TIBER DAM
AUXILIARY OUTLET WORKS

by

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by Melvin A. Jabara,1/ F. ASCE, and William E. Wagner,2/ F. ASCE

INTRODUCTION

A supplemental outlet capacity for Tiber Dam became necessary when the foundation for the spillway irreparably failed. Recently completed is a cofferdam constructed across the spillway inlet channel and modification of an existing incomplete high level canal outlet works. The modified outlet facility is designated as the auxiliary outlet works. With abandoned reservoir storage allocations, it provides sufficient additional discharge capacity to accommodate the inflow design flood. A principal feature of the new system is the drop inlet to a shaft which branches downward from the invert of the existing tunnel. Flows are directed from the shaft through a vertical elbow turning in a direction normal to the existing tunnel. Hydraulic model studies were conducted to determine the behavior of flows as they are deflected down to the branch inlet and elbow, and through the remainder of the system.

This paper deals primarily with the design and model testing of the inlet to the vertically downward branch from the existing tunnel's invert, the elbow, and the transition downstream from the high-pressure slide gate.

DESCRIPTION OF PROJECT

Tiber Dam, completed in 1954, is located on the Marias River approximately 80 miles north of Great Falls, Montana. It was constructed to provide 362,000 acre-feet of storage space for irrigation of land in the Marias River and Milk River Basins. The Milk River lies to the north of the Marias River and both are tributaries of the Missouri River. In anticipation of the execution of repayment contracts of irrigation distribution feature costs for Milk River Basin land, the headworks, designated as the canal outlet works was constructed in the left abutment of the dam. A dual-purpose flood control storage space of 413,000 acre-feet was also provided. The first purpose, obviously, was to store portions of major floods to permit releases within the safe channel capacity limit. The other was to allow retention of storage within the flood control pool upon recession of the spring flood until late summer when releases would be made and utilized for power generation at the Corps of Engineers Fort Peck Dam located on the Missouri River downstream from its confluence with the Marias River. Figure 1 is a plan of the dam and its appurtenant structures.

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As early as the summer of 1956 significant movement in the spillway crest structure was observed, and by the summer of 1967 the foundation materials underlying it, as evidenced by erratic settlement and seriously deteriorated concrete, and as shown by subsurface investigations, had irreparably failed. It was concluded that the structure could not be subjected to the predicted additional settlement and remain capable of safely accommodating large releases. To reduce the risk of catastrophic failure the initial reservoir storage allocations were abandoned. The reservoir water surface was lowered to a minimum level each succeeding spring prior to the historically heavy snow and rain runoffs. Complete restoration of flood control and recreation benefit would require replacement of the spillway. Adequate diversion capacity during construction and provision for future evacuation capability would be accomplished by converting the incomplete canal outlet works into a permanent discharge facility. A cofferdam across the present spillway inlet channel would be necessary to protect the work area. Because of fund limitations, spillway replacement could not be undertaken. However, to restore some of the lost benefits and to remove the risk of a major failure, authorization was granted to proceed with design and construction of the cofferdam and modification of the canal outlet works which has been redesignated "auxiliarly outlet works." With abandoned reservoir storage allocations, the auxiliary outlet works together with the existing river outlet works is capable of handling the design flood without encroachment on the established freeboard for the dam.

Figure 2 is a profile of the incomplete canal outlet works prior to its conversion to the auxiliary outlet works. It consisted of a twin 7- by 12-foot cut-and-cover conduit leading to a gate structure containing two 7- by 12-foot emergency slide gates and embedded metalwork for the future installation of two 7- by 12-foot regulating radial gates, and a 17-foot 0-inch diameter horseshoe tunnel dead ending 256 feet from the gate structure. The tunnel incorporated a stilling basin located immediately downstream from the gate structure. The radial gates were never installed.

FACTORS CONSIDERED IN DESIGN

Consideration was given to a variety of modification schemes. Because of remaining enthusiastic interest on the part of many water users in the Milk River Basin, it appears likely that a distribution system to that area will be supplied in the foreseeable future. One scheme which was seriously considered included extending the existing tunnel along its present alinement approximately 600 feet to a ravine where it would daylight, at which point a cut-and-cover conduit would branch laterally 90° to convey releases to the river below the dam. Upon close field examination, it was determined that the cut-and-cover system would be founded on slide material and was therefore withdrawn from further consideration.

Another scheme included a tunnel system branching laterally 90° from the existing tunnel and extending to the river. Subsequent subsurface explorations disclosed a highly weathered, gypsiferous, bentonitic shale extending from near the surface to a few feet below invert level of the proposed tunnel. Moreover, construction records indicated extreme difficulty in tunnelling operations for the canal outlet works.

The above conditions stimulated the pursuit of the adopted design which incorporates an intake structure equipped with trashracks, conversion of the existing tunnel to a pressure tunnel, a vertically downward branch from the existing tunnel's invert, a vertical elbow turning in a direction normal to the existing tunnel, a 10-foot 9-inch diameter circular tunnel leading to a gate chamber which houses one 7-foot 3-inch by 9-foot 3-inch high-pressure slide gate, a transition section connecting the gate and a 10-foot 9-inch diameter circular tunnel more than 1,300 feet in length, and a conventional hydraulic jump stilling basin. Figure 3 shows a profile of the auxiliary outlet works. Branching downward from the existing tunnel placed the new auxiliary outlet tunnel at a level to permit tunnelling through firmer shale.

To satisfy the reader's curiosity the 7-foot 3-inch by 9-foot 3-inch high-pressure gate was previously designed to meet conditions at another project. A second gate of identical dimensions was ordered, thereby eliminating design time and expediting delivery. Hence, the odd size. A profile of the adopted drop entrance and elbow is shown in Figure 4. The adopted transition which connects the regulating gate and the downstream 10-foot 9-inch diameter circular tunnel is shown in Figure 5.

Because of the likelihood of later construction of the canal distribution facilities, it became necessary to locate a gate in the new auxiliary outlet to permit uninterrupted flows to be directed through the canal system. The election to convert the existing tunnel, which was incapable of withstanding the imposition of potential internal pressures, to a pressure tunnel was provoked by the desirability, if indeed, not the necessity of maintaining the control at the gate in the new system for all flow conditions. A reinforced concrete lining having a minimum thickness of 8 inches provided a nearly circular cross section designed to tolerate the maximum internal head. The lower portion has a radius of 7 feet 10 inches while the upper portion has a radius of 7 feet 8 inches. This was done to provide sufficient space in the crown for concrete placement.

PRELIMINARY DESIGN OF DROP INLET TO THE VERTICAL BRANCH

After considering and evaluating several shapes, it was elected to first model and test an entrance designed as a circular bellmouth with an elliptically shaped cross section. The minor axis was dictated by the width of the original horseshoe tunnel, the diameter of the tunnel elbow, and thickness of the new concrete lining. The major axis was chosen to be four times the minor axis. For ease of construction and what was believed to offer the best flow characteristics the bellmouth was made to begin from a horizontal plane which provided a flat surface beginning 9 feet 3 inches upstream from the center of the drop inlet and extending the same distance beyond. The transverse dimension was coincident with the bellmouth width which was limited to 12 feet 6 inches to preserve the structural integrity of the original tunnel lining while being excavated. A 4:1 slope connected the invert of the circular tunnel lining and the horizontal plane. The width of this transition was made identical to that of the bellmouth and the horizontal plane. The 9-foot 6-inch diameter elbow was placed on a centerline radius of 20 feet. Figure 6 describes the preliminary drop inlet.

PRELIMINARY DESIGN OF TRANSITION BETWEEN HIGH-PRESSURE SLIDE GATE AND DOWNSTREAM TUNNEL

The Bureau's design philosophy includes the general use of a modified horseshoe tunnel (flat invert) where free flow exists downstream from a rectangular regulating gate. The sidewalls of the preliminary transition between the gate and tunnel were made to flare from the gate width of 7 feet 3 inches to the width of an 8-foot 6-inch wide flat invert downstream tunnel. To prevent an abrupt angle change at the beginning of the flare a circular curve was used. Total length of the transition was made 41 feet 10 inches. The profile of the invert was governed by the elevation of the tunnel invert at the end of the transition and that of the downstream end of the gate frame as shown in Figure 7.

THE MODEL

Hydraulic model studies on a scale of 1:17.5, Figure 8, were conducted to develop the hydraulic design of the drop inlet, to check the proposed modifications to the existing canal outlet tunnel, and to determine the flow characteristics in the canal and auxiliary outlet tunnels. The model included the portion of the modified canal outlet works from the emergency gates to the dead end of the tunnel, the drop inlet and circular tunnel to the gate section, and about 120 feet of tunnel downstream from the control gate. Most of the tunnel and gate sections were constructed in transparent plastic to permit visual observations of flow through critical portions of the tunnel.

A control gate was installed at the dead end of the existing tunnel to study hydraulic conditions over the drop inlet for releases of irrigation water through the canal system when it is completed. Simultaneous releases to the canal system and through the auxiliary outlet works would occur only under extreme emergency conditions or by operating personnel mismanagement.

DROP INLET STUDIES

Hydraulically, the most critical portion of the outlet works is the drop inlet which withdraws water from the bottom of the modified canal outlet works tunnel. The flow drops vertically into a 90° elbow and a nearly horizontal pressure tunnel. Because the length of the pressure tunnel is relatively short (140 feet), back pressure is low and pressures along the flow surfaces of the drop inlet could reach the cavitation range unless the inlet is properly shaped.

PRELIMINARY DROP INLET

As originally envisioned, the auxiliary outlet works would be placed in operation with the minimum reservoir surface at a level 3 inches below the crown of the tunnel intake, which would result in free flow in the modified canal outlet works tunnel. As the reservoir level rose, the tunnel would submerge and become pressurized. Thus, both free surface and pressure flows in the modified canal outlet works tunnel were investigated in the model.

Generally, flow conditions through the preliminary drop inlet were unsatisfactory. As the auxiliary regulating gate was opened during the filling of the tunnel system, the elbow gradually filled with water and considerable quantities of air were entrained at the inlet. At 50 percent gate, a standing wave or partial hydraulic jump formed over the inlet and large amounts of air continued to be carried through the system, Figure 9.

Surges generated by the jump were reflected back from the dead end of the tunnel and occassionally reached resonance, submerged the jump, and significantly reduced the rate of flow through the inlet. The depth of flow in the tunnel then increased, producing subcritical flow, and a large, unstable, air-entraining vortex formed over the inlet, Figure 10. The higher head increased the flow through the inlet and eventually a hydraulic jump again formed. This cycle was repeated at irregular time intervals.

Pressures measured along the elliptical surface of the drop inlet reached the cavitation range when the auxiliary gate was at 70 percent or greater opening.

Several devices, including deflectors in the elbow and guide vanes parallel to the flow in the tunnel and the drop inlet, were tested in unsuccessful attempts to suppress or eliminate the vortex and stabilize the flow. A deflector wall placed transversely to the flow over the drop inlet helped significantly in turning the flow into the inlet.

Because of the unstable flow conditions observed in the drop inlet and the adverse pressures measured on the surfaces of the elliptical entrance, it was apparent that major modifications to the inlet shape were needed to improve the hydraulic characteristics.

RECOMMENDED DROP INLET

In developing the recommended drop inlet, several inlet shapes were tested in an attempt to raise the subatmospheric pressures and improve the flow characteristics in the bend. The 4:1 slope, horizontal plane, and small elliptical entrance in the preliminary design were replaced with a single 12-foot 7-inch radius curve from the invert of the modified canal outlet works tunnel to the P.C. of the elbow, Figure 4. In addition the diameter of the elbow and downstream tunnel was increased from 9 feet 6 inches to 10 feet 9 inches (see Gate Transition Studies) and the radius of the bend was increased from 20 feet to 21 feet 4-1/2 inches. These modifications provided a more gradual change in direction for the flow from the horizontal tunnel to the vertical elbow and decreased the flow velocity in critical areas of the entrance and elbow.

To help turn the flow into the inlet and suppress vortices that tended to form, a deflector extending from the crown of the tunnel to the tunnel centerline was placed over the drop inlet, Figure 4. The upstream surface of the deflector was curved on a 15-foot 6-inch radius to gradually turn the flow into the inlet. This deflector was very effective in suppressing vortices and improving the general flow conditions in the drop inlet. Without the deflector, an air-entraining vortex formed over the

inlet. The swirling vortex flow carried air through the elbow and into the downstream tunnel and auxiliary outlet works regulating gate. After passing through the gate, the rope of air in the swirling flow expanded, disrupted the smooth flow, and caused the downstream tunnel to nearly fill, Figure 11. By contrast, the deflector suppressed the vortex and provided smooth flow through the drop inlet, elbow, gate, and downstream tunnel, Figure 12.

Pressures measured throughout the drop inlet and elbow were above atmospheric for all discharges and reservoir elevations.

AIR VENTS

The problem of air collecting in the modified canal outlet works tunnel was recognized early in the design because the crown of the tunnel over the drop inlet is about 2 feet higher than the crown just downstream from the emergency gates; thus, air collecting along the crown of the tunnel could not escape through the air vents located in the gate structure. This problem was emphasized when methods of filling the tunnels were tested in the preliminary studies. To assure the removal of air from the tunnel before operating the auxiliary outlet works gate, it was necessary to raise the minimum reservoir elevation for the auxiliary outlet works operation to about 5 feet above the highest point in the crown of the tunnel. Thus, the tunnel will always operate under a slight pressure.

Early in the studies, tests were conducted to determine the best method of filling and unwatering the tunnels. Original plans called for filling the auxiliary outlet works tunnel before the modified canal outlet works tunnel filled by opening the emergency gates and controlling the flow with the auxiliary outlet works gate. As shown in Figure 13, air is carried into the drop inlet. Because of the drag of the flowing water, the air collects in a pocket immediately upstream from the auxiliary outlet works gate at partial gate openings. If the regulating gate is closed or lowered to reduce the drag forces on the air pocket, the air pocket which is under pressure moves upstream and is released in the modified canal outlet works tunnel with an explosive-type force. To prevent damage by such a "blow back," the auxiliary outlet works regulating gate will not be opened until the tunnels are filled with water under a slight pressure. When unwatering the tunnels, the emergency gates will be closed and the auxiliary outlet works gate will be slightly opened to drain the water from the tunnels. The air vents in the gate structure are large enough to supply adequate amounts of air and replace the water being drained at small gate openings.

An 8-inch air vent also was placed in the high point of the tunnel crown about 67 feet upstream from the drop inlet. Tests with this air vent indicated that the drag forces of the water prevented the air pockets from completely venting at all discharges. Air pockets collected in the tunnel crown near the drop inlet and extended upstream for some distance. The air vent was then moved to a point about 40 feet upstream from the drop inlet where the air pockets appeared to accumulate in the model. Also, a 4-inch vent pipe was placed along the tunnel crown through the

deflector to remove air from the downstream end of the modified canal outlet works tunnel. These two additional air vents adequately removed air from the tunnels during filling operations and normal releases.

GATE TRANSITION STUDIES

As stated previously, operation of the preliminary drop inlet disclosed the formation of a vortex that entrained air which caused rough operation as it expanded and was released in the transition immediately downstream from the gate. The rough flow conditions nearly caused the downstream tunnel to fill. Since the downstream tunnel was designed for free flow, several transitions downstream from the rectangular gate section were investigated to improve the flow conditions in the transition and tunnel.

Preliminary Transition

The Bureau normally uses a modified horseshoe cross section (flat invert) for free-flow tunnels. In keeping with this practice the preliminary plans called for a modified horseshoe tunnel downstream from the auxiliary outlet works regulating gate, Figure 7. Except for the vortex flow disturbances described previously, flow through the transition leading to the flat bottom tunnel was generally satisfactory. However, because of the relatively poor rock conditions at the site it was decided to use the more structurally competent circular tunnel. A 10-foot 3-inch diameter tunnel was chosen based on its theoretical hydraulics.

Tests at maximum discharge indicated that the depth of flow at the upstream end of the 10-foot 3-inch diameter circular tunnel was about 0.8 of the tunnel diameter. Since the slope of tunnel is subcritical, the depth of flow could be expected to be deeper at the downstream tunnel portal. To provide more freeboard in the tunnel and as added assurance that the tunnel would not fill at maximum discharge, the diameter was increased 6 inches to 10 feet 9 inches in the recommended design.

Recommended Transition

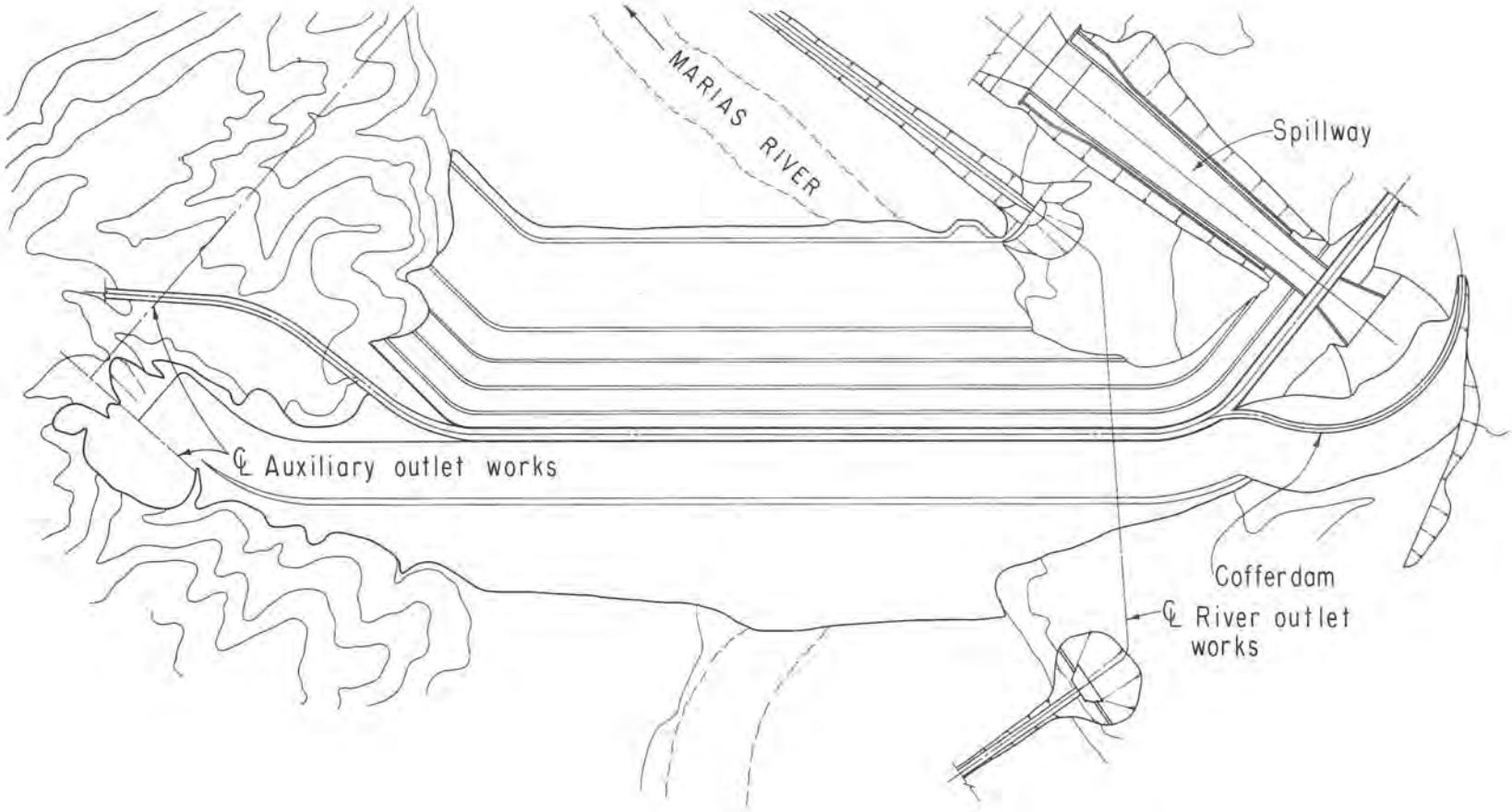
The recommended transition included several desirable features developed in the earlier transition studies. For example, the break in the surface at the intersection between the vertical walls and the circular crown of the transition disrupted the flow and caused fins of water to form along the sides of the transition. In the recommended transition, the circular crown was made tangent to the vertical sides in the downstream two-thirds of the transition. This change, plus a slightly longer transition and larger downstream tunnel, greatly minimized the size of water fins that tended to form in the transition. The operation of the final transition at maximum discharge is shown in Figure 12. Pressures measured along the invert and sidewalls were nearly equal to or above atmospheric for all reservoir elevations and discharges.

TESTS TO INTRODUCE AIR INTO FLOW

Consideration was also given to offsetting the transition walls and invert away from the flow at the gate frame to introduce air along the sides of and under the jet to reduce the cavitation potential of the concrete flow surfaces immediately downstream from the gate. Experience on other Bureau structures shows that no cavitation damage will occur at irregularities on concrete surfaces if the flow is adequately aerated.

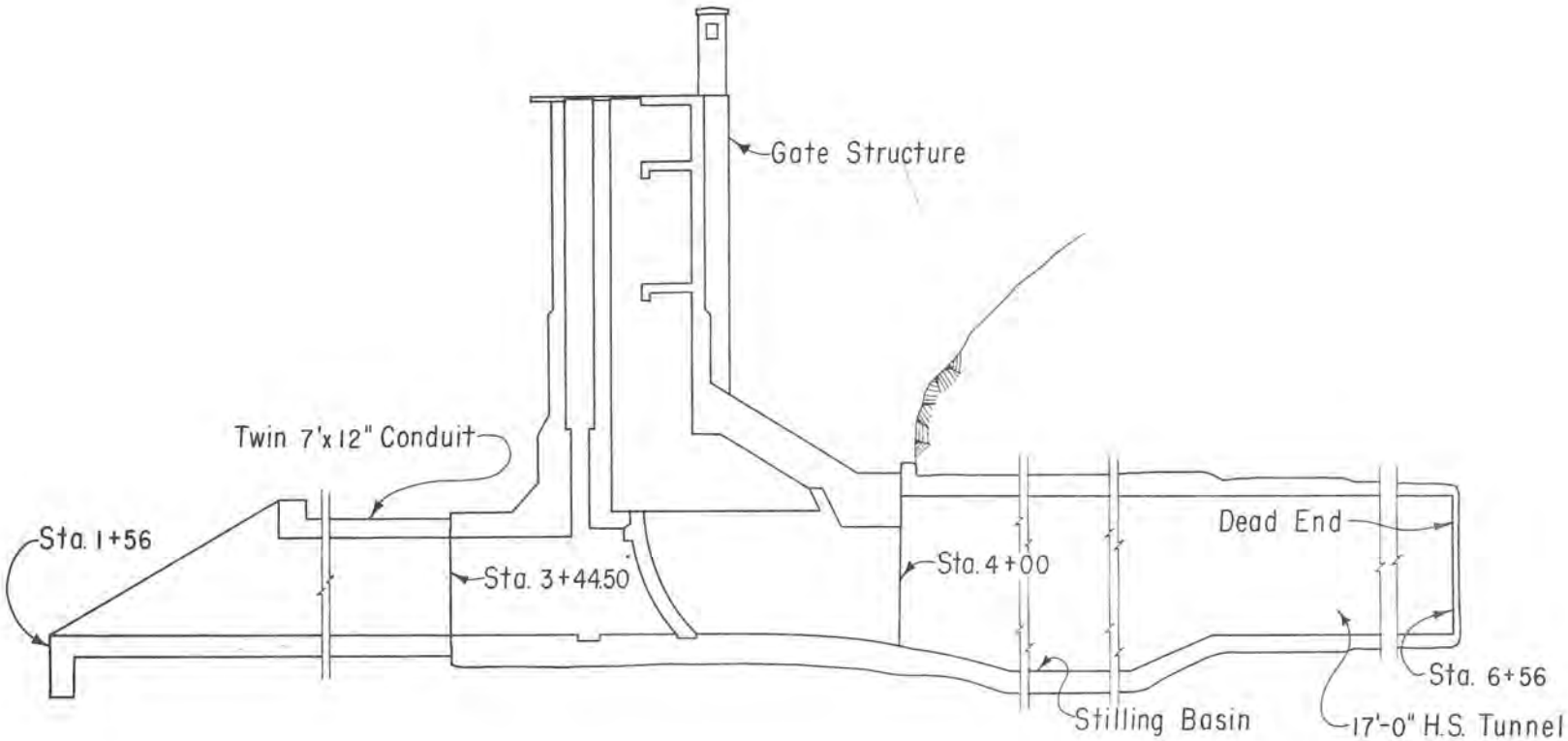
Up to 12-inch offsets in the sidewalls and invert were investigated. The model showed that, in this structure, offsets in the sidewalls increased the tendency for fins of water to form where the jet impinged on the sidewalls and invert. Indeed, the fins of water were so pronounced that at maximum discharge the flow crossed over the crown of the transition and appeared to fill the downstream tunnel.

Tests also were conducted with a 2-foot offset in the invert and no offset in the sidewalls. Air was supplied through two 8-inch-diameter vents terminating in the vertical face of the offset. The investigation showed that the offset and air vents filled with water at gate openings above 90 percent for minimum reservoir elevation and 97 percent for maximum reservoir elevation. Figure 14 shows the model operation at 97 and 100 percent gate openings and maximum reservoir. Although the objectionable fins of water were suppressed at all flows, it was concluded that limiting the range of gate openings to avoid filling the offset was infeasible and operation with the offset filled with water was undesirable because such operation, may indeed increase the cavitation potential of the flow surfaces. No doubt a larger offset or a steeper slope of the transition and downstream tunnel would have corrected the objectionable flow conditions described above; however, because of the elevation of the downstream river channel, a larger offset or a tunnel with a steeper slope was not practicable. Therefore, tests of offsets in the transition to aerate the flow were discontinued.



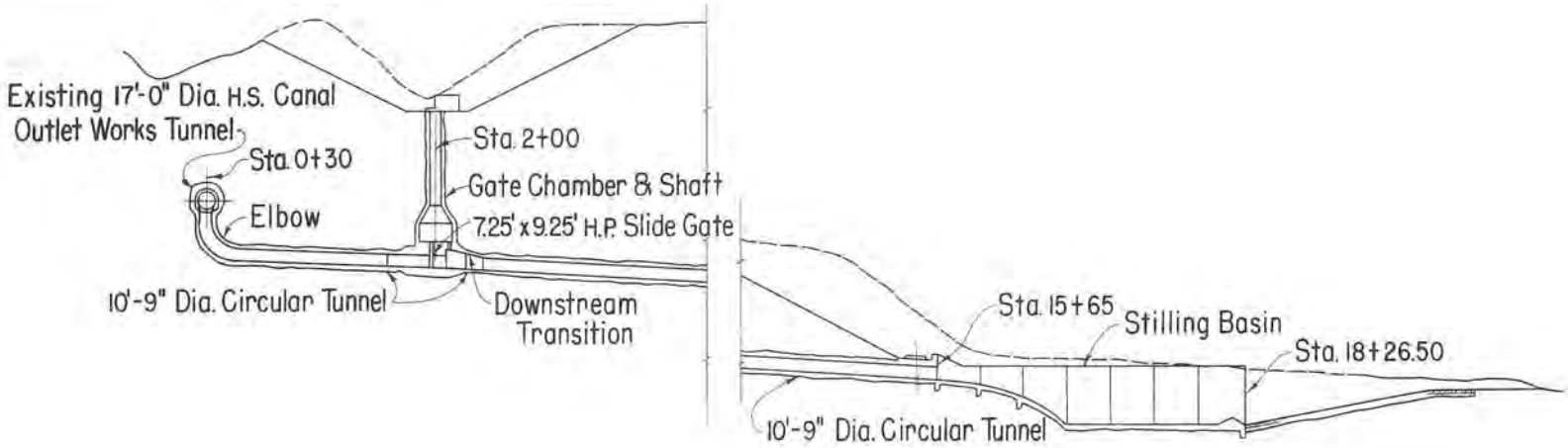
GENERAL PLAN

Figure 1



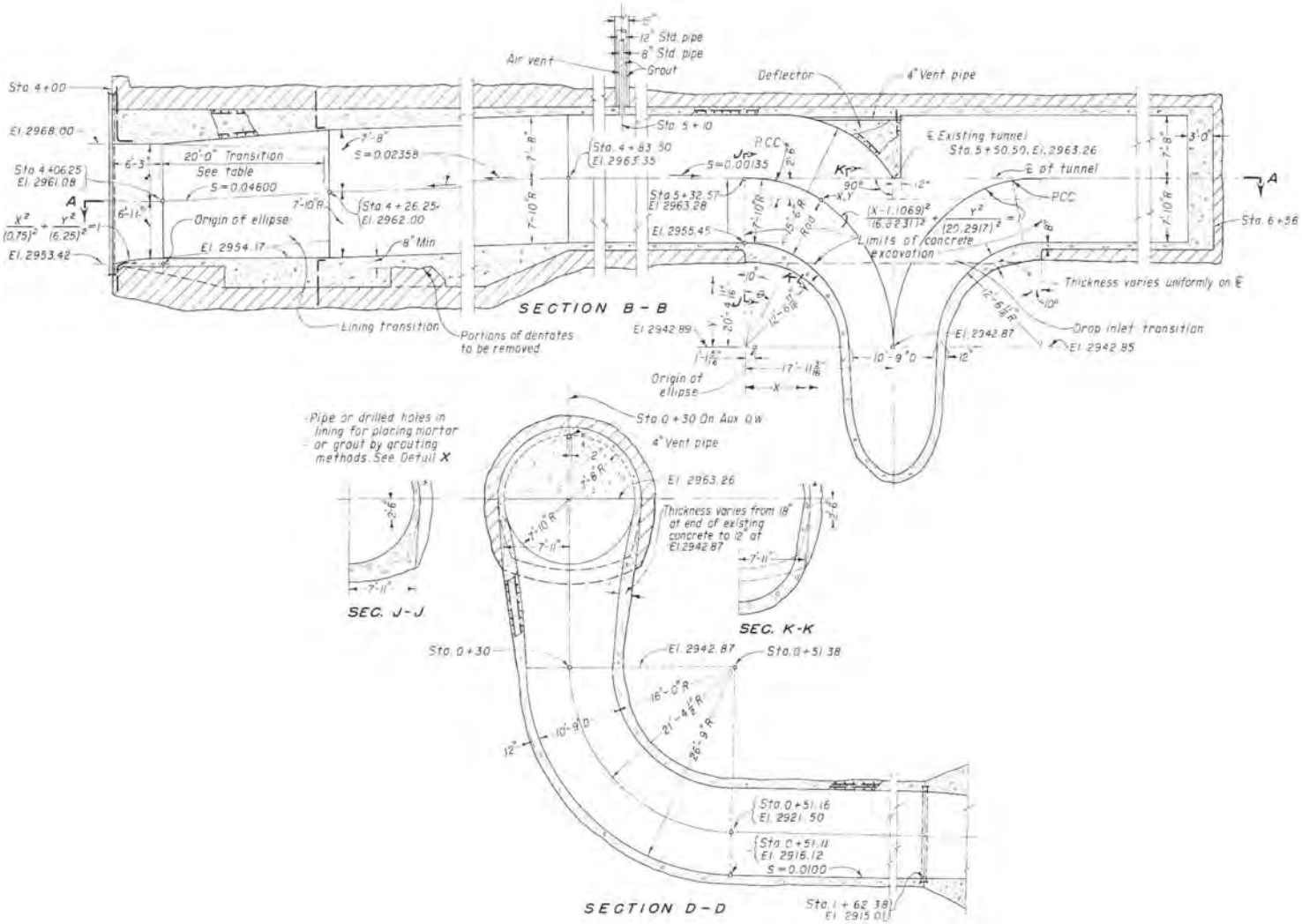
EXISTING CANAL OUTLET WORKS

Figure 2



AUXILIARY OUTLET WORKS
(FINAL DESIGN)

Figure 3



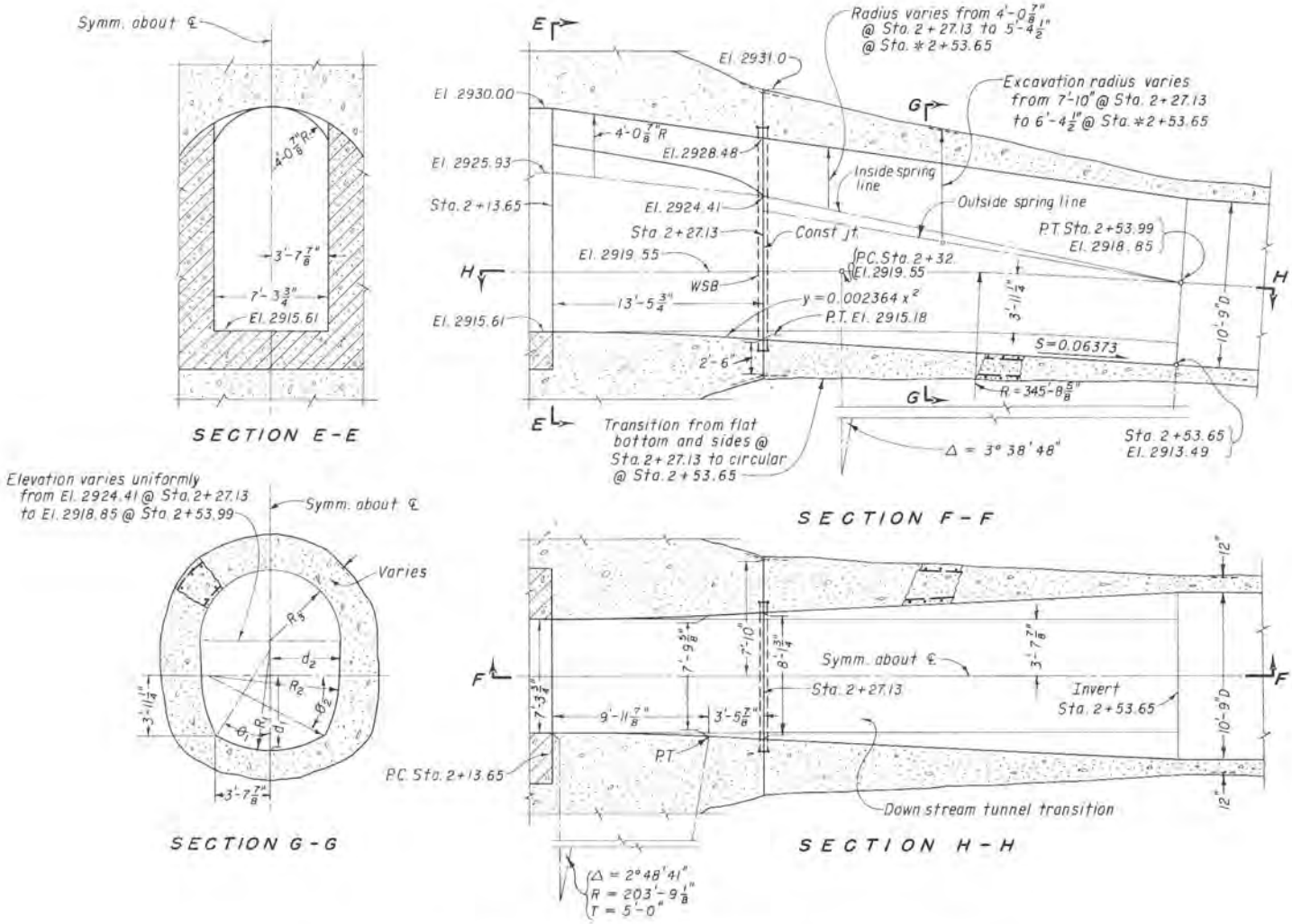
θ	X	Y	Rad.
0	0	20'-4 15/16"	7'-10"
10°	3'-6 1/2"	20'-0 15/16"	7'-10"
20°	6'-11 1/8"	19'-0 7/16"	7'-8 7/16"
30°	9'-11 9/16"	17'-3 1/16"	7'-4 7/16"
40°	12'-6 3/16"	14'-11"	6'-10 15/16"
50°	14'-6 3/16"	12'-2 1/2"	6'-5 3/16"
60°	16'-0 13/16"	9'-3 5/16"	6'-0"
70°	17'-1 7/16"	6'-2 3/4"	5'-7 15/16"
80°	17'-8 3/4"	3'-1 1/8"	5'-5 3/8"
90°	17'-11 3/16"	0	5'-4 1/2"

DROP INLET TRANSITION TABLE

MODIFIED CANAL OUTLET WORKS TUNNEL

(FINAL DESIGN)

Figure 4



STA.	d_1	R_1	θ_1	d_2	R_2	θ_2	R_3
2+13.65	3'-11 1/4"	—	0	3'-7 7/8"	—	0	4'-0 7/8"
2+16.65	3'-11 9/16"	314'-2 7/8"	0° 40'	3'-8 1/8"	351'-2 3/8"	0° 38'	
2+19.65	4'-0 5/16"	78'-7 1/8"	2° 40'	3'-8 15/16"	87'-10 1/16"	2° 34'	
2+22.65	4'-1 9/16"	35'-0 1/8"	6° 0'	3'-10 1/4"	39'-1 7/16"	5° 47'	
2+23.64	4'-2 1/8"	28'-5 7/16"	7° 23'	3'-10 13/16"	31'-9 5/16"	7° 7'	
2+25.65	4'-3 3/8"	19'-9 5/8"	10° 38'	4'-0"	22'-9 1/16"	9° 58'	
2+27.13	4'-4 7/16"	15'-9 1/4"	13° 24'	4'-0 7/8"	18'-10 1/16"	12° 4'	4'-0 7/8"
2+28.65	4'-5 5/8"	12'-11 9/16"	16° 23'	4'-1 3/4"	16'-0 9/16"	14° 13'	4'-1 3/4"
2+32	4'-8 1/8"	9'-4 13/16"	22° 53'	4'-3 3/4"	12'-2"	18° 54'	4'-3 3/4"
*2+34.65	4'-10 1/16"	7'-10 9/16"	27° 39'	4'-5 5/16"	10'-3 1/4"	22° 33'	4'-5 5/16"
*2+37.65	4'-11 7/8"	6'-10 11/16"	32° 02'	4'-7 1/16"	8'-9 7/16"	26° 39'	4'-7 1/16"
*2+40.65	5'-1 1/2"	6'-2 13/16"	35° 54'	4'-8 13/16"	7'-8 11/16"	30° 40'	4'-8 13/16"
*2+43.65	5'-2 11/16"	5'-10 1/16"	38° 46'	4'-10 5/8"	6'-11 1/4"	34° 37'	4'-10 5/8"
*2+46.65	5'-3 5/8"	5'-7 1/16"	40° 52'	5'-0 3/8"	6'-4"	38° 29'	5'-0 3/8"
*2+49.65	5'-4 3/16"	5'-5 5/16"	42° 13'	5'-2 1/8"	5'-10 5/16"	42° 15'	5'-2 1/8"
*2+53.65	5'-4 1/2"	5'-4 1/2"	42° 52'	5'-4 1/2"	5'-4 1/2"	47° 8'	5'-4 1/2"

* Stations shown are invert stations. Elements are measured and placed along radial lines.

D.S. TUNNEL TRANSITION TABLE

DOWNSTREAM TRANSITION
(FINAL DESIGN)

Figure 5

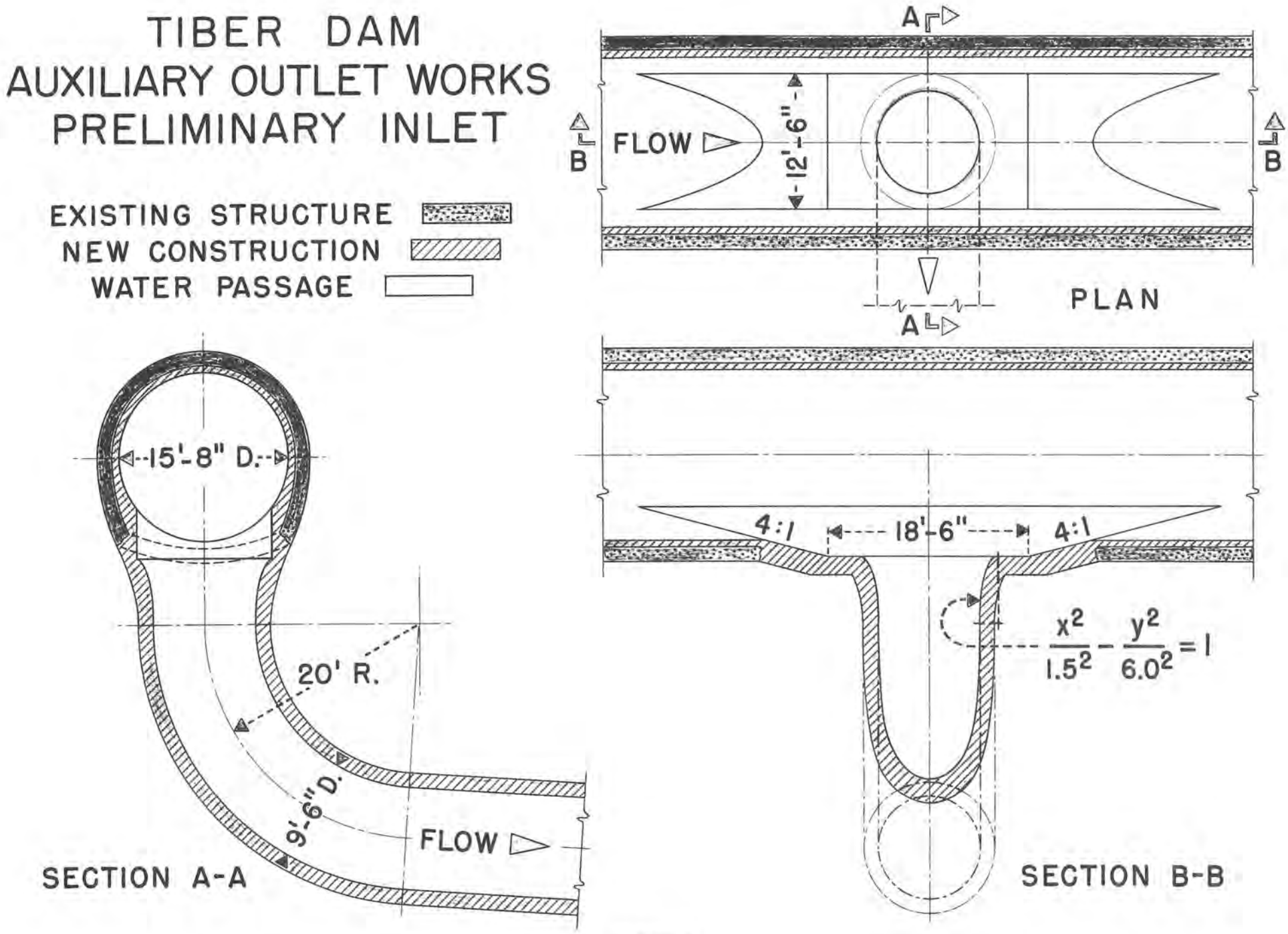

TIBER DAM
AUXILIARY OUTLET WORKS
PRELIMINARY INLET
EXISTING STRUCTURE
NEW CONSTRUCTION
WATER PASSAGE
A
B
FLOW
12'-6"
PLAN
15'-8" D.
20' R.
9'-6" D.
FLOW
SECTION A-A
4:1
18'-6"
4:1
$\frac{x^2}{1.5^2} - \frac{y^2}{6.0^2} = 1$
SECTION B-B

Figure 6

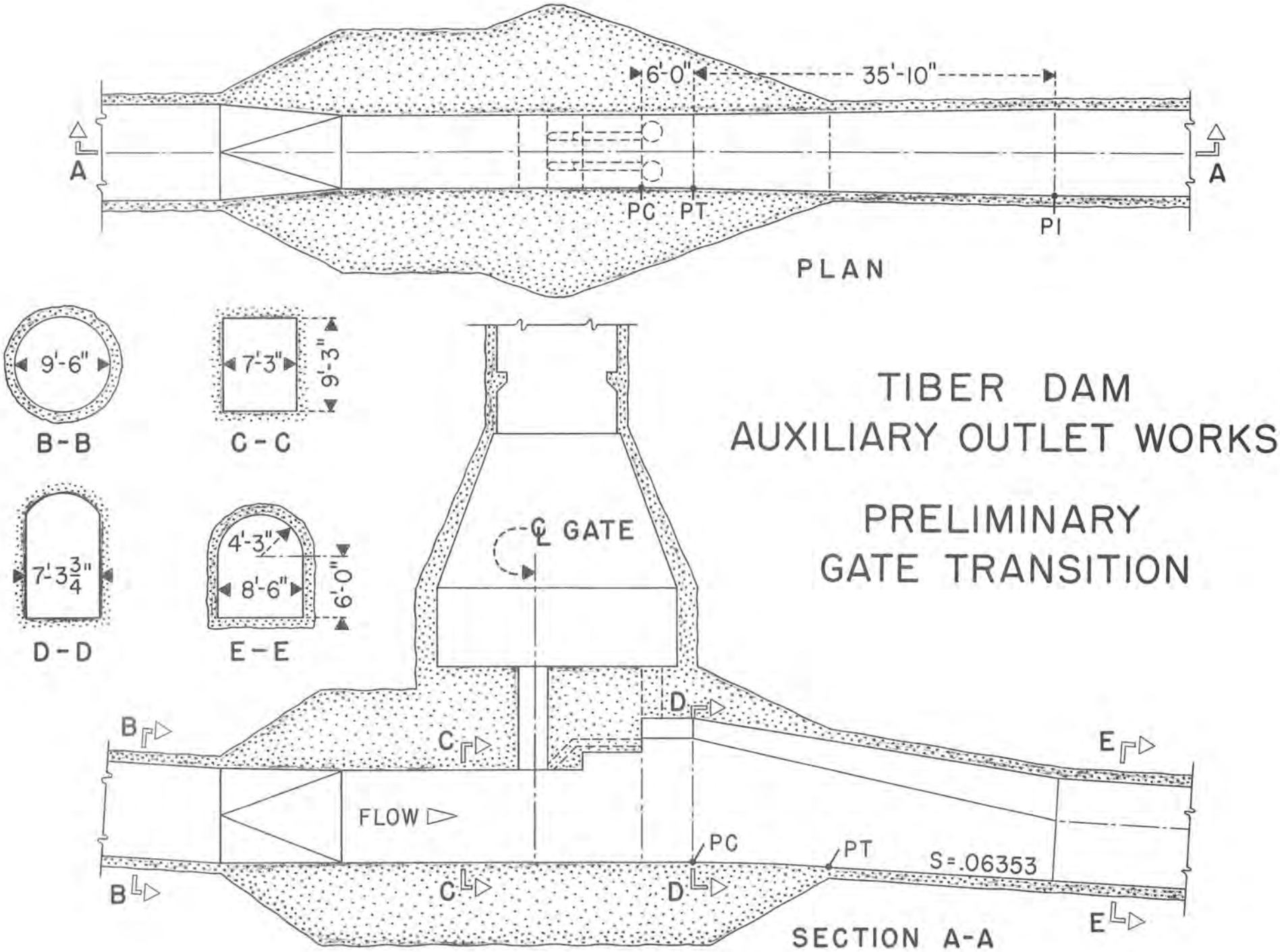

6'-0"
35'-10"
A
A
PC
PT
PI
PLAN
9'-6"
B-B
7'-3"
9'-3"
C-C
7'-3 3/4"
D-D
4'-3"
8'-6"
6'-0"
E-E
℄ GATE
TIBER DAM
AUXILIARY OUTLET WORKS
PRELIMINARY
GATE TRANSITION
B
C
D
E
FLOW
PC
PT
S=.06353
SECTION A-A

Figure 7

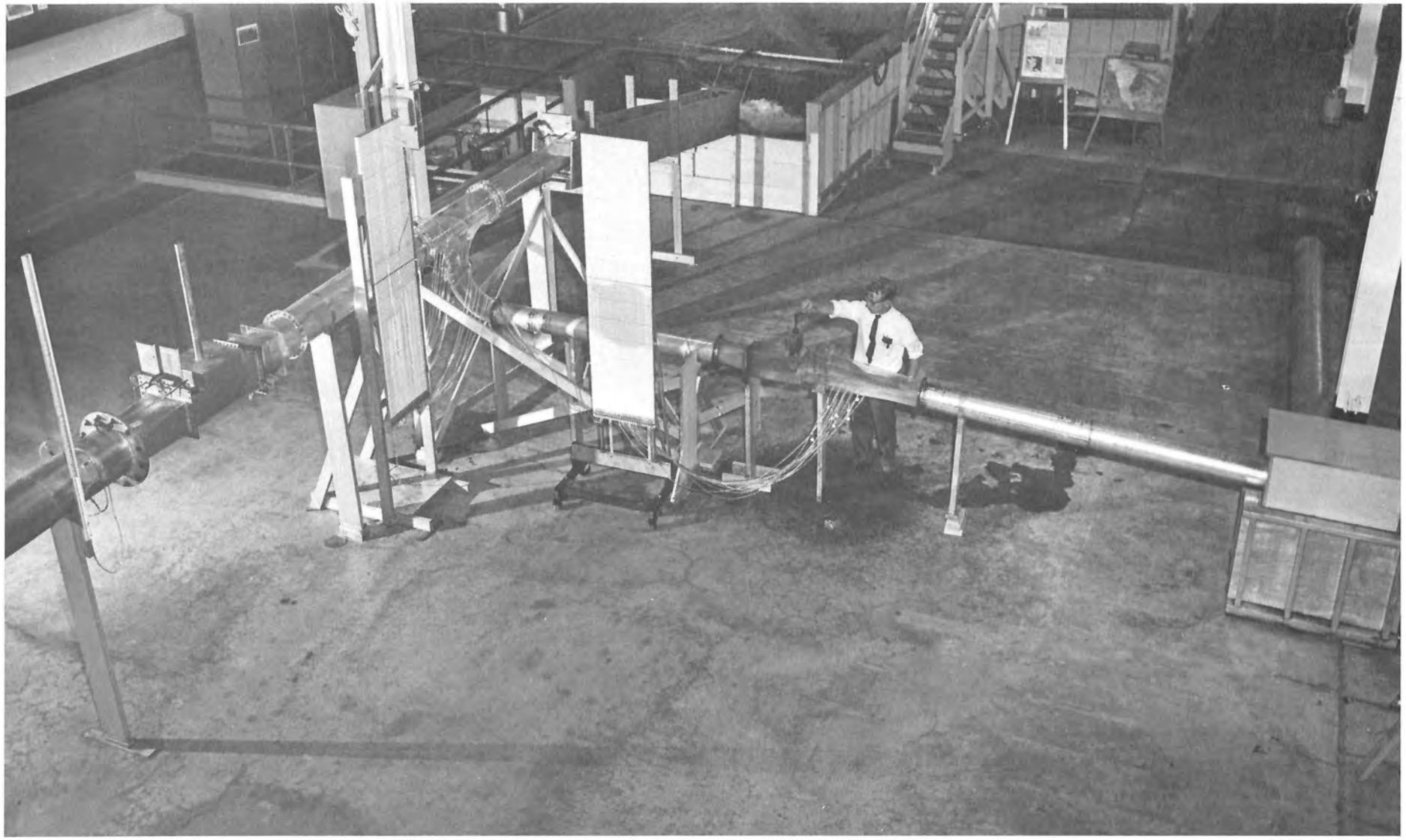


Figure 8. The 1:17.5 Scale Model. Photo PX-D-64684NA

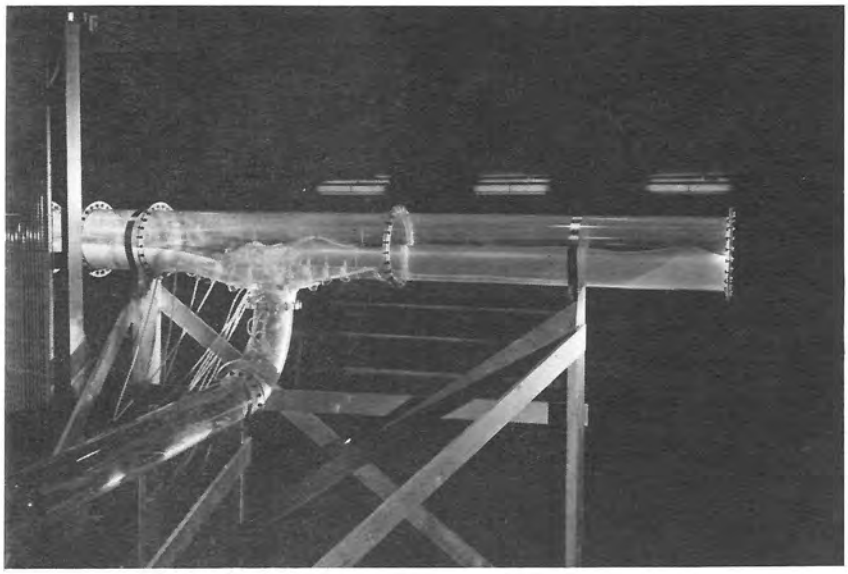


Figure 9. Operation of Preliminary Inlet at 50% Gate.
Photo PX-D-64680NA

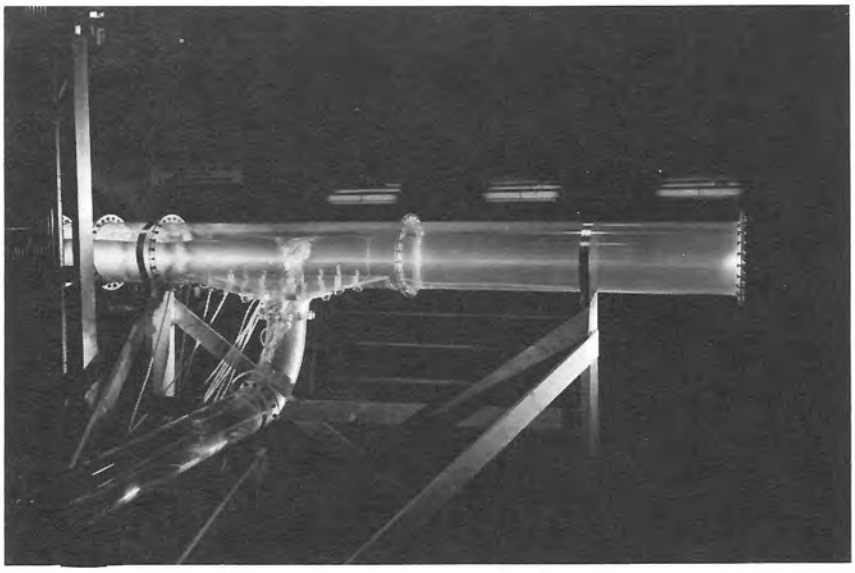


Figure 10. Vortex Formed over Preliminary Inlet.
Photo PX-D-64681NA

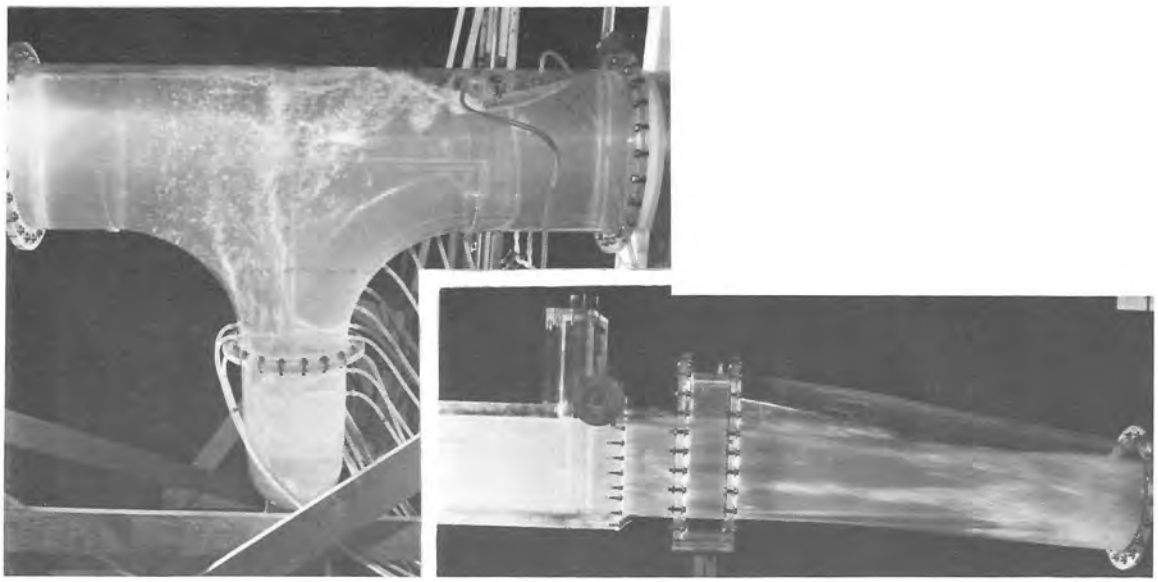


Figure 11. Operation of Recommended Inlet and Transition without Deflector. Photo PX-D-64685NA

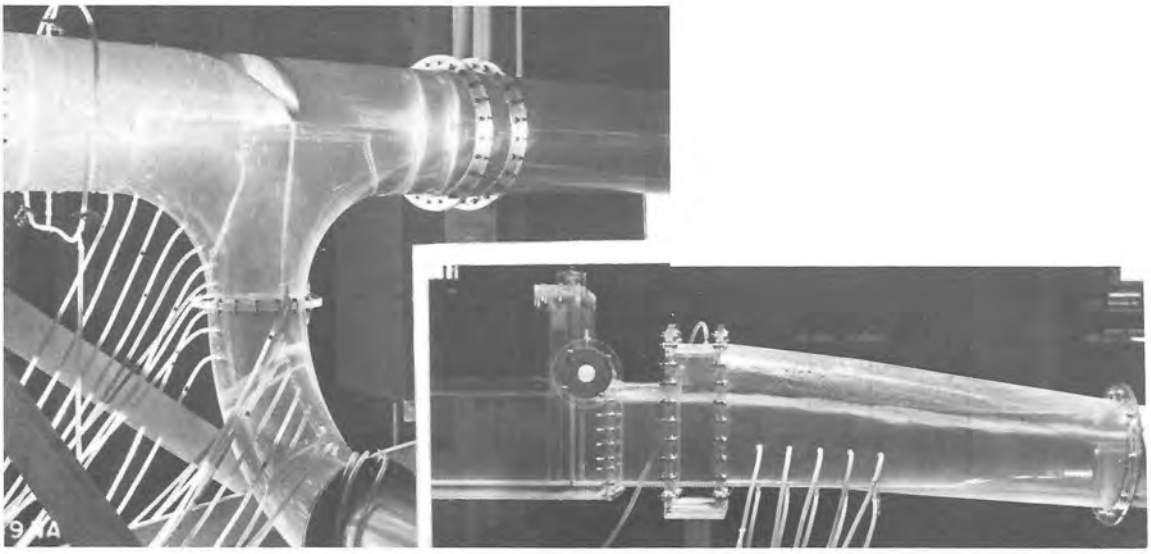


Figure 12. Operation of Recommended Inlet and Transition with Deflector. Photo PX-D-64688NA

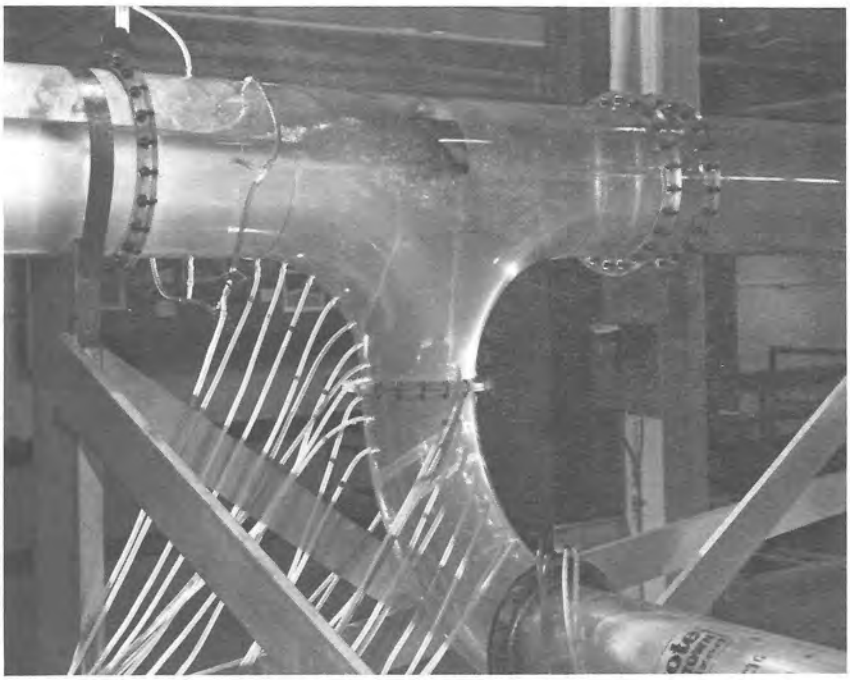
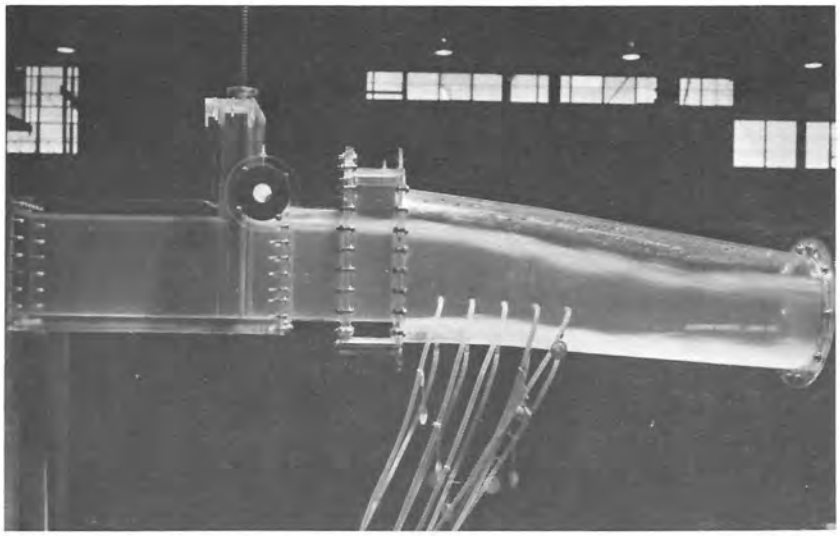
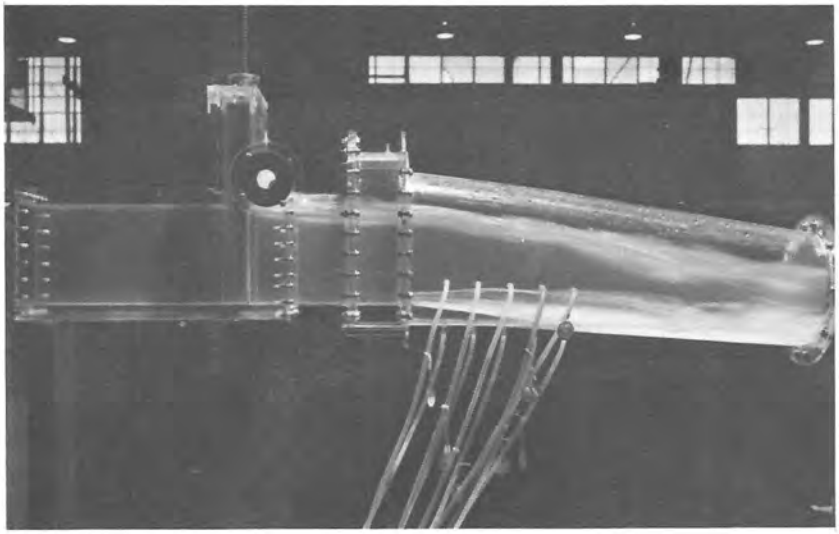


Figure 13. Air Pocket in Crown of Tunnel.
Photo PX-D-64689NA



Gate 100 percent open. Photo PX-D-64682NA



Gate 97 percent open. Photo PX-D-64683NA

Figure 14. Operation at Maximum Reservoir with 2-foot Offset in Transition Invert.