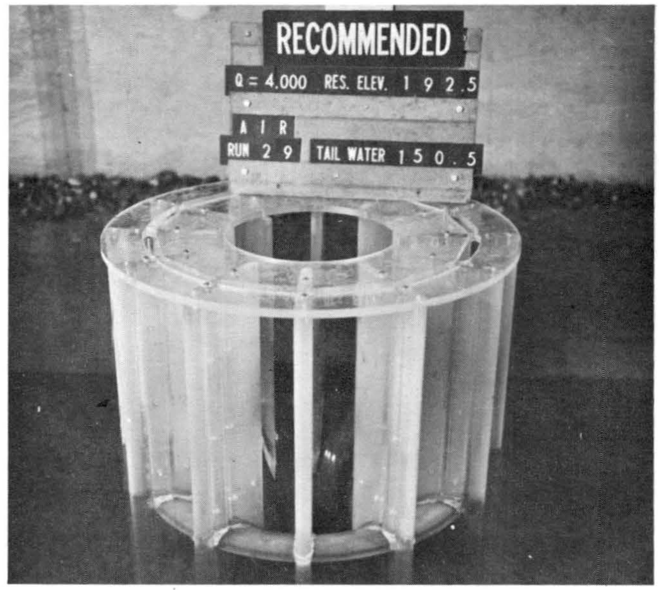


Fig. 21(a). Flow through spillway bays.
Q = 4, 000 cfs.

Fig. 21(b). Flow through spillway bays.
Q = 19, 000 cfs.

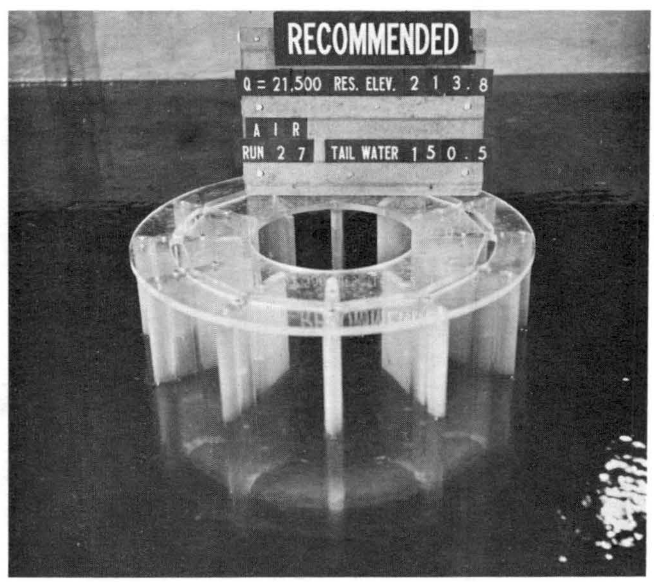


Fig. 21(c). Flow through spillway bays.
Q = 21, 500 cfs.

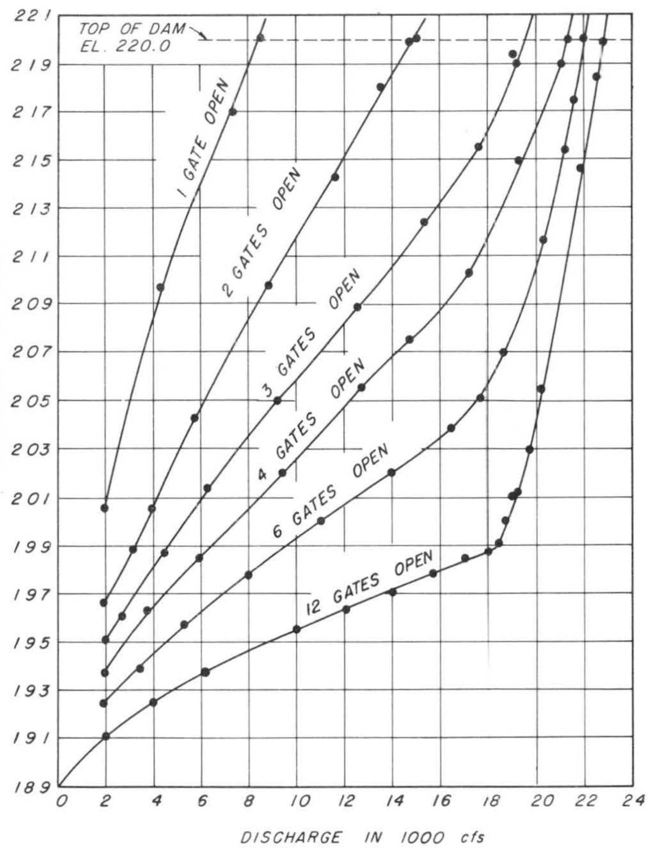


FIGURE 22 MODEL DISCHARGE RATING CURVES FOR SYMMETRICAL GATE COMBINATIONS

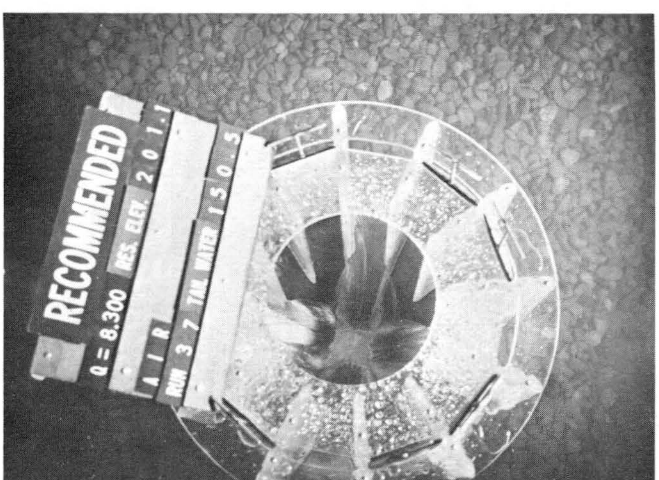


Fig. 23(a). Flow into the morning glory spillway with 4 gates open. Q = 8, 300 cfs.

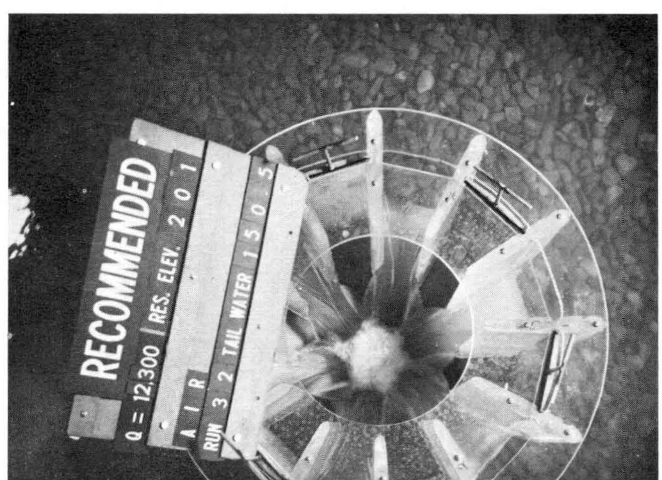


Fig. 23(b). Flow into the morning glory spillway with 6 gates open. Q = 12, 300 cfs.

The Vertical Bend

General flow conditions through the vertical bend were satisfactory after the air vents and the deflector were installed. At low discharges the pressures were positive throughout the elbow. At higher discharges with aeration, the pressures along the inside of the radius were only slightly negative as mentioned before. For pressure data see table A-2 of Appendix A. The wedge and the air flow into the bend created a flow condition illustrated in the photographs of Fig. 24. A hydraulic jump formed near the bottom of the vertical bend which entrained the air admitted above, but neither the hydraulic jump nor the entrainment of air appeared to create any difficulty.

The air flow in the model was measured by a calibrated 1/2-in x 3/8-in venturi meter. The maximum air demand in the model was 120 cfs (prototype). The required air flow rates for the entire range of spillway discharges are shown in Fig. 25, where the maximum rate as mentioned above was 120 cfs. In the design manual of the Corp of Engineers[3] it is suggested that air vent pipes be sized so that air velocities of not more than 150 ft per sec be created through the pipe. Using this as a guide, the total area of the air vents should be about 1.1 square feet, assuming a maximum air velocity of 110 ft per sec. A 14-inch I. D. pipe or two 10-inch I. D. pipes should be adequate for ventilation. Although two vents were used in the model, one pipe of adequate size would provide the same function. It is recommended that the single 14-inch pipe be used for the air vent since the associated head losses will be less than for two 10-inch pipes. The vent must be sloped to permit self draining. If a water lock should form in the vent pipe there is always the possibility that some damage could occur before the water plug is "blown out." An arrangement for the vent similar to that shown in Fig. 26 was suggested by the consulting engineers for incorporation in the prototype design. The vertical pipe portion of the vent system is intended to be used for lowering a submersible type pump to dewater the 23.5-ft diameter conduit for inspection and maintenance purposes. The effect of this vertical pipe on flow conditions was tested in the model and no detrimental results were observed. For discharges up to 19,000 cfs, the vertical pipe is in a region of positive pressure and no air is drawn through it. For discharge above 19,000 cfs, it also acts as an air vent. The total air flow remained about the same compared to tests without the vertical pipe.

The Conduit

Flow conditions through the conduit were satisfactory for all discharges. Some negative pressures were measured along the crown of the conduit near the portal. See Appendix A for pressure data. All other piezometers indicated positive pressure heads.

The air entrained at the throat of the morning glory or from the air intakes passed through this conduit without difficulty. At low discharges the air separated from the water and slugs of air passed through the conduit as shown in Fig. 27. For discharges above 18,000 cfs, the flow through the conduit was similar to that shown in Fig. 28 where the entrained air passed through the conduit in small bubbles that tended to rise and flow along the crown of the conduit.

Horizontal and vertical velocity profiles at the portal were measured to determine if unequal velocity distributions were created within the conduit. The velocities were measured with a pitot tube. From the velocity profiles for two discharges shown in Fig. 29, it can be seen that no unusual condition prevailed.

Stilling Basin I

The preliminary design of the stilling basin was shown in Fig. 3. This type of basin is principally a hydraulic jump energy dissipator. The purpose of the chute blocks and floor blocks is to decrease the length of the basin from that which would be required for a normal hydraulic jump, by stabilizing the jump in a fixed position relative to the basin.

Pressures on the chute and basin floor were positive for all discharges tested at various tailwater conditions. Pressure data are given in table C-1 of Appendix C. Some negative pressures were observed on the baffle block at piezometer F11 and F12 located in the side faces of the block (see Fig. 14 for piezometer locations) for conditions of high discharge and low tailwater levels. Some erosion of the concrete baffle blocks can be expected because of the negative pressures, but this type of floor block has been used in many existing stilling basins without serious deterioration and maintenance difficulty.

The spreading jet of water at supercritical velocities in the chute created a fin at the walls. These fins did not overtop the wall and did not create interference with the flow, hence aside from spray, did not create any problem. The basin satisfactorily dissipated the kinetic energy of the flow. However, due to the turbulence and undulations of the hydraulic jump at near maximum discharges, the water would overtop the original wall at elevation 153 as shown in

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[3] Corps of Engineers, Hydraulic Design Criteria, sheet 050-1, "Air Demand-Regulated Outlet Works," Revised 1-64.

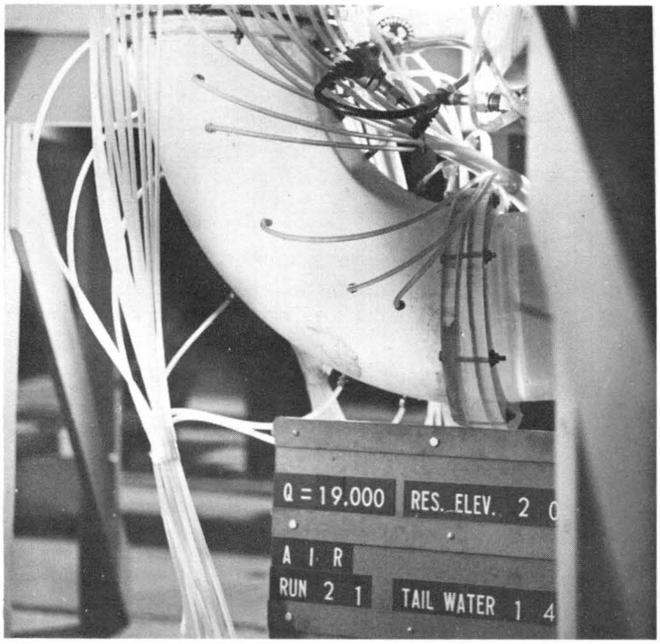

Fig. 24(a). Flow through the vertical bend.
Q = 19, 000 cfs.

Fig. 24(b). Flow through the vertical bend.
Q = 23, 800 cfs.

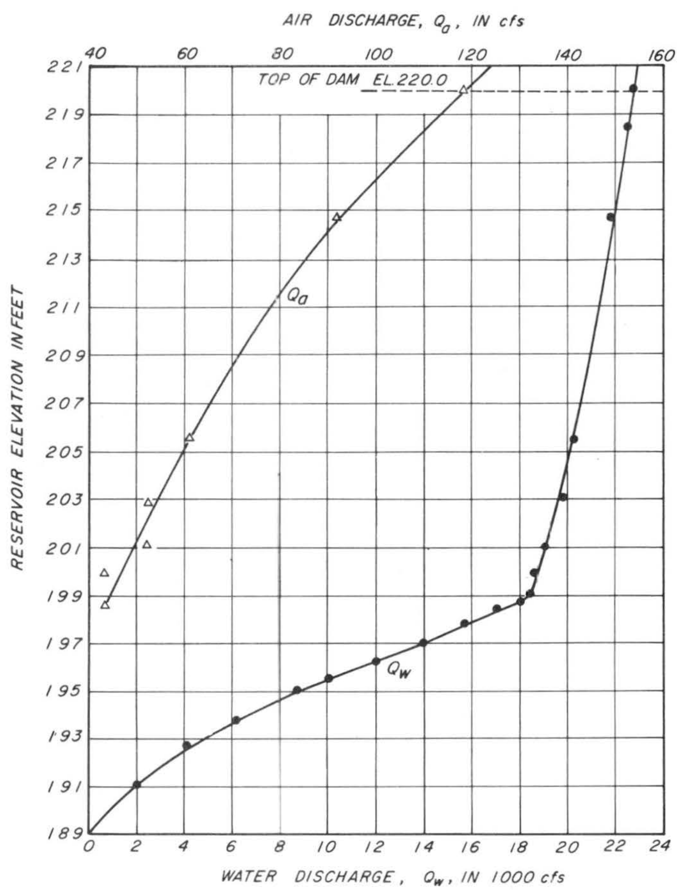

FIGURE 25 AIR DEMAND FOR RECOMMENDED WATER DISCHARGE

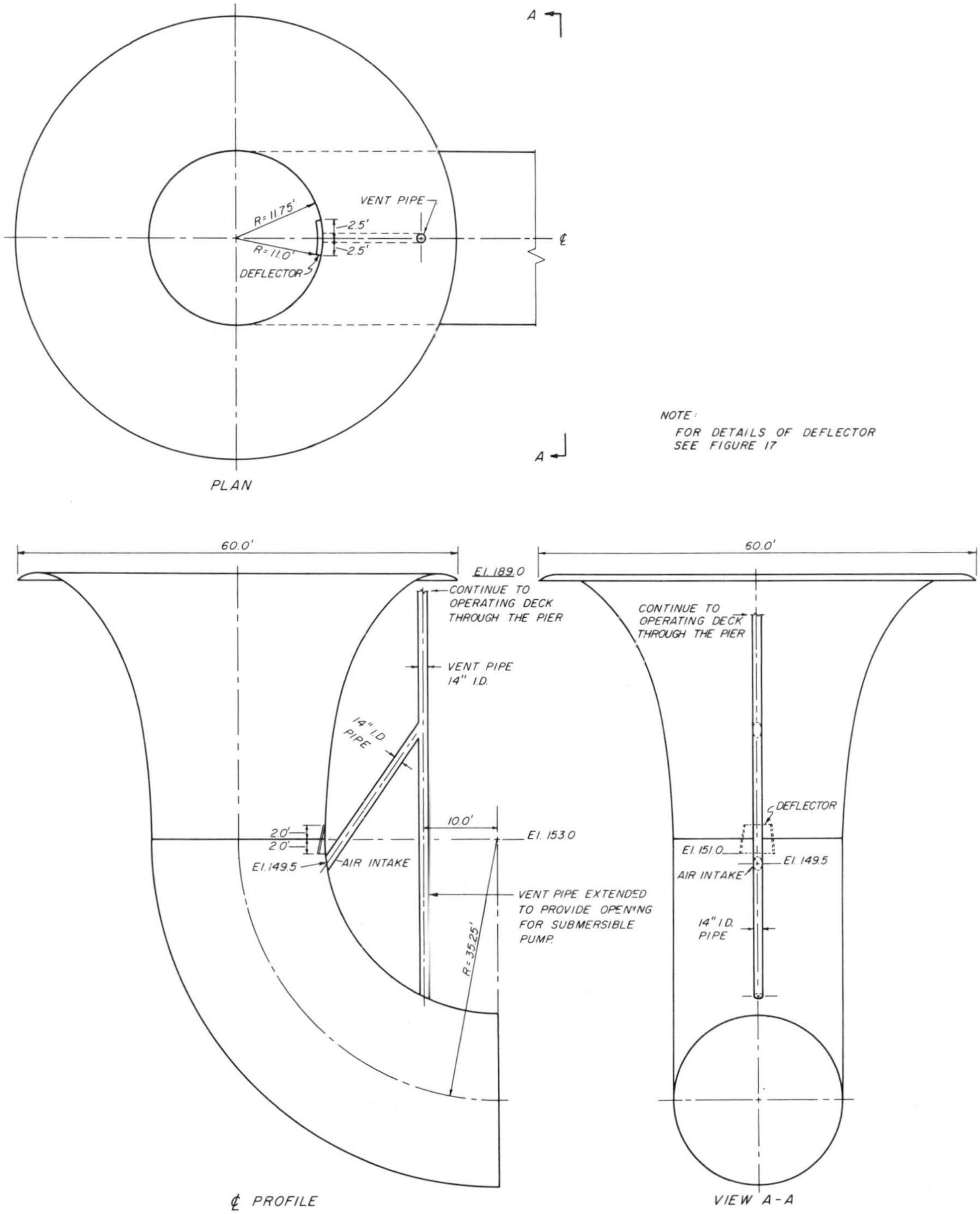

FIGURE 26 RECOMMENDED AIR VENT ARRANGEMENT

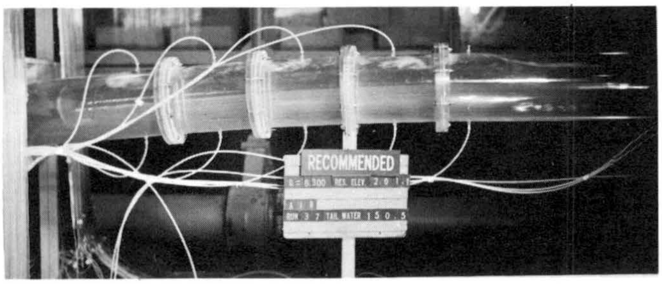

Fig. 27. Air slugs in the conduit. Q = 8, 300 cfs.

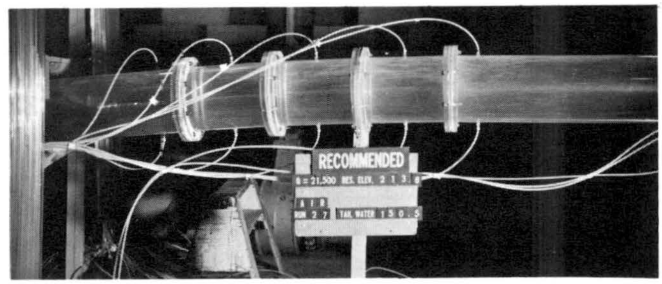

Fig. 28. Air entrained flow through the conduit. Q = 21, 500 cfs.

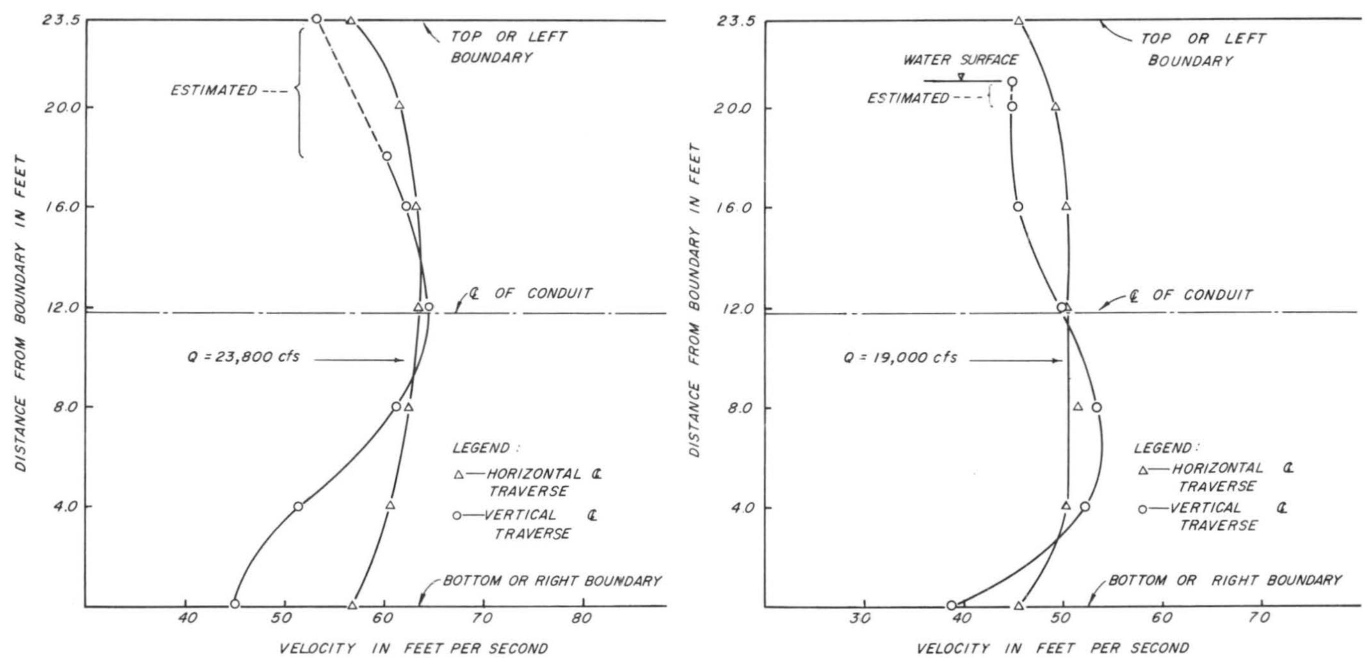

FIGURE 29 PORTAL VELOCITY PROFILES

Fig. 30. Otherwise, the hydraulic jump in the stilling basin was satisfactory. If the stilling basin were to contain the hydraulic jump within the confines of the walls, it would have been necessary to increase the height of the walls by approximately 8 ft, including requirement for freeboard. In an attempt to effect some economy in the structure, tests were made with a raised floor level of the basin. The results are described in the next section.

Stilling Basin II

The relative position of the baffle blocks to the chute blocks and the overall length of the stilling basin remained the same as stilling basin I. Dimensions of the chute and the basin and the piezometer locations of stilling basin II are given in Fig. 15. The same type of chute and baffle blocks were used as in stilling basin I. Elevations and locations of the piezometers on the blocks were as shown in Fig. 14.

Generally, flow conditions in the modified basin were satisfactory. However, to insure that negative pressures along the boundary immediately downstream from the tunnel portal did not occur because of the sudden change in geometry from a circular to rectangular section, fillets were placed in the corners as shown in Fig. 31. These fillets also assisted in reducing the height of the fin created by the spreading jet at the chute walls. Pressures on the face of the fillets, the chute and the floor were measured. Positive pressures were recorded for all discharges and tailwater levels. Data are given in table C-2 of Appendix C. Piezometers F11 and F12 again indicated negative pressures on the baffle blocks. In an attempt to reduce the negative pressures the blocks were streamlined by using a 1-foot radius to round the upstream corners of the blocks. Details of the block (hereafter referred to as block A) and the piezometer locations on the block are shown in Fig. 14. Streamlining created even more adverse pressure conditions. Piezometer F11 indicated a pressure head of -40 feet of water[4] at a discharge of 23, 800 cfs and tailwater level of 150. 5. Pressure data are given in table C-3 of Appendix C. Considering the appearance of the jump, the extent of air entrainment, and the turbulence downstream of the basin, block A, was considerably less effective than the original baffle blocks.

Photographs of the jump profile in stilling basin II at two discharges with the original baffle blocks are shown in Fig. 32. In each case the water surface reached the top of the basin wall at elevation 158. 0 feet. To prevent overtopping of the walls and therefore washing behind the walls, it is recommended that at least 3 feet of additional height be added to the basin walls to provide a total of 10. 5 feet of freeboard above the maximum tailwater elevation of 150. 5. This freeboard is also shown in Fig. 32 as a line at elevation 161. 0.

Scour Control

Sand was used for the channel bed in the model downstream from the stilling basin with pea-sized gravel (1/4-in mean diameter) placed in a layer 5 feet deep (prototype) to represent rip rap approximately 10-inches in diameter, downstream from the stilling basin for a distance of 140 feet. Tests were made to determine depth and pattern of scour for different discharge and tailwater levels. Two test results for discharges of 24, 000 cfs and 19, 000 cfs with tailwater level at 150. 5 are shown in the photographs of Fig. 33. It can be seen that the maximum depth of scour was 10 feet at a location immediately downstream from the end sill.

The pea-sized gravel was replaced with 3/4-in. mean diameter gravel and scour tests were again made. The scour pattern developed with the larger gravel are shown in the photographs of Fig. 34. There was essentially no movement of the larger gravel for any discharge or tailwater level. The average sized rip rap in the model when scaled up to prototype size would be approximately 24 inches in diameter. The maximum size of gravel in the model represented stone approximately 39 to 40 inches in diameter. The size of rip rap required for an average velocity of 17 fps, which would occur at the maximum discharge of 23, 800 cfs, based upon data developed by the Bureau of Reclamation[5] would be 42-inch diameter stones placed in a graded layer at least 63 inches thick, where the rip rap is placed over gravel bedding. It is recommended that for the earth channel downstream of the spillway, graded rip rap ranging in sizes from 10 to 42-in. in diameter be placed in a layer five feet thick, including a gravel bed, for a distance of at least 200 feet downstream from the end sill of the stilling basin.

Channel Downstream from the Stilling Basin

There are two alternatives in designing an acceptable channel to convey the spillway discharge downstream from the stilling basin. One alternative is to design a channel to carry the total discharge within its banks which will require that the channel be about 410 feet wide and 15 feet deep. The second is to design a smaller channel with provision for overbank flow for discharges greater than at certain minimum flow. The second alternative is suggested for the Conroe project. At the site of the dam the valley provides considerable width of overbank flow. The main channel stem should have a bottom width

[4] Pressures below the vapor pressure of water have no physical significance except to indicate possible cavitation in the prototype. Pressures less than vapor pressures were measured in the model because of scale.

[5] Peterka, A.J., Hydraulic Design of Stilling Basins and Energy Dissipators, Engineering Monograph No. 25, U. S. Bureau of Reclamation, revised July 1963, pp. 207-217.

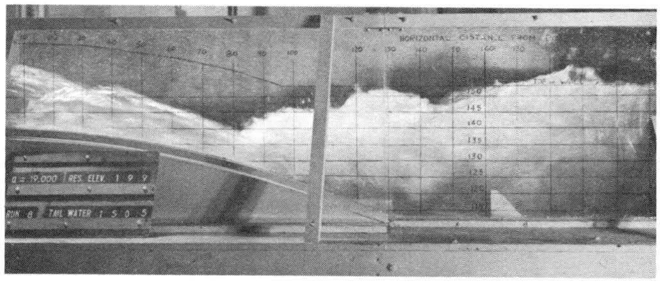

Fig. 30. Hydraulic jump profile in stilling basin I.

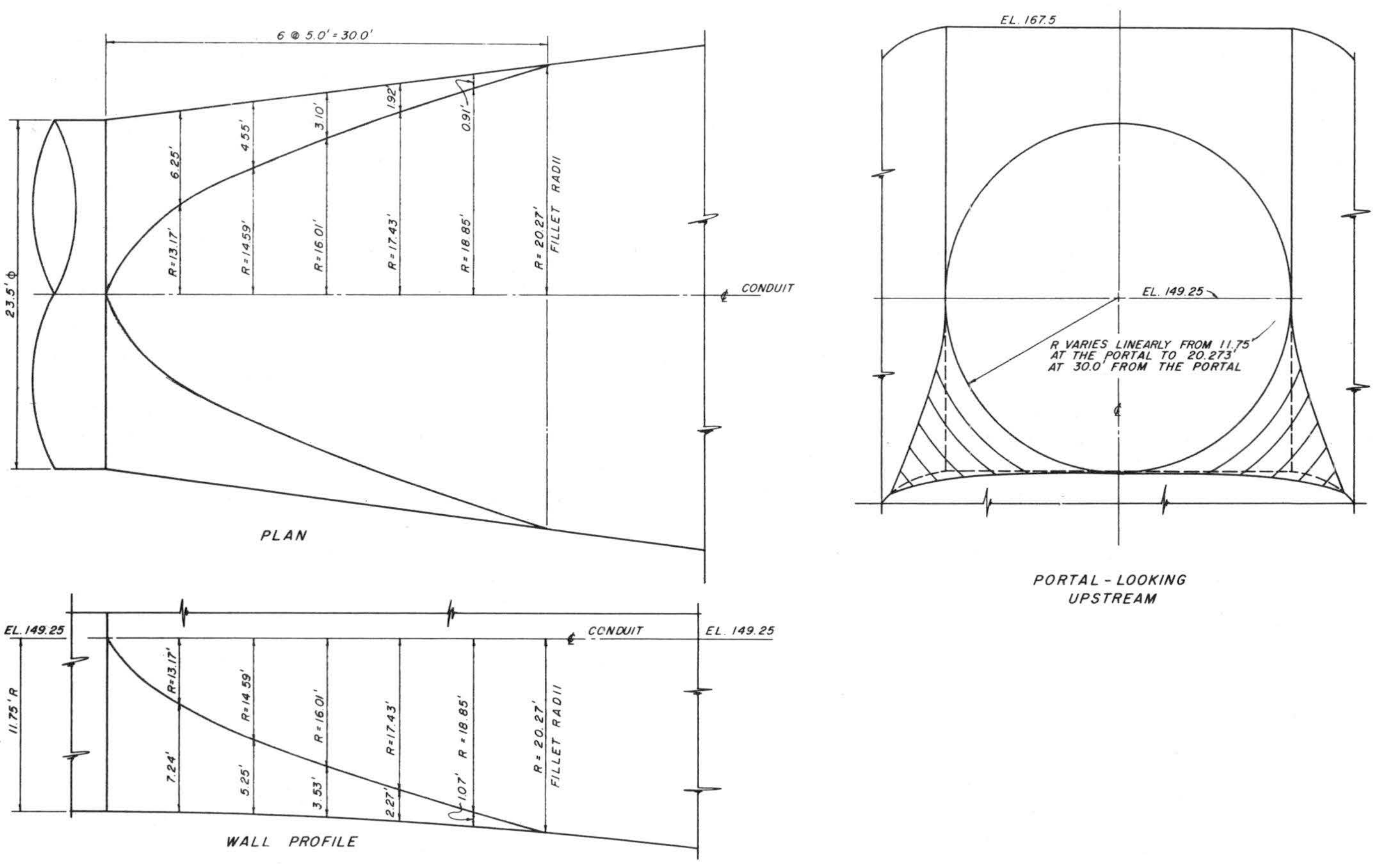

FIGURE 31 DETAIL OF FILLET DOWNSTREAM OF PORTAL

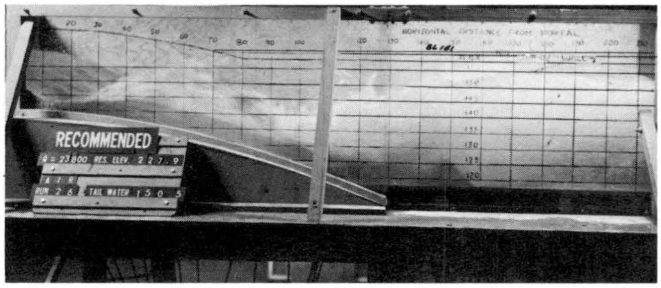

Fig. 32(a). Hydraulic jump profile in stilling basin II. Q = 23,800 cfs.

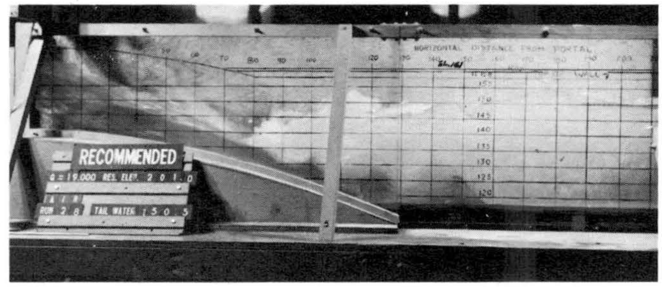

Fig. 32(b). Hydraulic jump profile in stilling basin II. Q = 19,000 cfs.

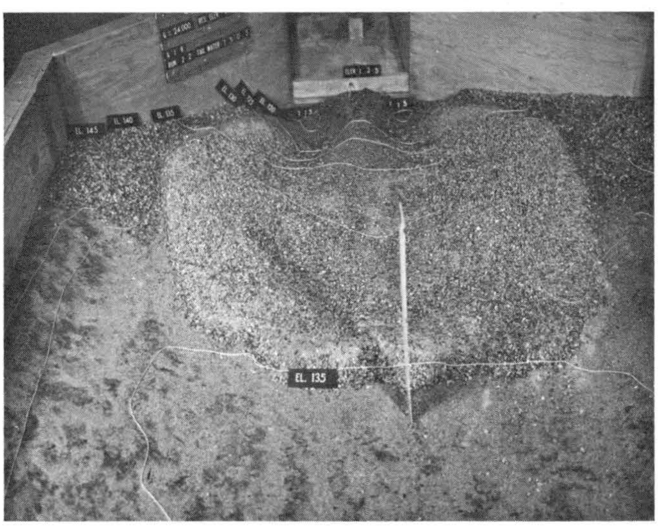

Fig. 33(a). Scour downstream from stilling basin II at tailwater 150.5. Q = 24,000 cfs.

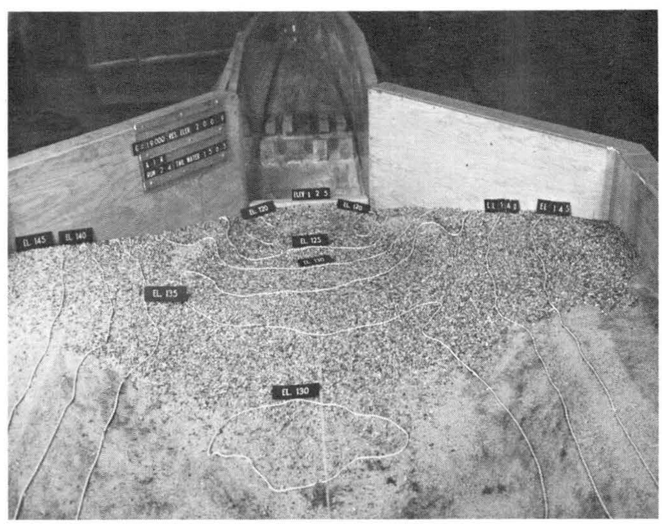

Fig. 33(b). Scour downstream from stilling basin II at tailwater 150.5. Q = 19,000 cfs.

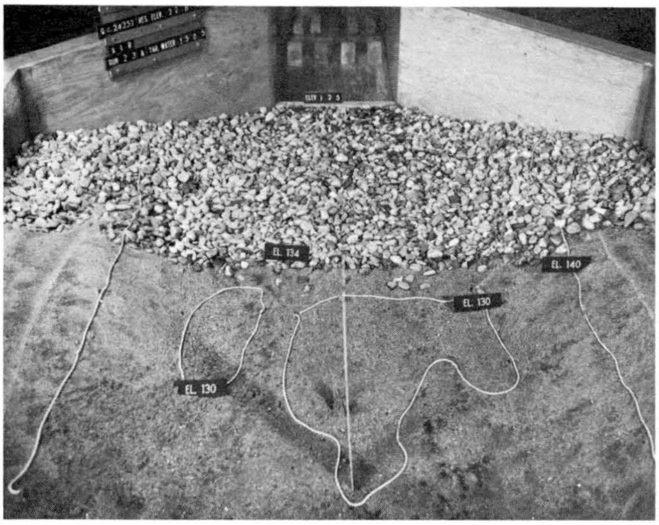

Fig. 34(a). Scour downstream from stilling basin II at tailwater 150.5. Q = 24,250 cfs.

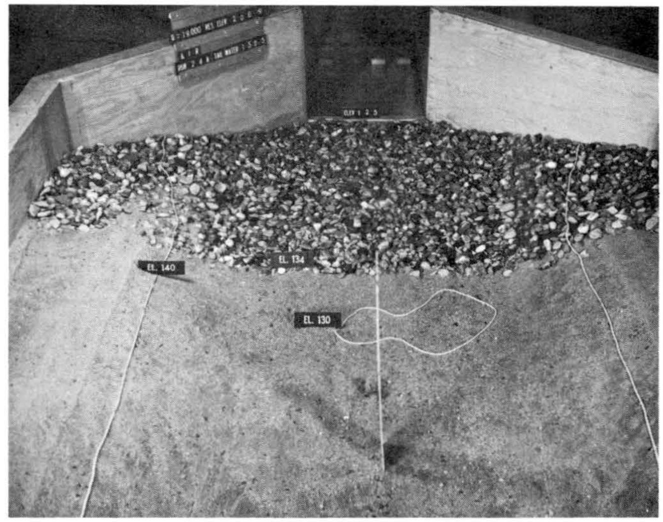

Fig. 34(b). Scour downstream from stilling basin II at tailwater 150.5. Q = 19,000 cfs.

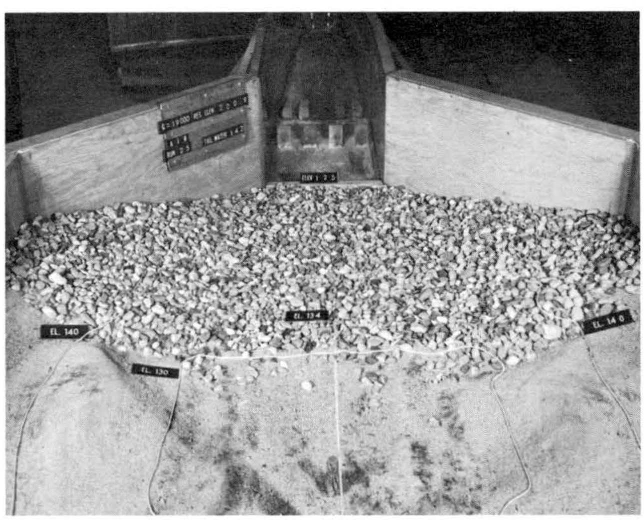

Fig. 34(c). Scour downstream from stilling basin II at tailwater 142.0. Q = 19,000 cfs.

of approximately 200 feet at an elevation near 135.5 so that with a longitudinal slope of about 0.0001 the channel bed will coincide with the existing river bed level at the junction. The channel is suggested to be 6.5 feet deep, with side slopes between 2:1 to 3:1. This main channel will carry a discharge of approximately 2500 cfs. Beyond this discharge, overbank flow will result. In order to somewhat restrict the overbank flow, a dike should be constructed between the left wing wall of the stilling basin and the service outlet, and another extending from the right wing wall to the hill located to the right of the basin. The top of the dike should be at elevation 155.0. The suggestions are indicated on Fig. 35 along with a cross section of the main channel and overbank flow section required to carry the maximum discharge. It is recommended that the ground level in the overbank section be excavated to 142.0. The minimum width of 700 feet suggested will probably not be of concern at the site. The available overbank flow width will be greater than 700 feet.

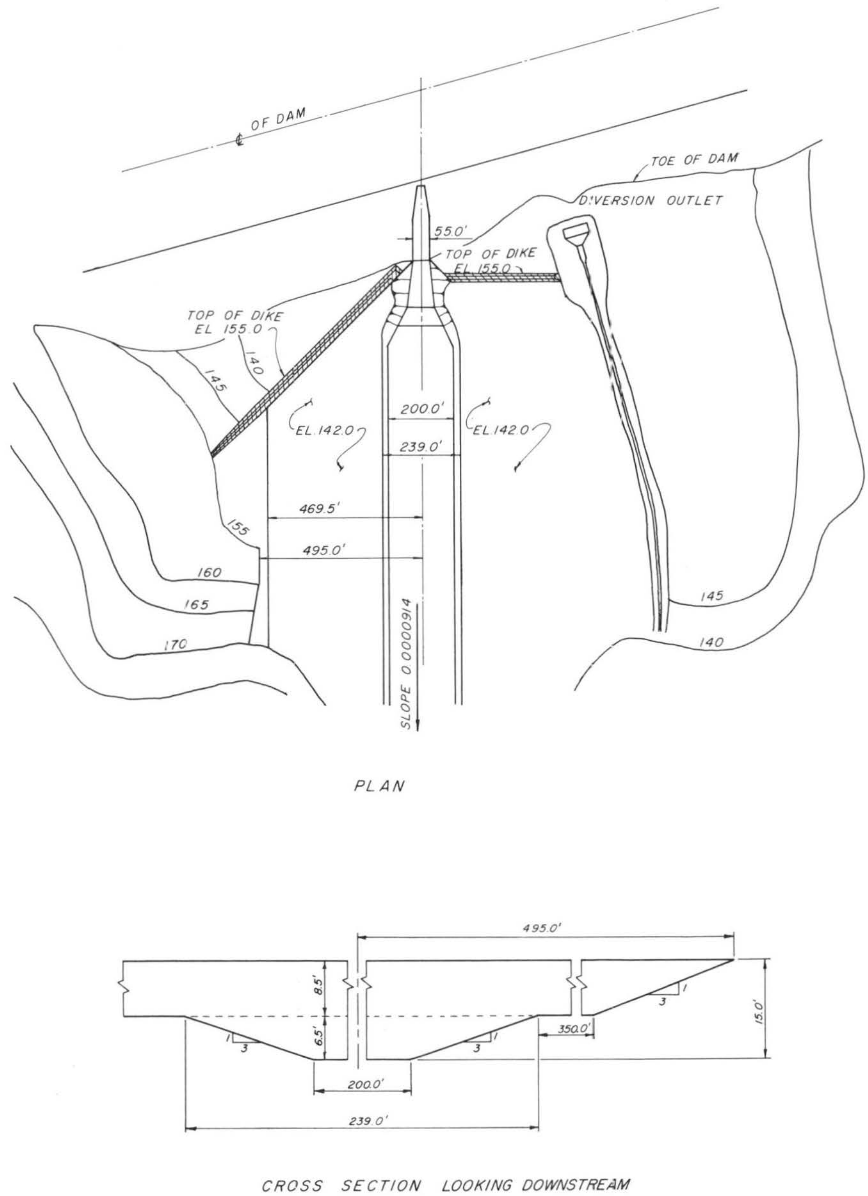

FIGURE 35 CHANNEL PLAN AND CROSS SECTION

CONCLUSIONS AND RECOMMENDATIONS

Morning Glory Crest

The morning glory performed satisfactorily for all symmetrical combinations of open gates (2, 3, 4 6 and 12 gates open). Pressures on the face of the crest were satisfactorily positive for all discharges, reservoir levels and combinations of open gates. No modification was required.

Operation of the morning glory spillway at reservoir elevation 199.0 and all gates open created an oscillatory condition in the throat that could set up detrimental vibrations in the structure. This oscillation occurred when more than 6 gates were open. Opening of one gate only should be discouraged because the jet of water impacts against the opposite side of the spillway and erosion of the concrete surface could occur there. Gate openings should be symmetric in order to maintain balanced flows at the spillway.

Vertical Bend

Flow conditions in the vertical bend were made satisfactory by the addition of an air vent and deflector at the P. C. of the bend. The maximum air flow rate required was 120 cfs (prototype). It is suggested that the air vent be a 14-inch I. D. pipe centered at elevation 149.5. The size and orientation of the recommended deflector wedge above the air vent are shown in Fig. 26.

Conduit

Conditions of flow and pressures in the conduit were satisfactory for all discharges.

Stilling Basin

To effect some economy in excavation of both the stilling basin and downstream channel, the floor level of the basin may be raised to elevation 117.0. To provide additional free board the top of the basin wall should be set at elevation 161.0.

No modification to the chute, chute blocks, baffle blocks or end sill were required excepting a reduction in the chute length resulting from the raised floor level. Pressures were positive for all discharges at all locations in the stilling basin with the exception of the baffle blocks. Negative pressures indicated the possibility of cavitation on the sides of the baffle blocks, but based upon other basins, maintenance of the blocks should not be serious.

An overbank flow section is recommended for the channel downstream from the stilling basin. The main flow channel should be about 200 feet wide and 6.5 feet deep and the over bank section should be about 700 feet wide. Graded rip rap of 39 to 42-in. maximum size in a layer five feet thick should be provided for a distance of 200 feet of the basin to prevent scouring of the earth channel.

APPENDICES

Appendix A

Table A-1 - Pressure heads on the morning glory spillway, vertical bend, and conduit with no modification
Table A-2 - Pressure heads on the morning glory spillway, vertical bend and conduit with recommended air intakes and deflector installed

Appendix B

Table B-1 - Pressure heads on the morning glory spillway crest for various numbers of open gates

Appendix C

Table C-1 - Pressure heads on the chute, floor, chute blocks and baffle blocks of stilling basin I
Table C-2 - Pressure heads on the chute, floor, chute blocks, and baffle blocks of stilling basin II
Table C-3 - Pressure heads on the chute, floor, chute blocks, and baffle block A of stilling basin II

TABLE A-1

PRESSURE HEADS ON THE MORNING GLORY SPILLWAY, VERTICAL BEND, AND CONDUIT WITH NO MODIFICATION

Pressure Heads in Feet of Water

Run No.	70	61	9	8	4	7	6	5
Reservoir Elevation	219.2	213.0	200.9	199.0	197.0	195.5	193.5	192.5
Discharge cfs	23,500	21,900	20,000	19,000	13,000	10,000	6,000	4,000
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
A 1	28.5	20.5	7.0	3.0	3.5	4.0	3.5	3.0
2	26.8	17.0	4.8	-0.5	1.0	1.5	2.5	1.5
3	26.8	16.5	6.0	0.0	0.5	0.5	1.0	1.0
4	26.7	16.0	7.0	-1.5	-1.0	-0.5	0.0	0.0
5	26.5	17.5	8.0	-2.0	**	-1.5	-0.5	-0.5
6	25.7	17.0	9.0	-2.0	-3.0	-2.5	-1.5	-1.0
7	25.2	18.0	9.5	-0.5	-2.9	-2.5	-1.5	-1.0
8	22.7	17.0	10.0	-2.0	-4.0	-2.0	-1.5	-1.0
9	19.5	15.5	9.0	6.0	-2.0	-1.0	-1.0	-1.0
10	17.0	13.5	8.5	7.0	-0.5	-0.5	-0.5	0.0
11	11.5	9.0	5.0	5.0	-2.0	-1.5	-1.0	-1.0
12	21.3	18.0	1.0	2.0	-0.5	-0.5	0.0	0.0
13	-23.0	-17.7	-11.5	-9.0	**	0.0	2.0	4.0
14	-8.0	-10.0	-12.0	-8.0	**	4.5	9.5	9.0
15	-9.0	-8.0	-7.0	-3.5	**	27.0	16.0	13.0
16	-3.0	-0.7	2.0	5.5	**	20.5	20.0	19.0
17	+6.0	8.8	11.8	15.0	**	22.0	24.5	26.0
18	**	16.0	19.0	21.5	**	**	**	**
19	**	25.0	25.0	25.5	**	**	**	**
20	**	19.2	19.0	19.5	**	**	**	**
21	**	12.2	12.5	12.5	**	**	**	**
22	**	6.1	6.5	7.5	**	**	**	**
23	**	1.0	1.0	1.0	**	**	**	**
24	0.0	-1.5	-1.5	0.5	**	**	**	**
25	**	-4.3	-4.3	-3.5	**	**	**	**
26	-3.0	-6.0	-6.0	-4.5	**	**	**	**
27	**	-7.5	-7.1	-5.5	**	**	**	**
28	-5.0	-7.7	-7.1	-10.0	**	**	**	**
B 1	28.7	19.5	7.0	4.0	4.5	4.0	3.5	3.5
2	26.7	16.0	4.0	-0.5	1.0	1.5	1.5	2.5
3	26.8	16.5	5.5	-0.5	0.7	1.0	1.0	1.0
4	26.8	16.5	6.5	-2.0	-1.0	-0.5	0.2	0.0
5	26.5	17.0	8.0	-3.0	-2.0	-1.5	-0.5	-0.5
6	26.0	17.5	8.5	-1.0	-3.0	-2.5	-1.0	-1.0
7	25.5	18.5	9.5	1.0	-3.0	-2.5	-1.5	-1.0
8	23.2	17.5	9.8	3.5	-3.0	-2.5	-1.5	-1.5
9	20.3	16.0	9.0	6.5	-2.0	-2.0	-1.0	-1.0
10	18.2	14.5	9.0	8.0	-1.0	-1.0	-0.5	-0.5
11	16.2	13.0	9.3	9.0	-1.0	-1.0	-0.5	0.0
12	16.8	14.0	11.5	11.5	-1.0	-1.0	0.0	0.0
13	27.3	24.5	22.0	21.5	9.5	4.5	2.5	4.5
14	34.2	31.0	28.0	28.0	20.5	16.5	14.0	13.0
15	46.0	43.0	39.5	39.5	29.0	28.0	22.5	22.0
16	51.5	48.5	45.7	46.0	34.0	32.5	29.0	28.5
17	52.3	49.5	46.7	47.5	35.5	33.5	31.5	30.5
C 1	28.8	20.0	8.0	4.5	4.5	4.5	3.5	3.5
2	26.7	16.0	5.0	0.0	1.0	1.5	1.5	1.5
3	26.8	16.0	6.0	0.0	-0.5	1.0	1.3	1.0
4	26.5	16.5	7.0	-2.0	-1.0	-0.5	0.0	0.0
5	26.2	17.0	8.0	-3.0	-2.0	-1.5	-0.5	-0.5
6	25.8	18.0	9.0	-2.3	-3.0	-2.0	-1.0	-0.5
7	25.5	18.5	9.8	0.0	-3.0	-2.0	-1.0	-1.0
8	23.5	18.0	10.3	4.5	-3.0	-2.0	-1.0	-1.0
9	20.5	16.5	9.5	8.0	-2.5	-2.0	-1.0	-1.0
10	19.5	15.5	10.5	9.5	-1.5	-1.0	-0.5	-0.5

* See Figures 8 and 12 for piezometer locations.
** Data not recorded.

Continued

TABLE A-1 (Continued)

Run No.	70	61	9	8	4	7	6	5
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
C 11	19.5	16.0	12.0	11.0	-2.0	-1.0	0.0	0.0
12	26.0	22.5	8.0	17.0	1.0	-0.5	0.0	0.5
13	47.7	43.0	37.0	36.0	27.5	17.0	9.0	9.5
14	56.5	52.0	45.5	44.5	38.0	34.0	26.0	22.0
15	72.5	68.0	61.0	60.0	52.5	47.0	39.0	35.5
16	82.0	77.5	70.5	69.5	60.5	54.5	45.5	43.5
17	82.7	78.5	72.0	71.0	62.0	56.0	48.0	45.0
18	64.5	62.0	58.5	58.5	50.0	46.5	44.0	43.0
19	53.0	50.5	48.5	50.5	46.0	44.0	42.0	40.5
20	46.8	44.5	43.0	44.0	42.5	41.0	38.5	46.5
21	39.7	37.0	36.5	37.0	38.0	37.0	34.0	31.5
22	33.5	31.5	30.0	30.5	33.0	32.0	29.0	36.5
23	27.0	25.0	24.0	24.5	28.0	27.0	24.0	21.5
24	23.5	21.5	18.2	22.0	25.8	25.0	22.0	19.0
25	21.0	18.5	18.9	19.5	23.5	23.0	19.2	17.0
26	18.5	17.0	16.9	17.5	22.0	21.5	18.0	15.0
27	17.2	15.5	15.5	16.5	20.5	20.5	16.0	14.0
28	14.0	11.5	12.5	13.5	16.5	16.0	13.0	11.5
D 1	28.5	20.5	7.0	4.5	4.5	4.0	3.5	3.5
2	26.5	16.5	4.5	0.5	1.0	1.5	1.5	1.5
3	25.5	16.5	5.5	0.0	0.7	1.0	1.0	1.0
4	26.5	16.5	6.5	-1.5	-1.2	-0.5	0.0	0.0
5	26.2	17.5	7.8	2.5	-2.5	-1.5	-0.5	0.0
6	25.7	18.0	8.5	-1.0	-3.2	-2.5	-1.0	-1.0
7	25.5	18.5	9.7	1.0	-3.0	-2.5	-1.0	-1.0
8	23.0	17.5	10.0	5.0	-2.0	-2.5	-1.5	-1.0
9	20.2	16.0	9.5	6.5	-1.5	-2.0	-1.0	-1.0
10	18.0	15.0	9.5	8.0	-1.0	-1.0	-0.3	0.0
11	15.5	12.5	9.0	9.0	-1.0	-1.0	-0.5	0.0
12	17.7	15.0	12.0	12.0	0.5	-0.5	0.0	0.5
13	26.8	24.0	21.5	21.5	9.5	4.0	2.5	4.5
14	34.2	31.0	28.0	28.0	19.5	16.5	13.5	14.0
15	45.5	42.5	39.0	39.0	30.0	26.0	23.0	21.5
16	51.2	48.5	46.0	45.5	36.0	31.0	28.5	28.5
17	52.5	50.0	47.3	47.0	38.5	33.0	30.5	30.5

TABLE A-2

PRESSURE HEADS ON THE MORNING GLORY SPILLWAY, VERTICAL BEND AND CONDUIT
WITH RECOMMENDED AIR INTAKES AND DEFLECTOR INSTALLED

Pressure Heads in Feet of Water

Run No.	26	64	27	28	29
Reservoir Elevation	227.9	218.5	213.8	201.0	192.5
Discharge cfs	23,800	22,500	21,500	19,000	4,000
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
A 1	37.1	29.0	23.2	8.5	2.5
2	35.3	27.8	21.5	5.5	1.0
3	35.5	27.0	22.0	6.5	0.8
4	35.0	27.0	22.2	7.5	0.0
5	34.7	27.0	22.3	9.0	-0.5
6	34.0	26.7	22.1	9.8	-1.0
7	33.5	26.5	22.3	10.5	-1.0
8	30.3	24.5	21.0	11.0	-1.5
9	27.0	27.0	19.3	11.0	-1.0
10	24.1	20.0	18.1	11.0	-0.5
11	18.3	16.0	14.5	9.5	-1.0
12	29.7	26.0	24.7	18.0	7.5
13	-5.5	-3.5	-2.0	-0.5	**
14	-5.0	-3.5	-2.0	-0.5	**
15	-6.5	-3.5	-1.5	-0.5	**
16	-5.0	-3.5	-3.0	4.0	**
17	-6.0	-3.5	-2.5	19.0	**
18	1.0	**	**	**	**
19	**	**	**	**	**
20	**	**	**	**	**
21	**	**	**	**	**
22	**	**	**	**	**
23	1.0	**	**	**	**
24	0.0	0.0	1.0	2.0	**
25	-2.0	**	0.0	0.0	**
26	-4.7	-2.0	-0.5	-0.5	**
27	-5.5	**	-1.3	-2.0	**
28	-5.0	-2.5	-1.0	-0.5	**
B 1	37.5	28.3	24.0	8.0	3.0
2	35.3	26.5	22.2	5.5	1.5
3	35.7	26.7	22.7	7.0	1.0
4	35.3	26.7	22.7	8.0	0.0
5	34.8	26.8	23.2	9.0	0.0
6	34.2	26.5	22.8	9.7	-0.5
7	33.6	26.5	22.8	10.5	-1.0
8	30.5	24.5	21.5	11.5	-1.0
9	27.2	27.5	20.0	11.5	-1.0
10	24.5	21.0	19.0	12.0	-0.5
11	22.3	19.5	18.0	12.0	0.0
12	21.8	20.5	18.5	13.5	-1.0
13	31.8	29.7	28.0	23.5	4.0
14	37.2	35.2	33.7	31.0	14.5
15	44.0	42.5	41.8	39.0	21.5
16	42.5	43.4	44.5	45.5	28.0
17	39.5	52.5	45.0	47.5	30.5

Run No.	26	64	27	28	29
Reservoir Elevation	227.9	218.5	213.8	201.0	192.5
Discharge cfs	23,800	22,500	21,500	19,000	4,000
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
C 1	37.1	28.5	23.7	8.5	3.2
2	35.3	26.5	22.7	5.8	0.5
3	35.5	26.8	22.3	7.0	1.5
4	35.0	26.8	22.6	8.0	0.5
5	34.5	26.7	22.7	9.0	0.0
6	33.8	26.5	22.8	10.0	-0.5
7	33.5	26.5	23.0	11.0	-0.5
8	30.5	25.0	21.7	11.7	-1.0
9	27.6	22.7	20.3	11.7	-0.5
10	26.2	22.0	20.0	13.0	-0.2
11	25.3	22.3	20.3	14.0	0.0
12	32.3	28.5	26.8	20.0	1.5
13	53.8	48.8	46.5	38.0	10.0
14	51.8	57.0	54.7	46.0	21.0
15	75.5	70.8	68.5	61.0	34.0
16	80.5	77.5	76.0	70.5	42.5
17	79.2	77.5	76.7	72.5	44.5
18	50.5	55.5	59.2	61.0	43.0
19	49.0	51.0	52.0	51.5	40.5
20	45.0	46.0	46.7	46.0	36.0
21	38.0	39.2	40.2	39.5	31.5
22	32.0	33.5	34.5	34.0	26.5
23	26.0	26.8	28.3	28.0	21.5
24	24.0	24.0	25.5	25.2	19.0
25	20.7	21.2	22.7	22.5	16.7
26	27.5	19.0	20.5	20.7	15.0
27	16.5	18.0	19.5	19.5	14.0
28	11.0	13.8	15.8	15.0	11.3
D 1	37.7	28.3	24.0	8.0	3.0
2	35.5	26.5	22.0	5.0	1.0
3	35.6	26.0	22.5	6.5	1.0
4	35.2	26.5	22.5	7.5	0.0
5	34.7	26.5	22.7	8.5	-0.5
6	34.0	26.5	22.5	9.5	-1.0
7	33.5	26.3	22.7	10.5	-1.0
8	30.3	24.5	21.3	11.5	-1.0
9	26.7	22.3	19.7	11.0	-1.0
10	25.4	20.7	19.0	12.0	-0.5
11	21.7	19.2	17.5	12.0	-1.0
12	24.0	21.0	20.0	15.0	1.0
13	31.1	29.0	27.5	23.0	3.5
14	36.2	35.0	33.2	28.5	14.5
15	43.5	42.0	41.6	38.5	21.0
16	42.7	42.7	44.2	45.0	28.0
17	40.0	42.5	45.5	47.5	30.0

* See Figures 8 and 12 for piezometer locations.
** Data not recorded.

TABLE B-1

PRESSURE HEADS ON THE MORNING GLORY SPILLWAY CREST
FOR VARIOUS NUMBERS OF OPEN GATES

Pressure Heads in Feet of Water

Run No.	64	27	28	65	31	32	66	36	37
Reservoir Elevation	218.5	213.8	201.0	220.0	213.0	201.0	220.0	214.0	201.1
Discharge cfs	22,500	21,500	19,000	21,800	20,300	12,300	21,250	19,000	8,300
Number of Gates Open	12	12	12	6	6	6	4	4	4
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
A 1	29.0	23.2	8.5	25.7	18.0	4.5	20.0	11.5	4.5
2	27.8	21.5	5.5	22.5	14.3	-0.5	14.5	4.3	-1.0
3	27.0	22.0	6.5	23.0	15.0	-1.5	16.0	6.0	-1.8
4	27.0	22.2	7.5	23.3	16.3	-3.5	17.5	6.7	-3.7
5	27.0	22.3	9.0	24.3	17.0	-4.0	19.5	9.5	-4.3
6	26.7	22.1	9.8	25.0	18.5	-4.7	21.5	13.3	-4.5
7	26.5	22.3	10.5	25.5	19.5	-3.5	23.0	16.5	-3.5
8	24.5	21.0	11.0	24.5	19.8	-1.0	23.5	19.7	-1.3
9	27.0	19.3	11.0	22.7	18.7	0.0	22.3	20.5	0.5
10	20.2	18.1	11.0	21.3	17.6	0.0	21.0	20.0	0.0
11	16.0	14.5	9.5	17.0	14.3	-1.0	17.5	17.0	-0.8
12	26.0	24.7	18.0	26.5	23.3	2.0	26.5	24.0	2.0
B 1	28.3	24.0	8.0	**	**	**	21.0	12.5	5.0
2	26.5	22.2	5.5	**	**	**	15.0	5.7	-0.4
3	26.7	22.7	7.0	**	**	**	16.5	7.2	-1.0
4	26.7	22.7	8.0	**	**	**	17.5	9.0	-3.0
5	26.8	23.2	9.0	**	**	**	20.0	11.8	-3.5
6	26.5	22.8	9.7	**	**	**	22.0	14.3	-3.5
7	26.5	22.8	10.5	**	**	**	24.0	17.2	-2.7
8	24.5	21.5	11.5	**	**	**	24.0	20.5	-0.5
9	27.5	20.0	11.5	**	**	**	22.8	21.0	0.5
10	21.0	19.0	12.0	**	**	**	26.5	20.8	-0.3
11	19.5	18.0	12.0	**	**	**	20.0	19.3	0.0
12	20.5	18.5	13.5	**	**	**	21.0	21.5	-0.5
C 1	28.5	23.7	8.5	21.0	17.5	5.5	21.0	13.0	5.5
2	26.5	22.7	5.8	17.0	13.3	0.0	14.5	4.0	-0.3
3	26.8	22.3	7.0	18.5	14.8	-1.0	16.5	6.0	-0.7
4	26.8	22.6	8.0	23.0	16.5	-3.0	18.0	8.0	-3.0
5	26.7	22.7	9.0	23.5	17.5	-4.0	20.0	10.8	-3.5
6	26.5	22.8	10.0	25.0	19.0	-3.2	22.0	14.2	-3.3
7	26.5	23.0	11.0	26.2	20.3	-2.0	24.0	17.3	-2.0
8	25.0	21.7	11.7	26.0	20.5	0.0	25.0	20.5	0.0
9	22.7	20.3	11.7	22.7	19.5	0.5	23.0	21.0	0.5
10	22.0	20.0	13.0	23.0	19.5	0.0	22.0	21.2	0.0
11	22.3	20.3	14.0	22.7	20.0	0.0	22.0	22.0	0.0
12	28.5	26.8	20.0	29.2	24.5	1.0	28.5	27.3	0.7
D 1	28.3	24.0	8.0	**	**	**	21.0	12.5	5.2
2	26.5	22.0	5.0	**	**	**	15.0	4.5	-0.7
3	26.0	22.5	6.5	**	**	**	16.2	6.7	-1.0
4	26.5	22.5	7.5	**	**	**	17.0	8.2	-3.3
5	26.5	22.7	8.5	**	**	**	19.0	10.7	-4.0
6	26.5	22.5	9.5	**	**	**	21.2	13.6	-4.0
7	26.3	22.7	10.5	**	**	**	23.0	16.3	-2.8
8	24.5	21.3	11.5	**	**	**	24.5	20.2	-0.7
9	22.3	19.7	11.0	**	**	**	23.5	20.5	-0.3
10	20.7	19.0	12.0	**	**	**	21.5	20.5	0.0
11	19.2	17.5	12.0	**	**	**	20.7	19.3	-0.5
12	21.0	20.0	15.0	**	**	**	22.5	22.0	1.0

* See Figure 8 for piezometer locations

** Data not recorded.

Continued

TABLE B-1 (Continued)

Run No.		67	47	48	68	50	51	69	53	54
Piezometer Number*		Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
A	1	13.0	6.5	5.0	4.7	5.0	4.5	4.0	5.0	5.0
	2	3.7	-5.0	-1.0	-9.3	-6.5	-1.0	-12.0	-7.0	-2.5
	3	5.5	-6.0	-2.0	-8.7	-7.5	-1.5	-12.0	8.0	-3.0
	4	7.5	-7.0	-3.5	-8.5	-10.0	-3.5	-14.0	-10.0	-5.5
	5	11.0	-6.0	-4.0	-4.5	-9.0	-4.0	-12.0	-9.0	-5.5
	6	14.7	0.5	-4.0	0.7	-7.0	-4.0	-9.3	-8.0	-5.5
	7	18.0	7.0	-3.0	2.5	-4.0	-3.0	-5.0	-4.5	-3.5
	8	22.5	16.5	-0.5	15.0	2.0	-0.5	1.0	0.0	-0.5
	9	23.0	18.5	0.5	17.5	5.5	0.5	1.5	0.5	0.5
	10	22.5	18.5	0.0	18.0	6.5	0.0	4.0	0.5	0.0
	11	20.0	16.0	-1.0	17.0	7.0	-1.0	4.0	0.5	-0.5
	12	26.5	21.5	1.5	22.5	12.0	2.0	9.0	4.0	1.5
C	1	**	**	**	7.7	6.0	5.5	**	**	**
	2	**	**	**	-10.5	-7.0	-1.0	**	**	**
	3	**	**	**	-8.5	-6.5	-1.0	**	**	**
	4	**	**	**	-8.5	-9.0	-3.0	**	**	**
	5	**	**	**	-4.5	-9.0	-4.0	**	**	**
	6	**	**	**	1.0	-7.0	-3.5	**	**	**
	7	**	**	**	6.7	-3.5	-2.5	**	**	**
	8	**	**	**	15.5	-2.0	0.0	**	**	**
	9	**	**	**	17.7	5.0	0.0	**	**	**
	10	**	**	**	18.0	4.5	-1.0	**	**	**
	11	**	**	**	18.0	8.0	-1.0	**	**	**
	12	**	**	**	19.0	10.0	2.0	**	**	**

TABLE C-1

PRESSURE HEADS ON THE CHUTE, FLOOR, CHUTE BLOCKS
AND BAFFLE BLOCKS OF STILLING BASIN I

Pressure Heads in Feet of Water

Run No.	15	3	8	16	4	7	6	5	9	11
Tailwater Elevation	150.5	150.5	150.5	150.5	150.5	150.5	150.5	150.5	142.0	142.0
Discharge cfs	25,300[1]	20,200	19,000	17,100	13,000	10,000	6,000	4,000	20,000	4,700
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
E 1	3.5	9.0	10.5	10.5	12.5	12.5	10.0	9.0	9.5	8.5
2	11.0	14.8	15.5	15.0	14.5	13.0	9.5	9.5	14.5	7.5
3	13.5	15.3	15.5	14.0	12.5	10.5	7.5	11.0	15.3	6.0
4	11.5	12.0	12.0	10.5	9.0	7.5	6.5	12.5	12.0	3.8
5	11.0	10.5	10.0	8.5	8.5	7.5	10.0	14.5	14.5	3.0
6	9.5	8.5	8.5	7.5	9.0	9.5	13.0	16.5	9.0	3.0
7	6.5	7.0	6.5	6.0	12.0	13.0	16.0	18.8	6.0	6.0
8	7.0	9.5	9.0	9.0	17.0	17.0	19.5	21.0	6.5	9.5
9	6.5	11.5	13.0	12.5	20.5	20.5	23.0	44.0	5.5	13.5
10	10.0	15.5	17.0	17.5	24.0	24.0	26.0	36.5	7.3	17.0
11	14.0	20.0	20.5	20.5	27.0	27.5	29.5	29.5	9.5	20.0
12	17.0	29.0	29.0	29.5	37.0	37.0	38.0	38.0	15.0	29.5
13	33.5	36.0	36.0	35.0	39.5	38.5	38.5	38.0	28.0	30.0
14	34.0	40.0	40.0	39.0	41.0	39.5	38.5	38.0	36.5	29.5
15	16.0	28.5	29.0	30.0	38.0	37.5	38.5	38.0	17.0	30.0
16	29.5	35.0	35.5	35.0	39.5	38.5	38.5	38.0	27.5	30.0
17	35.5	37.5	37.5	36.0	39.5	38.5	38.5	38.0	31.0	30.0
18	37.0	38.0	**	37.0	39.5	38.5	38.5	38.0	**	30.0
19	37.5	**	38.5	37.5	28.0	38.5	38.5	38.0	32.5	30.0
20	38.5	39.0	38.5	37.0	39.5	38.5	38.5	38.0	33.0	30.0
21	36.5	37.0	36.5	36.0	37.5	36.5	36.5	36.0	31.5	28.0
22	32.0	33.0	32.5	32.0	33.5	32.5	32.5	32.5	27.0	26.0
F 1	8.5	21.0	21.5	20.5	31.0	31.0	32.5	33.0	8.0	24.5
2	10.0	23.0	24.0	23.5	33.0	34.0	35.5	35.5	10.0	26.5
3	12.5	25.5	26.0	26.0	35.5	36.0	37.0	37.0	13.0	28.5
4	8.5	21.0	22.0	22.0	32.5	31.0	32.5	33.0	8.5	24.5
5	8.0	23.0	22.0	23.5	33.5	33.5	35.0	35.0	10.0	26.5
6	8.0	20.0	19.5	22.0	28.5	28.5	29.5	30.0	9.0	21.5
7	7.0	20.0	20.0	21.5	29.0	29.5	30.0	30.0	9.0	22.0
8	14.5	27.0	27.0	27.0	34.0	34.0	34.5	34.5	17.0	26.0
9	4.0	19.0	18.5	20.0	29.0	29.0	29.5	30.0	7.0	22.0
10	13.0	26.0	26.0	26.0	34.0	33.5	35.0	34.5	16.0	26.0
11	-21.0	**	**	13.0	**	**	**	**	**	22.0
12	-17.5	13.0	13.0	17.0	31.0	31.5	33.5	34.0	-6.0	26.0

1 Discharge used to test model stilling basin is greater than any expected prototype discharges.
* See Figures 13 and 14 for piezometer locations.
** Data not recorded.

TABLE C-2

PRESSURE HEADS ON THE CHUTE, FLOOR, CHUTE BLOCKS, AND BAFFLE BLOCKS
OF STILLING BASIN II

Pressure Heads in Feet of Water

Run No.	26	26B	64	64A	27	28	25	29
Tailwater Elevation	150.5	142.0	150.5	142.0	150.5	150.5	142.0	150.5
Discharge cfs	23,800	23,600	22,500	22,500	21,500	19,000	19,000	4,000
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
E 1	8.2	8.2	8.7	9.5	3.2	11.8	11.5	9.0
2	13.5	12.7	11.5	12.0	12.3	16.0	15.5	8.5
3	14.8	14.0	14.2	24.7	14.8	15.0	14.5	9.5
4	12.2	12.5	12.8	13.0	12.8	11.5	11.0	12.0
5	10.0	10.0	10.2	10.5	10.5	9.0	8.5	14.0
6	9.0	9.3	8.8	9.0	8.8	8.0	8.0	15.5
7	6.7	6.7	6.5	6.5	6.4	7.0	5.5	18.0
8	7.5	7.5	7.5	7.0	6.5	9.0	6.0	20.5
9	9.3	8.0	11.0	7.7	8.5	13.0	7.0	23.5
10	14.5	22.2	26.0	20.8	22.0	25.5	20.5	26.5
11	**	**	**	**	**	**	**	**
12	10.0	1.0	16.0	5.0	14.5	19.5	8.0	33.0
13	32.5	29.0	33.0	8.0	34.7	22.0	28.0	33.0
14	43.3	43.5	40.7	39.8	43.5	38.5	36.0	33.0
15	14.0	18.0	17.2	13.5	17.3	21.5	14.5	32.0
16	27.5	24.8	29.0	24.0	28.0	30.5	25.0	33.0
17	32.5	27.7	33.0	28.7	31.8	32.5	28.0	33.0
18	34.0	30.0	34.3	30.5	33.0	33.5	29.5	33.0
19	34.7	31.2	35.0	31.0	33.3	33.5	30.0	33.0
20	35.0	31.5	35.2	31.2	33.7	34.0	30.0	33.0
21	43.5	29.2	33.2	28.3	32.7	32.5	28.5	31.0
22	29.0	25.5	29.2	24.7	28.5	28.0	24.0	27.0
23	4.5	**	0.0	0.2	4.6	8.0	8.5	5.5
24	10.2	**	2.7	3.5	11.5	15.5	15.0	6.5
F 1	5.7	-4.5	9.5	1.0	12.7	13.0	4.0	28.0
2	7.7	-2.5	11.5	3.0	14.7	14.5	6.5	30.0
3	11.5	-0.3	15.0	6.3	17.0	18.5	10.0	32.0
4	6.3	-4.3	9.5	1.5	12.7	13.0	4.0	28.0
5	7.5	-3.5	11.0	3.0	14.2	15.0	6.0	30.0
6	8.5	16.0	10.0	10.5	7.5	13.5	9.0	24.5
7	8.0	16.3	10.0	10.0	8.5	13.0	9.0	25.0
8	15.5	20.5	14.0	17.0	16.0	20.5	15.5	29.0
9	6.0	13.5	8.0	9.5	5.7	12.0	7.0	25.0
10	13.5	19.0	15.5	14.0	14.5	20.0	14.5	29.0
11	21.0	-6.0	-14.5	-19.0	-16.5	-2.0	-14.0	25.0
12	15.0	-0.3	-10.0	-18.0	-11.0	0.5	-10.0	29.0

* See Figures 14 and 15 for piezometer locations.
** Data not recorded.

TABLE C-3

PRESSURE HEADS ON THE CHUTE, FLOOR, CHUTE BLOCKS, AND BAFFLE BLOCK A OF STILLING BASIN II

Pressure Heads in Feet of Water

Run No.	26D	26E	28D	28E
Tailwater Elevation	150.5	142.0	150.5	142.0
Discharge cfs	23,800	23,800	19,000	19,000
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head
E 1	7.8	8.0	11.8	12.0
2	12.5	12.7	16.0	16.0
3	14.0	14.0	14.8	14.8
4	12.5	12.5	11.1	11.3
5	10.0	11.0	8.8	8.8
6	9.2	9.3	8.5	8.5
7	6.8	6.8	6.5	6.5
8	7.2	7.3	7.7	6.5
9	8.0	8.0	11.0	4.0
10	12.5	22.1	24.5	9.0
11	**	**	**	**
12	2.0	-5.5	17.8	3.5
13	27.3	23.0	31.0	24.0
14	34.0	35.5	34.5	29.7
15	7.7	13.5	11.3	11.5
16	23.7	8.3	29.5	23.7
17	26.5	5.0	31.3	25.5
18	30.7	16.0	33.0	8.3
19	32.5	19.5	34.2	29.3
20	34.8	32.0	35.2	30.5
21	36.0	23.0	35.0	30.7
22	30.5	20.0	30.0	25.0
23	**	**	**	**
24	**	**	**	**
F 1	0.0	-4.7	12.0	1.2
2	2.3	-2.7	14.0	3.2
3	5.3	-1.5	17.5	6.0
4	0.5	-4.5	12.5	1.5
5	2.0	-3.5	13.5	3.2
6	-11.5	-1.5	5.8	-3.5
7	-6.5	0.3	8.5	0.2
8	7.5	2.0	19.0	1.5
9	-8.0	0.5	8.3	-0.5
10	7.5	1.5	19.0	12.5
11	-40.0[1]	-28.0	-7.0	-21.8
12	**	-46.0[1]	-24.5	-57.0[1]

* See Figures 14 and 15 for piezometer locations.
** Data not recorded.
1 Negative pressures reading below about -30.0 feet of water have no physical meaning in the prototype except to indicate possible cavitation.