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HYDRAULIC MODEL STUDIES OF TIBER DAM AUXILIARY OUTLET WORKS MISSOURI RIVER BASIN PROJECT MONTANA

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Engineering and Research Center
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16. ABSTRACT

The existing canal outlet works tunnel at Tiber Dam, Mont, is used as an intake and as the upstream portion of an auxiliary outlet works designed to provide additional reservoir release capacity. The existing 17-ft-dia horseshoe free flow tunnel is converted to a 15-ft 6-in.-dia pressure tunnel and is connected to a new 10-ft 9-in.-dia tunnel by a drop inlet and vertical bend. The smaller tunnel is equipped with a 7.25- by 9.25-ft slide gate and terminates in a stilling basin in the river channel. A 1:17.53 scale model was used to develop the hydraulic design of the auxiliary outlet works including: the drop inlet and vertical bend from the existing canal outlet works tunnel, and the transition in the tunnel downstream from the gate chamber. Details of the model testing and recommended modifications to the preliminary design prompted by the testing are presented.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS--/ *outlet works/ *hydraulic models/ slide gates/ irrigation systems/ *model tests/ tunnels/ *vents/ velocity/ vortices/ canals/ air/ calibrations/ bends/ pressure/ pressure tunnels/ operations/ transitions (structures)/ hydraulic design

b. IDENTIFIERS--/ *drop inlet/ Missouri River Basin Proj/ deflectors/ Tiber Dam, Mont

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by

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October 1970

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Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION
Ellis L. Armstrong
Commissioner

ACKNOWLEDGMENTS

The studies were conducted by T. J. Isbester and the writer under the supervision of the Applied Hydraulics Section Head, W. E. Wagner, now Hydraulics Branch Chief, and the direction of the former Hydraulics Branch Chief, H. M. Martin (retired). The report was reviewed by T. J. Rhone. The final plans evolved from these studies were developed with the cooperation of the Hydraulic Structures Branch of the Division of Design during the period February 1967 through January 1968.

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PURPOSE

The purpose of the study was to develop the hydraulic design of the auxiliary outlet works including the drop inlet from the canal outlet tunnel, the vertical bend in the auxiliary outlet tunnel, and the transition section from the gate chamber in the auxiliary outlet works tunnel.

CONCLUSIONS

1. The hydraulic design of the drop inlet was developed by providing a long radius curvature to the invert to gradually change the direction of the flow from horizontal to vertical without introducing flow disturbances in the tunnel or subatmospheric pressures on the flow surfaces.

2. Antivortex deflector placed in the crown of the tunnel above the drop inlet provided smooth flow into the inlet and through the gate chamber transition.

3. It was found desirable to install an 8-inch (20.31-cm) vent in the crown of the existing canal outlet tunnel near the drop inlet to remove large air bubbles that became trapped along the crown and did not move upstream to the air shaft in the existing canal outlet works gate chamber while the water was flowing.

4. The diameters of the drop inlet throat and tunnel were increased to match the radii of the curvatures developed for the inlet invert and the vertical bend and to decelerate the flow through the most critical low pressure region.

The curvature of the vertical bend from the drop inlet was lengthened to provide atmospheric pressures or above on the crown of the bend.

5. The shape of the transition and tunnel size downstream from the gate chamber were developed to provide adequate room for the high-velocity flow to pass from the rectangular section to the circular tunnel without causing wall fins of water or sealing the tunnel with spray or producing subatmospheric pressures on the flow surfaces.

6. Procedures for filling and dewatering the system as well as for normal operation of the auxiliary outlet works were checked to be sure that the prototype operation would be as intended.

7. The hydraulic performance of the system was investigated for possible future release of water from a gate control at the existing canal outlet dead end. An operating procedure for releasing this water either with or without the auxiliary outlet works gate discharging was recommended.

APPLICATION

Generally, the results are unique to the application at hand. However, the type of antivortex deflector developed might be applicable at another installation and the data on the offset transition that was tested are of a general nature.

INTRODUCTION

Tiber Dam, constructed in 1951, is on the Marias River in north central Montana and is part of the Missouri River Basin Project (Figure 1). The dam (Figure 2) is an earthfill structure about 4,300 feet (1,325.88 m) long and 205 feet (60.96 m) high with the crest at elevation 3021 feet (920.80 m). The principal hydraulic features of the dam are a flood control spillway and river outlet works in the right abutment and a canal outlet works in the left abutment.

A cofferdam presently blocks the approach to the spillway, which is to be rehabilitated. Until rehabilitation of the spillway becomes a reality, all releases from the reservoir will be made through the river outlet works (Figure 2) to the extent of its capacity. To provide for releases in excess of this, the canal outlet works tunnel which terminates in a dead end at Station 6+56 (199.95) (Figure 2) will be converted into an auxiliary outlet works (Figures 3 through 9).

The existing 17-foot (5.18-m) diameter horseshoe, free-flow canal outlet works tunnel (Figure 6) will be converted to a 15-foot 6-inch (4.72-m) diameter pressure tunnel. A drop inlet and vertical bend (Figure 6) will be installed in the canal outlet works tunnel at Station 5+50.50 (167.79) to discharge a design capacity of about 4,250 cfs (Figure 9) (120.28 cu m per second) at maximum reservoir elevation 3014.90 (918.94 m) downward into a newly constructed 10-foot 9-inch (3.28-m) diameter tunnel at right angles to the canal outlet works tunnel. This smaller tunnel will have a rectangular gate chamber (Figure 7) with a 7.25- by 9.25-foot (2.21- by 2.82-m) slide gate approximately 168 feet (51.21 m) downstream from the drop inlet. The tunnel will continue in a straight line from the gate chamber to a stilling basin at the river channel about 1,494.5 feet (455.52 m) farther downstream (Figure 3).

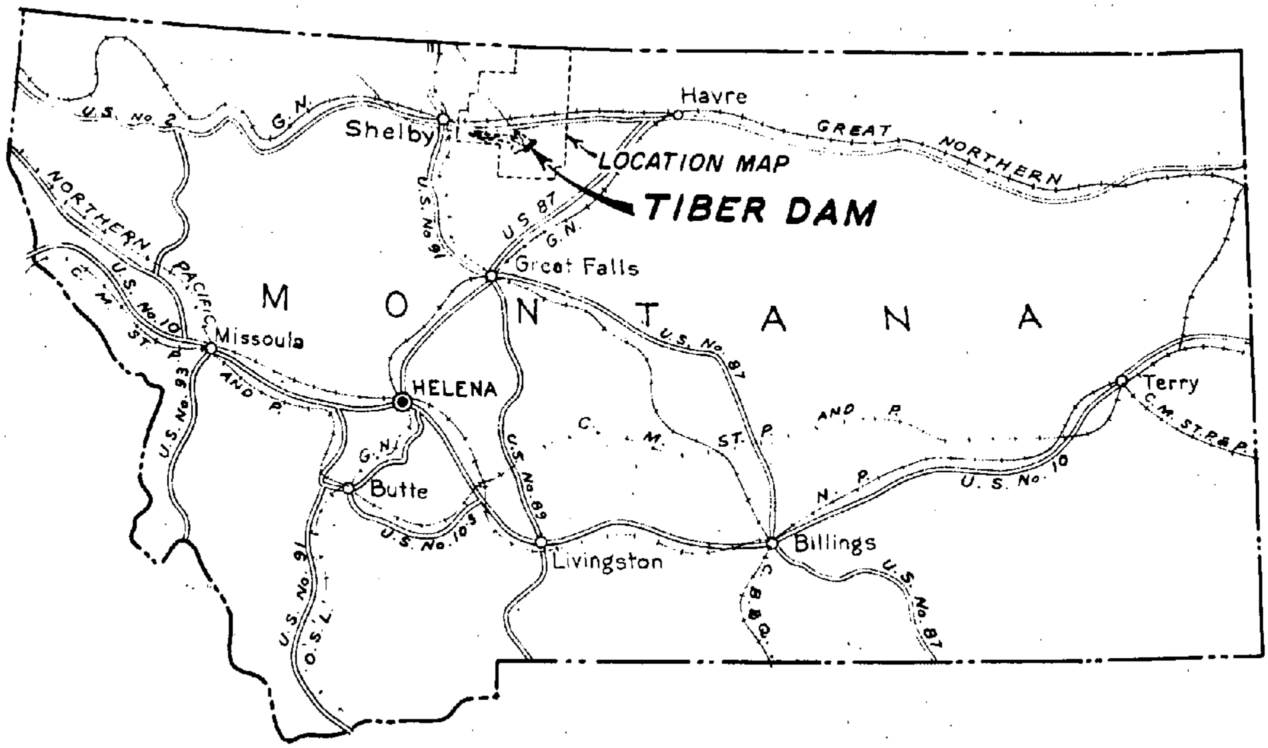


Figure 1. Tiber Dam location map.

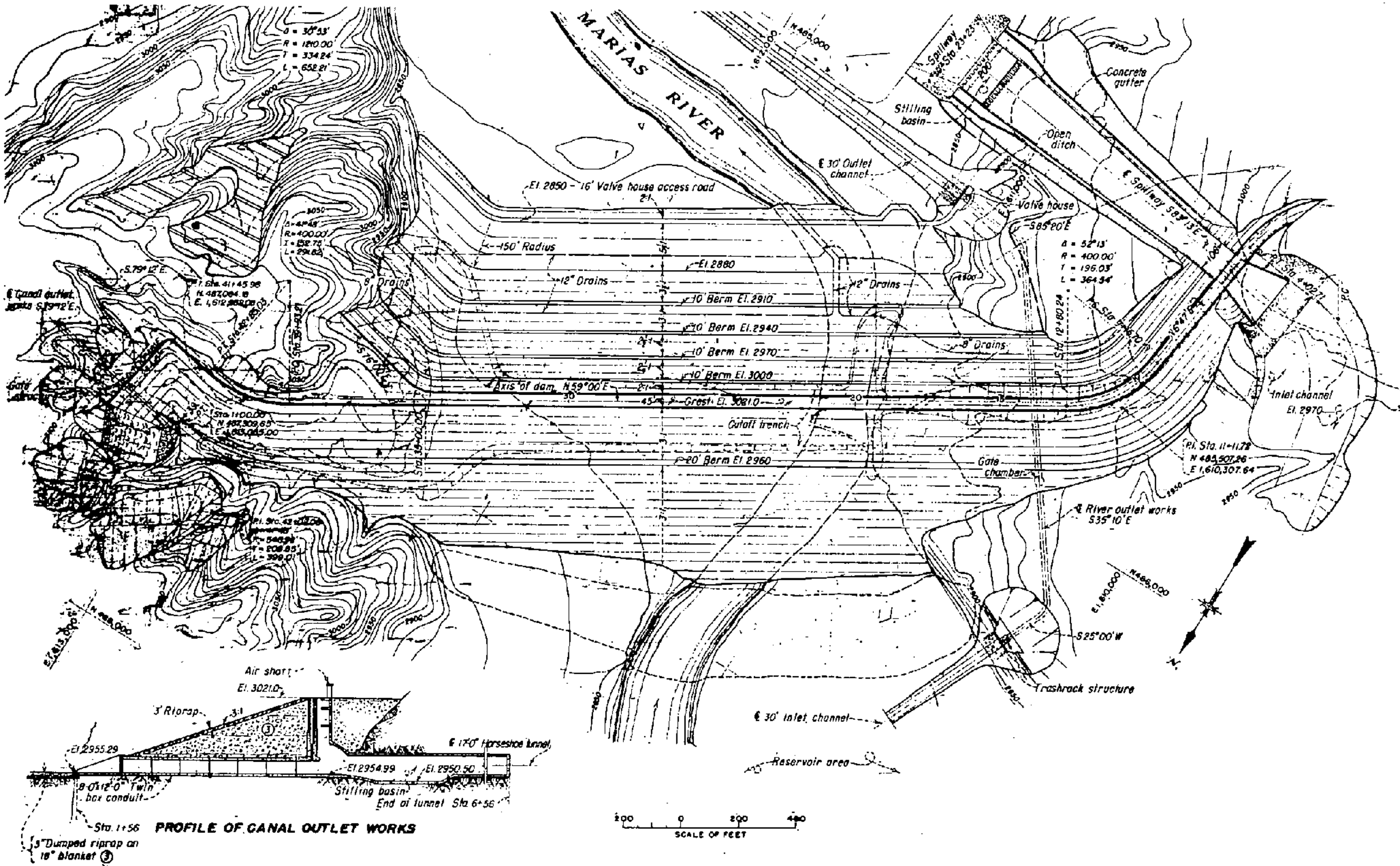


Figure 2. Tiber Dam general plan.

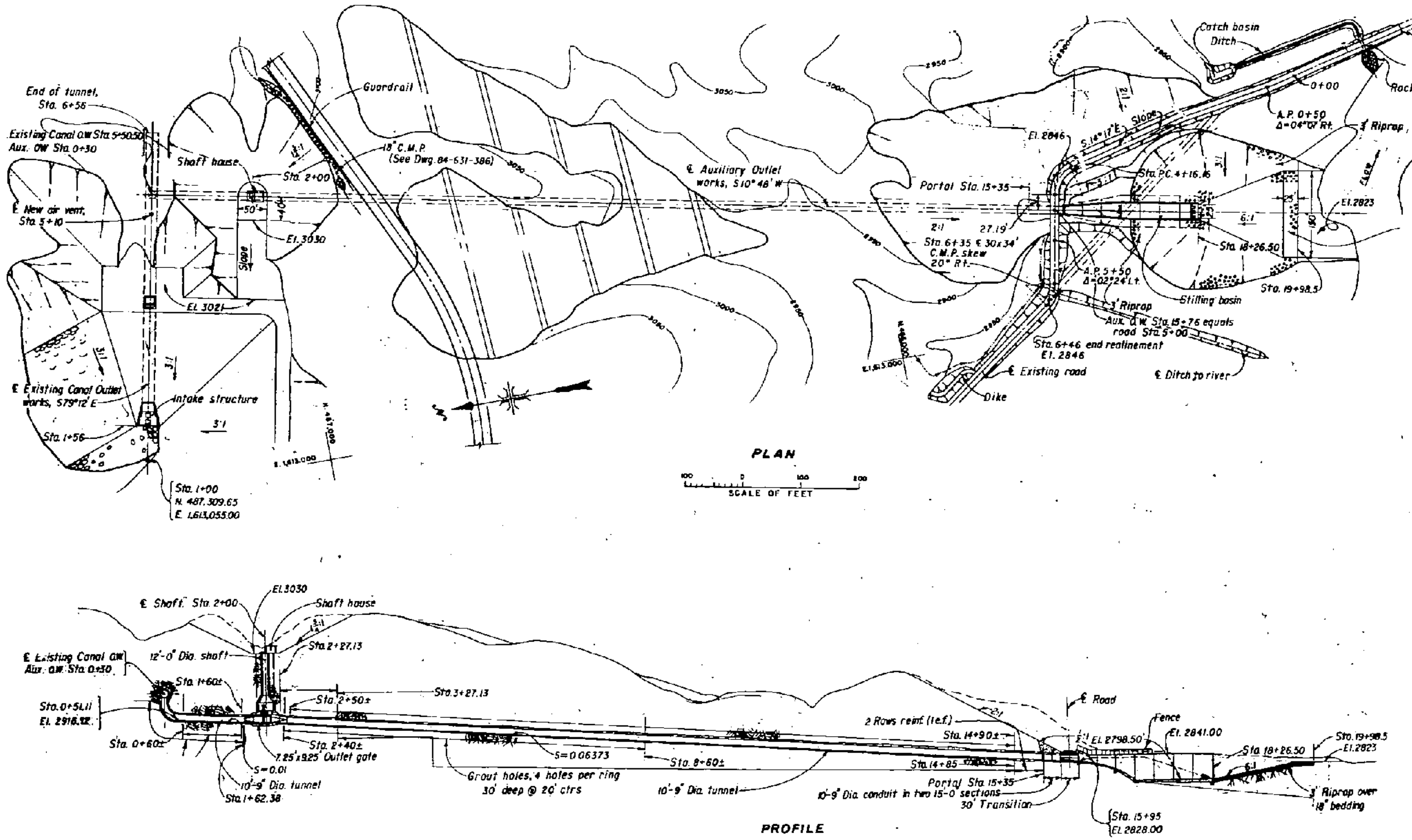


Figure 3. Tiber Dam Auxiliary Outlet Works—Plan and profile.

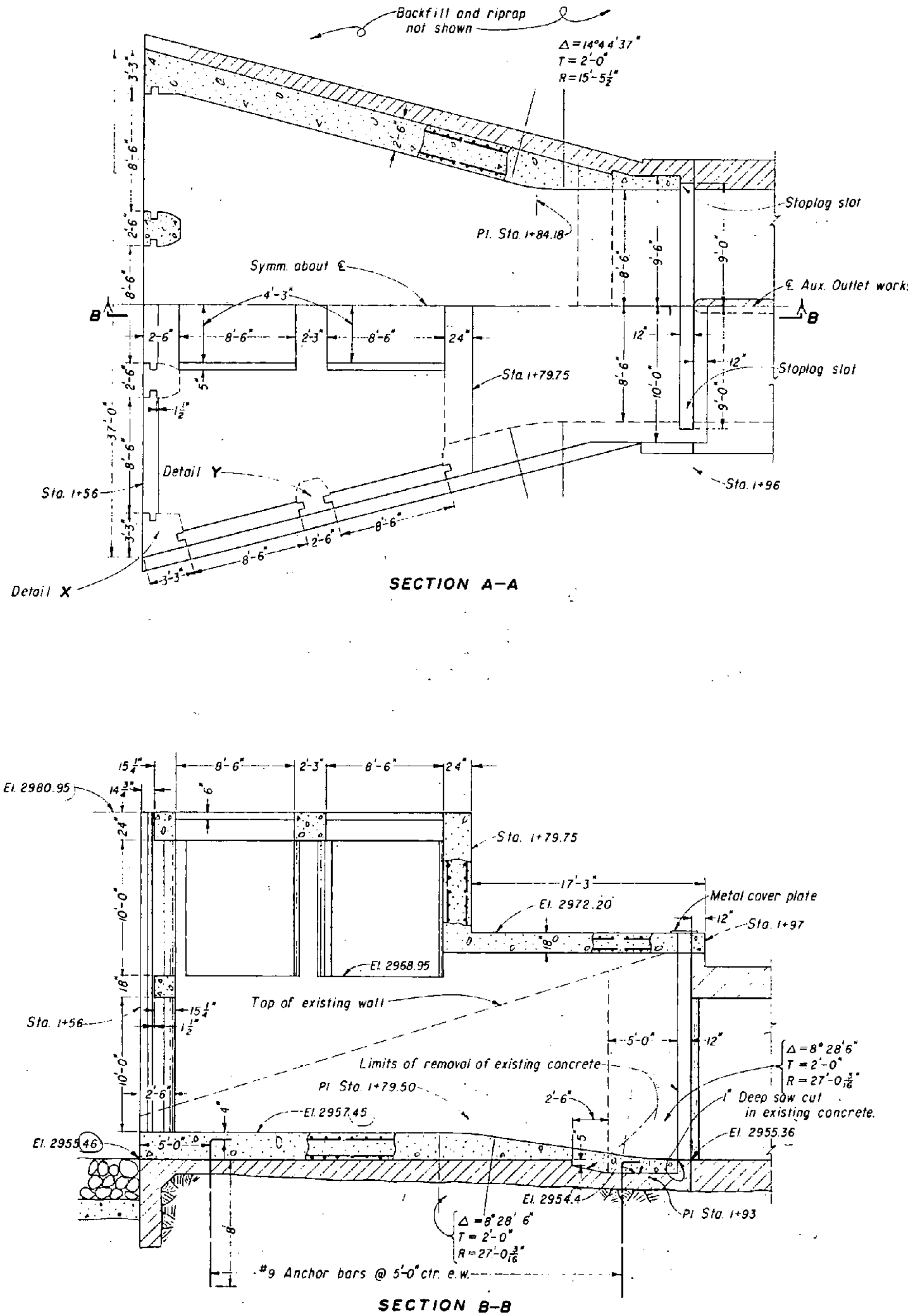


Figure 4. Tiber Dam--Canal outlet works intake structure.

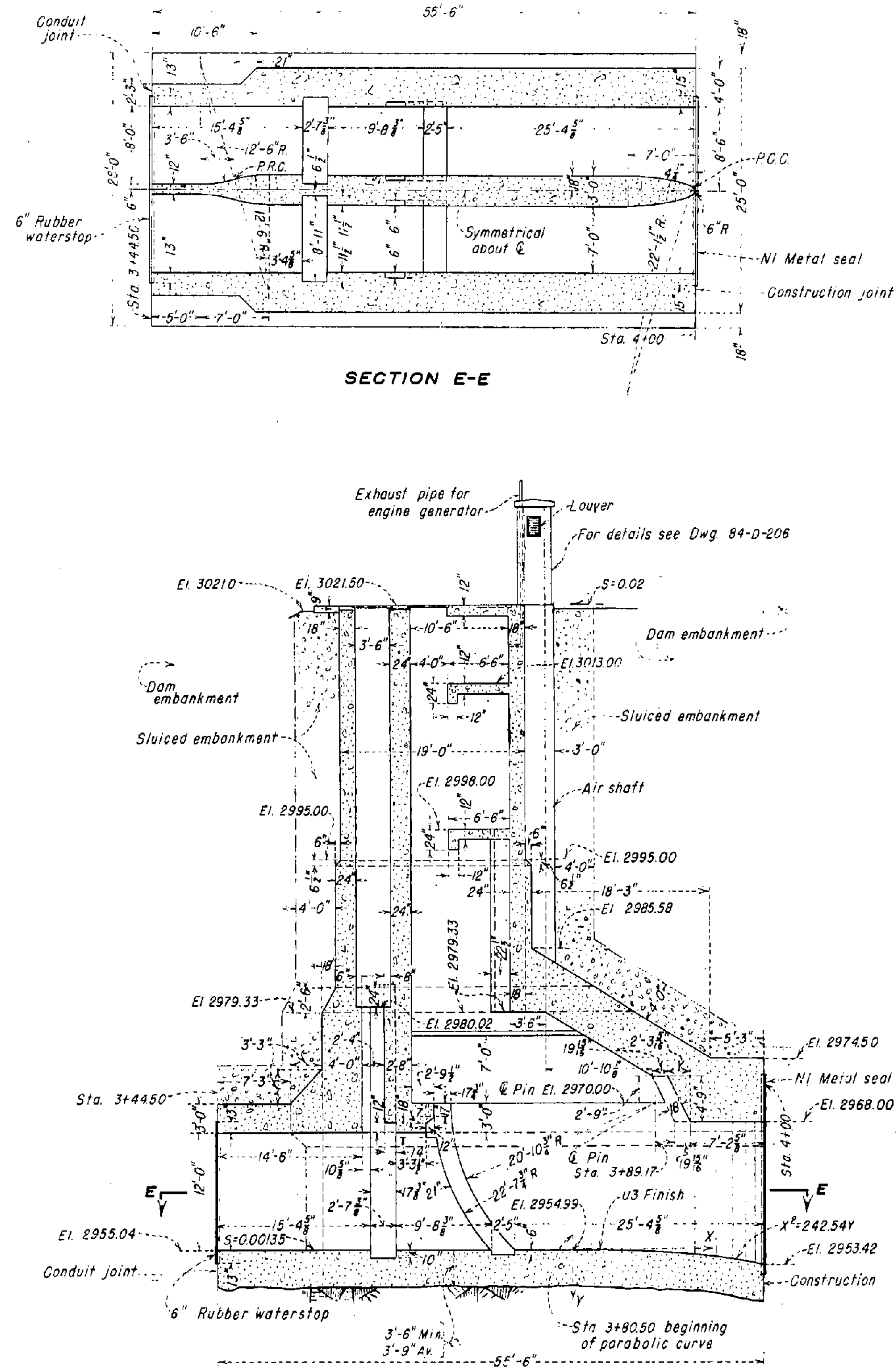
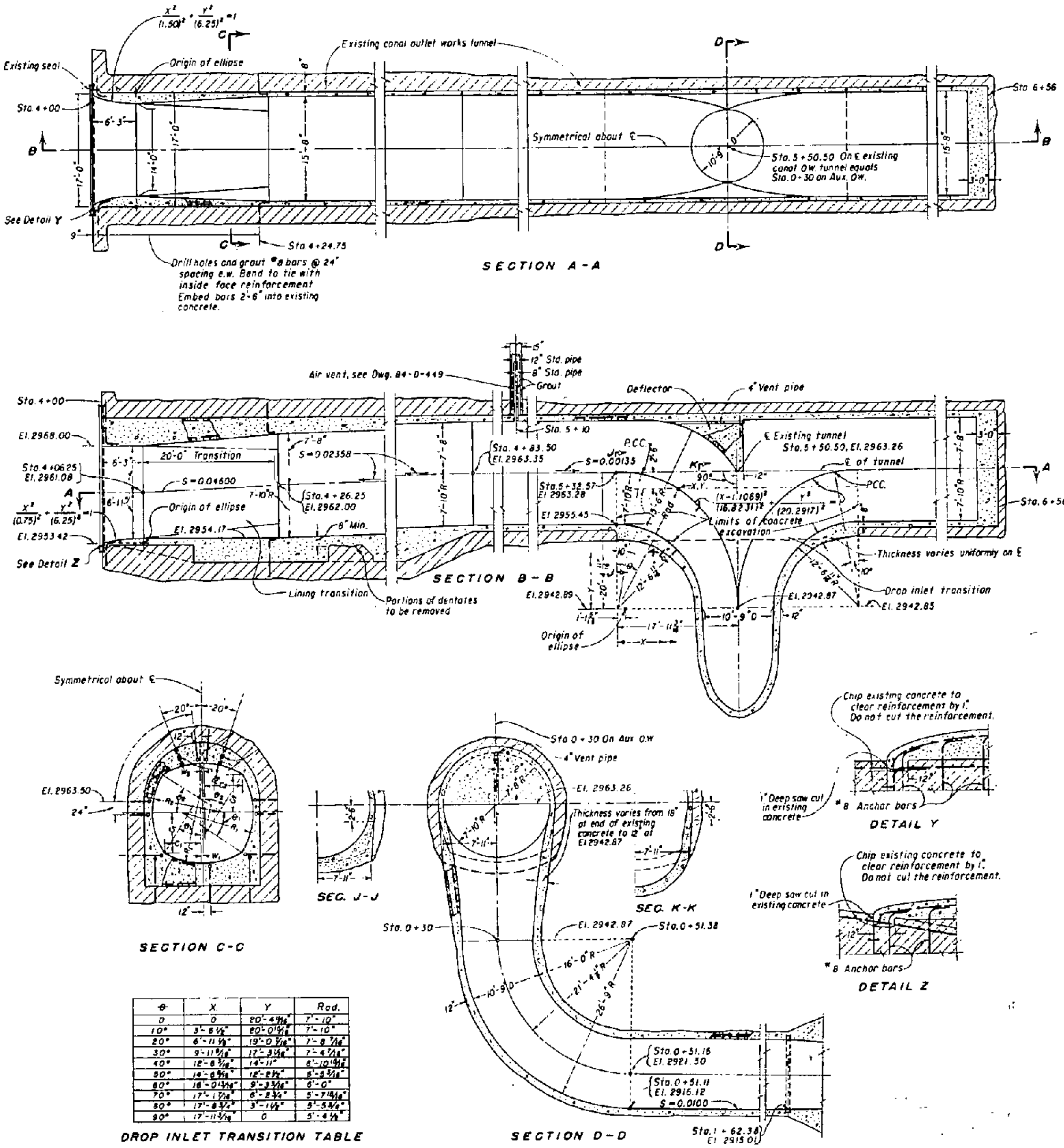


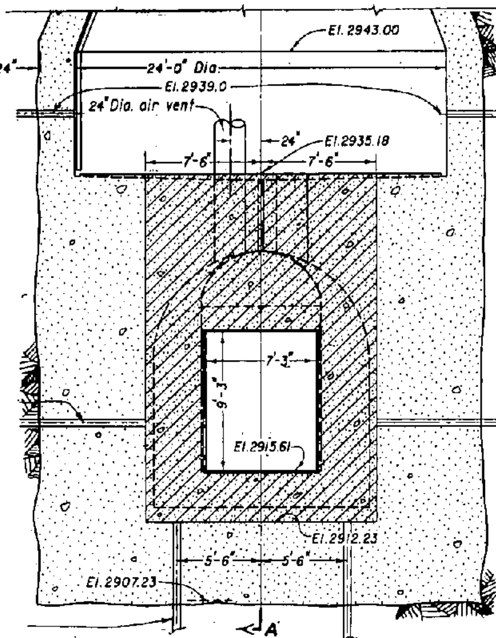
Figure 5. Tiber Dam—Canal outlet works gate structure.



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

DROP INLET TRANSITION TABLE

Figure 6. Tiber Dam Auxiliary Outlet Works—Existing canal outlet works tunnel and drop inlet.



SECTION B-B

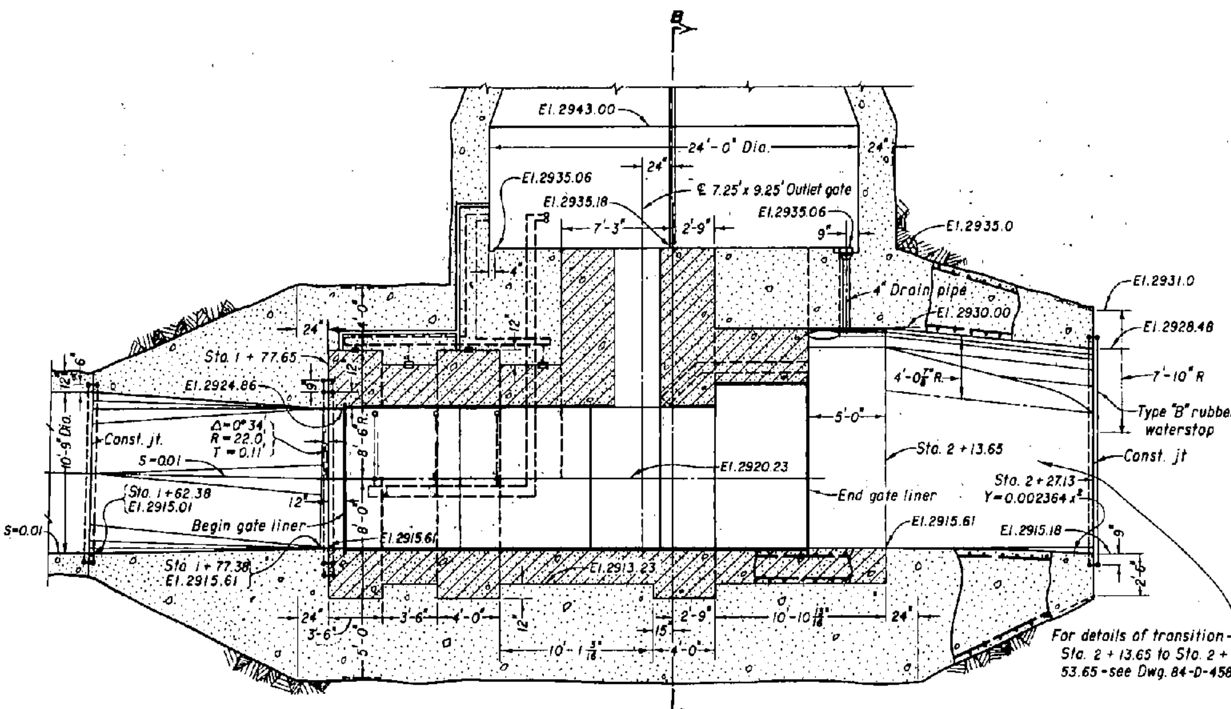
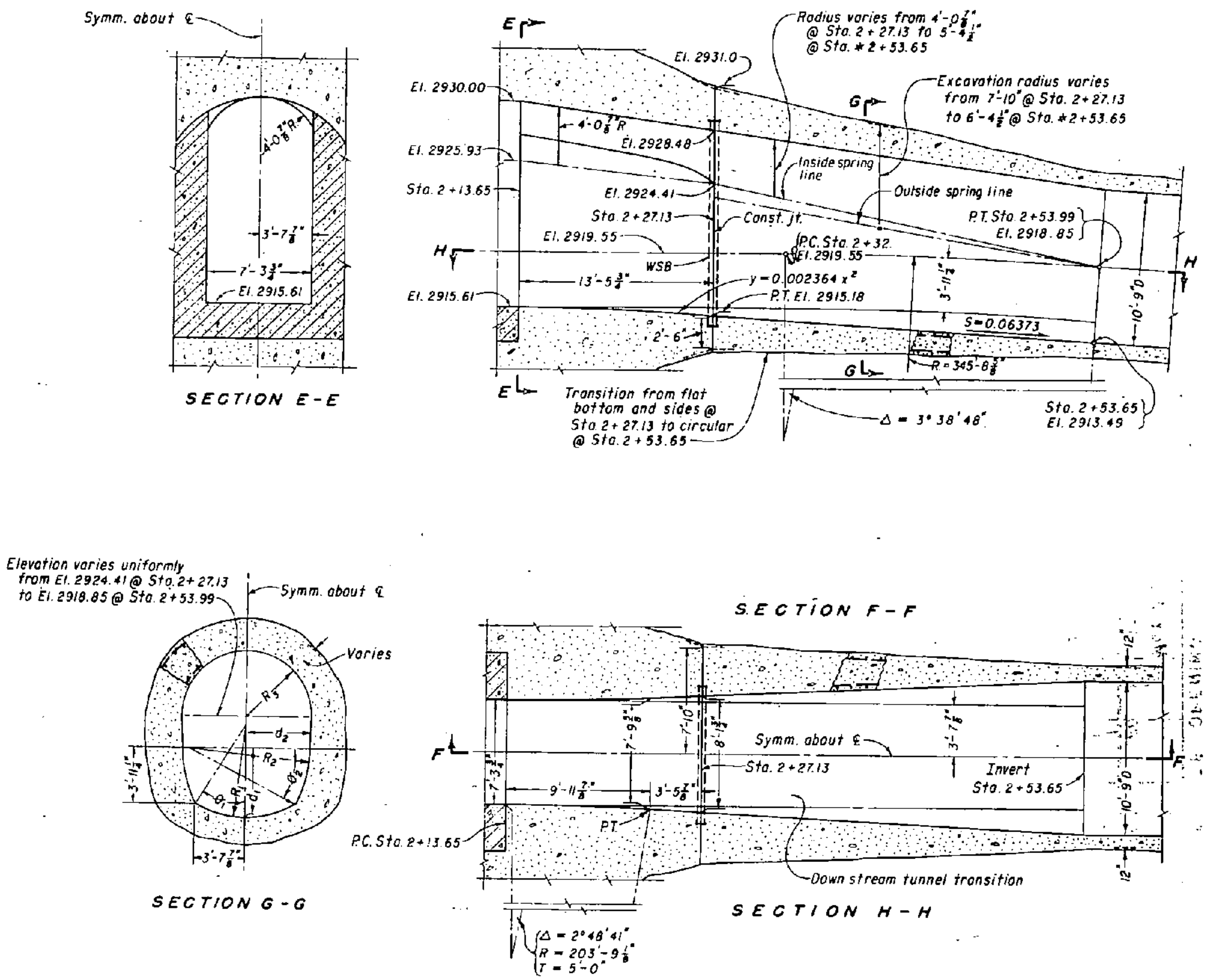


Figure 7. Tiber Dam Auxiliary Outlet Works—Gate chamber.

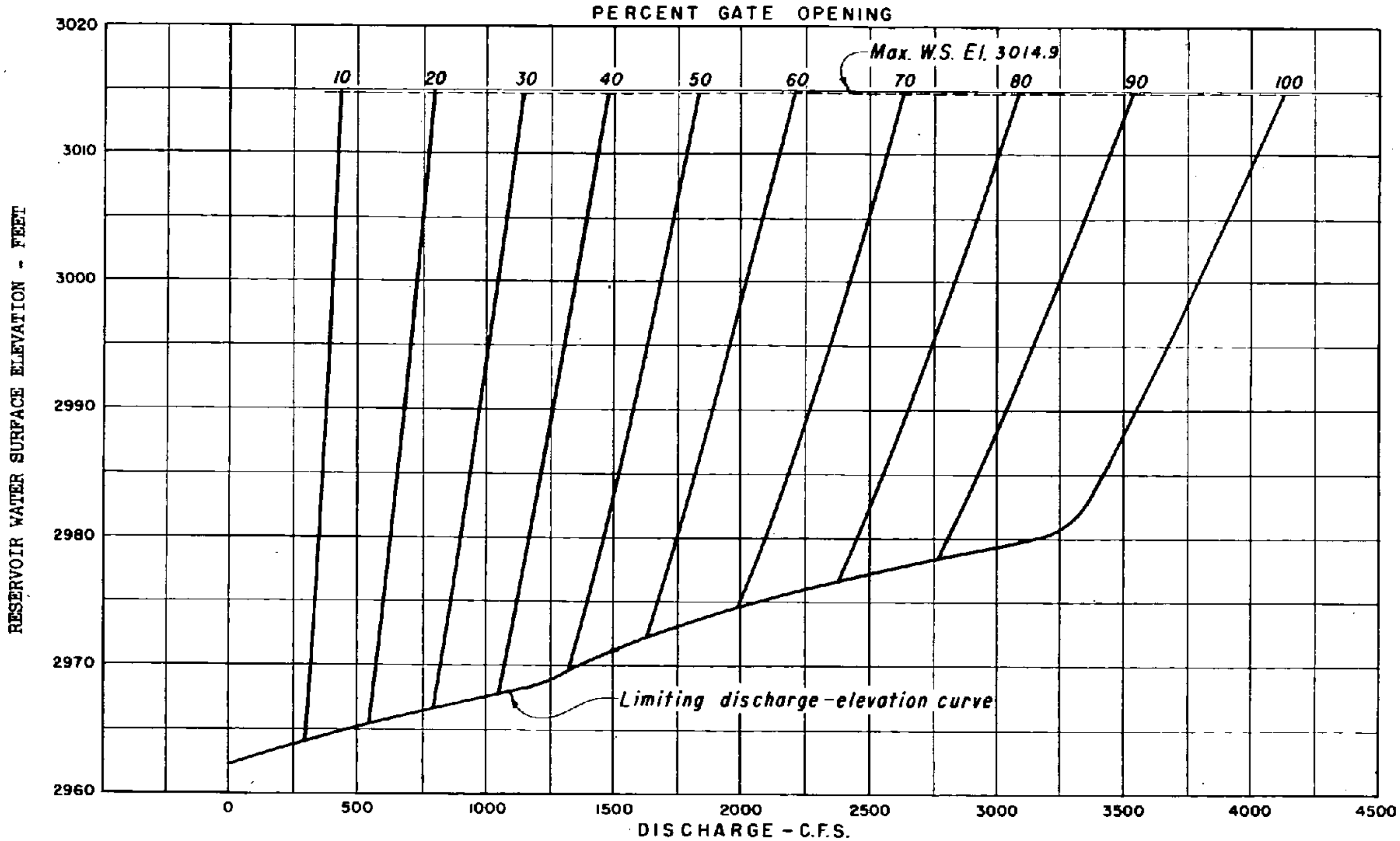


STA.	d_1	R_1	θ_1	d_2	R_2	θ_2	R_3
2+13.65	3'-11¼"	—	0	3'-7⅞"	—	0	4'-0⅞"
2+16.65	3'-11 9/16"	314'-2⅞"	0° 40'	3'-8⅛"	351'-2⅜"	0° 38'	
2+19.65	4'-0 5/16"	78'-7⅛"	2° 40'	3'-8 13/16"	87'-10 1/16"	2° 34'	
2+22.65	4'-1 9/16"	35'-0¼"	6° 0'	3'-10¼"	39'-1 1/16"	5° 47'	
2+23.64	4'-2⅛"	28'-5 7/16"	7° 23'	3'-10 13/16"	31'-9 5/16"	7° 7'	
2+25.65	4'-3⅜"	19'-9⅝"	10° 38'	4'-0"	22'-9 1/16"	9° 58'	
2+27.13	4'-4 7/16"	15'-9¼"	13° 24'	4'-0⅞"	18'-10 1/16"	12° 4'	4'-0⅞"
2+28.65	4'-5⅝"	12'-11 9/16"	16° 23'	4'-1¾"	16'-0 9/16"	14° 13'	4'-1¾"
2+32	4'-8½"	9'-4 13/16"	22° 53'	4'-3¾"	12'-2"	18° 54'	4'-3¾"
*2+34.65	4'-10 1/16"	7'-10 9/16"	27° 39'	4'-5 5/16"	10'-3¼"	22° 33'	4'-5 5/16"
*2+37.65	4'-11⅞"	6'-10 11/16"	32° 02'	4'-7 1/16"	8'-9 7/16"	26° 39'	4'-7 1/16"
*2+40.65	5'-1½"	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'-10⅝"	6'-11¼"	34° 37'	4'-10⅝"
*2+46.65	5'-3⅝"	5'-7 1/16"	40° 52'	5'-0⅜"	6'-4"	38° 29'	5'-0⅜"
*2+49.65	5'-4 3/16"	5'-5 3/16"	42° 13'	5'-2⅛"	5'-10 9/16"	42° 15'	5'-2⅛"
*2+53.65	5'-4½"	5'-4½"	42° 52'	5'-4½"	5'-4½"	47° 8'	5'-4½"

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

D.S. TUNNEL TRANSITION TABLE

Figure 8. Tiber Dam Auxiliary Outlet Works—Gate chamber Tunnel transition.



NOTES

7.25 feet (2.21 m) x 9.25 feet (2.82 m)
Outlet gate must not be operated below "Limiting discharge - elevation curve."
Any variations in discharge from percent gate opening curves, as determined by measurements of flow downstream from the auxiliary outlet works, should be reported to the Chief Engineer.

CONVERSION FACTORS - BRITISH TO METRIC UNITS OF MEASURE

Multiply feet by 0.3048 (exactly) to obtain meters
Multiply cubic feet per second by 0.0283 to obtain cubic meters per second

Figure 9. Tiber Dam Auxiliary Outlet Works—Discharge curves.

The auxiliary outlet works gate will be operated fully open only after the system is filled and the reservoir has reached elevation 2983 feet (909.22 m) and may continue to operate up to reservoir elevation 3014.9 feet (918.94 m) (Figure 9). Thus, the crown of the twin 8- by 12-foot (2.44- by 3.66-m) box conduits at the intake to the canal outlet works (Figures 2 and 4) will be submerged a minimum of about 16 feet (4.88 m) when the auxiliary outlet works is operating at full gate opening. The gates in the canal outlet works gate structure (Figure 5) and the new gates in the auxiliary outlet works gate chamber (Figure 7) will normally be fully open when the system is operating and the system will be operating under pressure. If water releases be made prior to complete filling of the system and while the auxiliary outlet works gate is partially open, the canal outlet works gates will be fully open and the auxiliary outlet works gate open no more than shown in Figure 9 to insure submergence of the drop inlet and control of the discharge at the auxiliary outlet works gate.

It is anticipated that at some future time a control gate may be installed at or near the dead end of the canal outlet to discharge water into a canal irrigation system. At that time, the canal outlet will serve a dual purpose of discharging into the auxiliary outlet works and into the canal system.

THE MODEL

The model, built to a scale of 1:17.53 (Figures 10 and 11), included the existing canal outlet works gate structure and slide gates; the newly lined tunnel to the dead end where a control gate was installed; the drop inlet to the auxiliary outlet tunnel; the tunnel and transition section to the auxiliary outlet works gate chamber; the gate chamber and gate; the transition section from the gate chamber to the circular tunnel; and approximately 120 feet (36.58 m) of the downstream tunnel.

Water was supplied to the model by a 12-inch (30.48-cm) pipe from the laboratory's permanent water supply system. A ring of piezometers was installed one pipe diameter upstream from a transition section to the rectangular canal outlet works control gate section to measure the computed pressure head at this point for a range of reservoir elevations (Figure 11). The total head above the tunnel invert at the piezometer ring was computed for prototype discharges at maximum reservoir elevation and plotted in Figure 12. The same was repeated for reservoir elevations 2975, 2981, and 2995 (784.86, 786.69, and 790.96). The model pressure heads could then be set at the piezometer ring based on these computations plotted in Figure 12.

The canal outlet works tunnel gate control section with air vent and the two slide gates were constructed of sheet metal. The lined canal outlet works tunnel was constructed in clear plastic; a sheet-metal slide gate was installed at the dead end in the tunnel to provide the operating condition if in the future the dead end is opened for canal irrigation flows.

The drop inlet and vertical bend in the auxiliary outlet works tunnel were constructed of clear plastic for observation of the flow patterns. The auxiliary outlet control gate was made of brass installed in a clear plastic gate section; the transition downstream from the gate section was also constructed of clear plastic. The tunnel upstream of the gate section and downstream from the transition was made of sheet metal.

The downstream end of the auxiliary outlet works tunnel discharged into a wooden box where the flow was wasted through a 10-inch (25.4-cm) pipe to the laboratory's supply reservoir beneath the laboratory floor. The canal irrigation flows from the dead end were discharged into a wooden flume wasteway to the laboratory's supply reservoir.

THE INVESTIGATION

The investigation was concerned with the development of the hydraulic design of the auxiliary outlet works including the drop inlet and vertical bend from the canal outlet tunnel to the auxiliary outlet works tunnel and the transition downstream from the gate chamber in the auxiliary outlet works tunnel (Figure 6). The plan of operation was investigated including (1) the filling and dewatering of the system; (2) the operation of the system while only partially filled; (3) the operation of the system under pressure for flows up to approximately 4,250 cfs (120.28 cu m/sec); and (4) the operation of the facility for releasing water to an irrigation system with and without flow through the auxiliary outlet works gate discharging.

Preliminary Drop Inlet and Vertical Bend

The preliminary auxiliary outlet works (Figure 13) provided a horizontal floor in the existing canal outlet works tunnel from which a 12.5-foot (3.81-m) diameter opening discharged the auxiliary outlet works flow into a 9.5-foot (2.90-m) diameter vertical bend

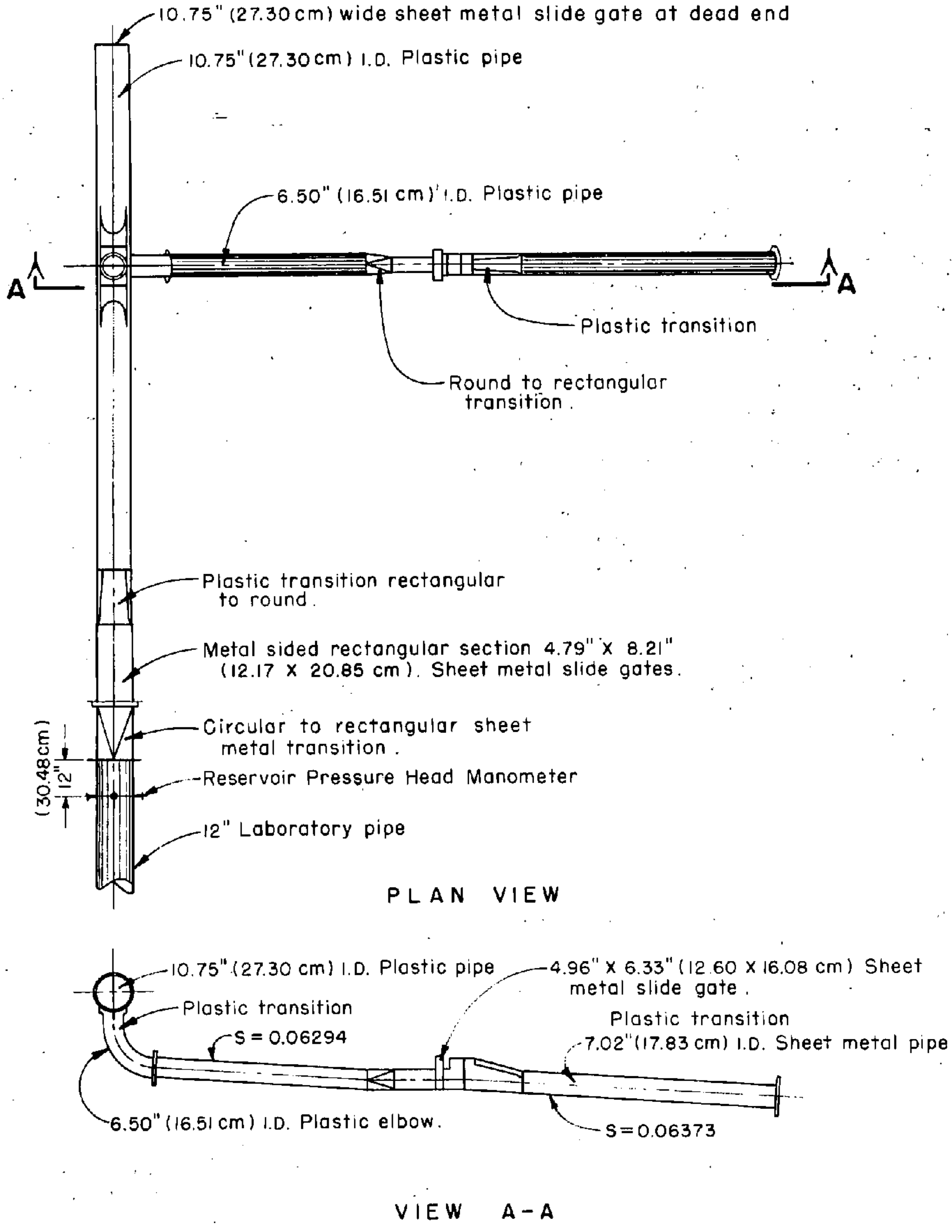


Figure 10. Tiber Dam Auxiliary Outlet Works—Model assembly—Preliminary design—1:17.53 scale model.

748

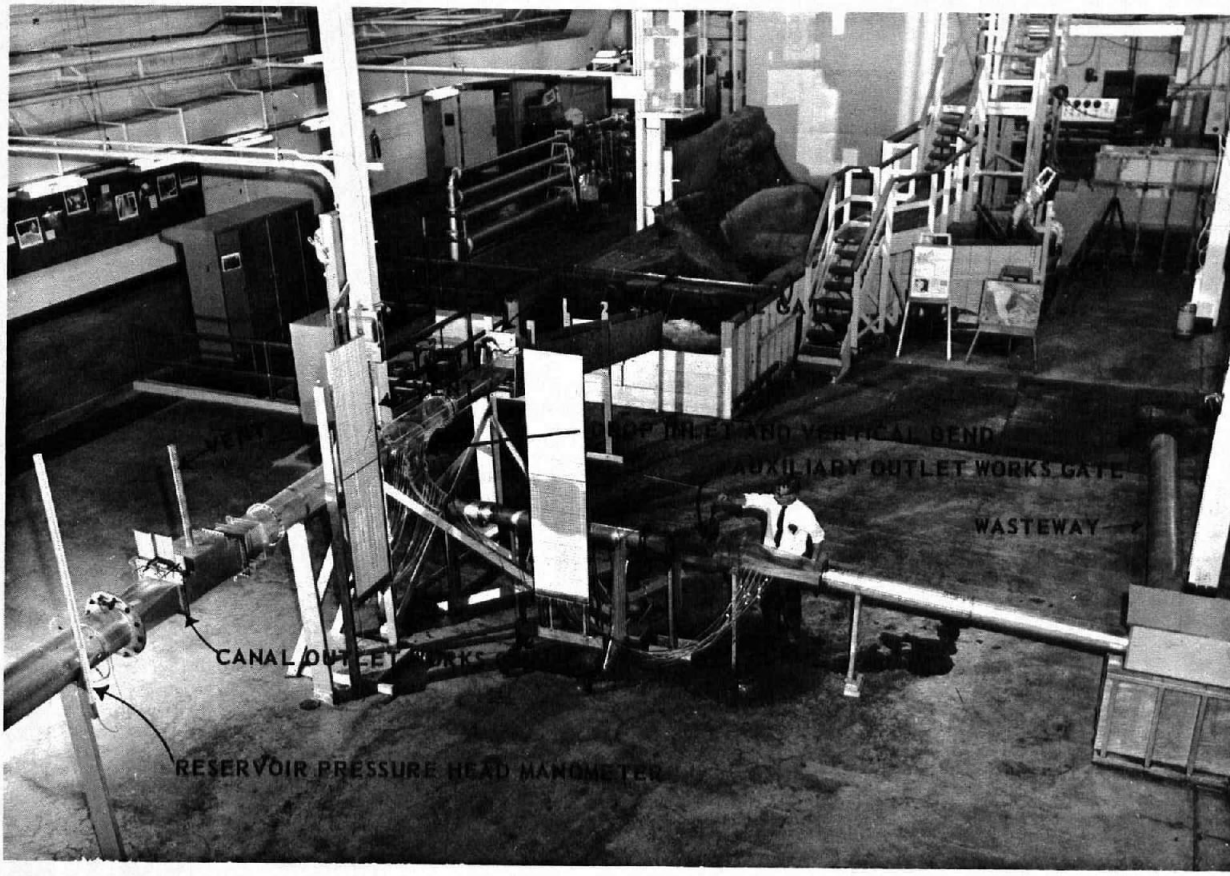
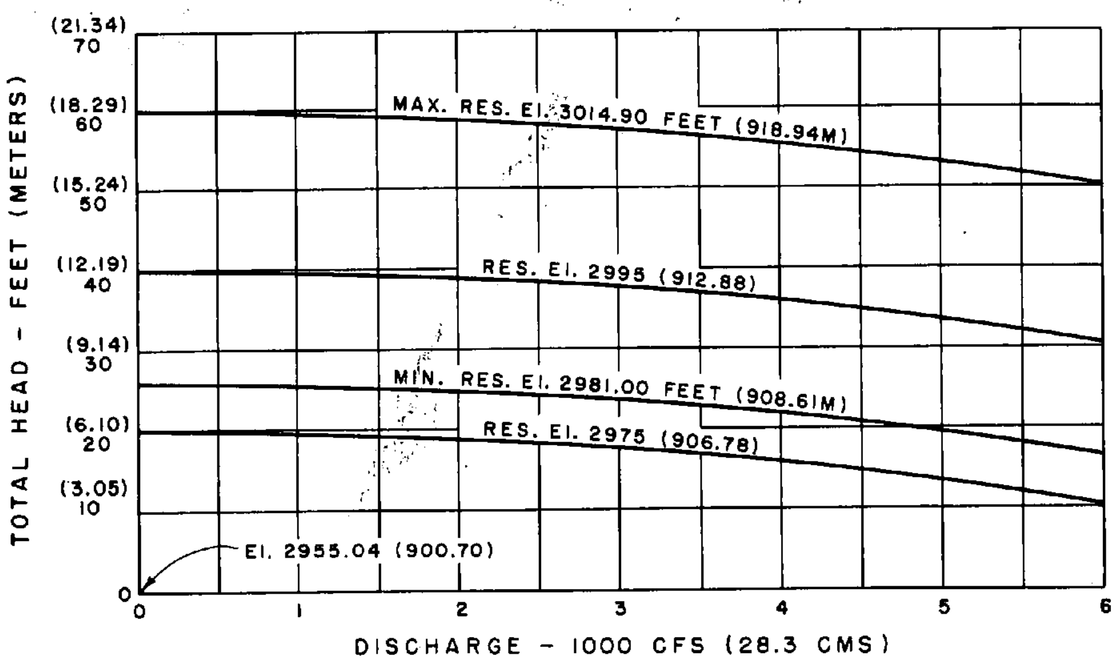


Figure 11. Tiber Dam Auxiliary Outlet Works—1:17.53 scale model. Photo P84-D-64684



EXPLANATION

Total head is computed above invert at Sta. 3+44.50 (105.00) upstream of canal outlet works gates using an entrance intake and trashrack loss coefficient of 0.37 and a roughness coefficient of 0.016 in the Darcy equation. From this total head the model pressure head was determined for setting reservoir elevation at the manometer pressure gage, Figures 10 and 11.

Figure 12. Tiber Dam Auxiliary Outlet Works—Head at the canal outlet works gates.

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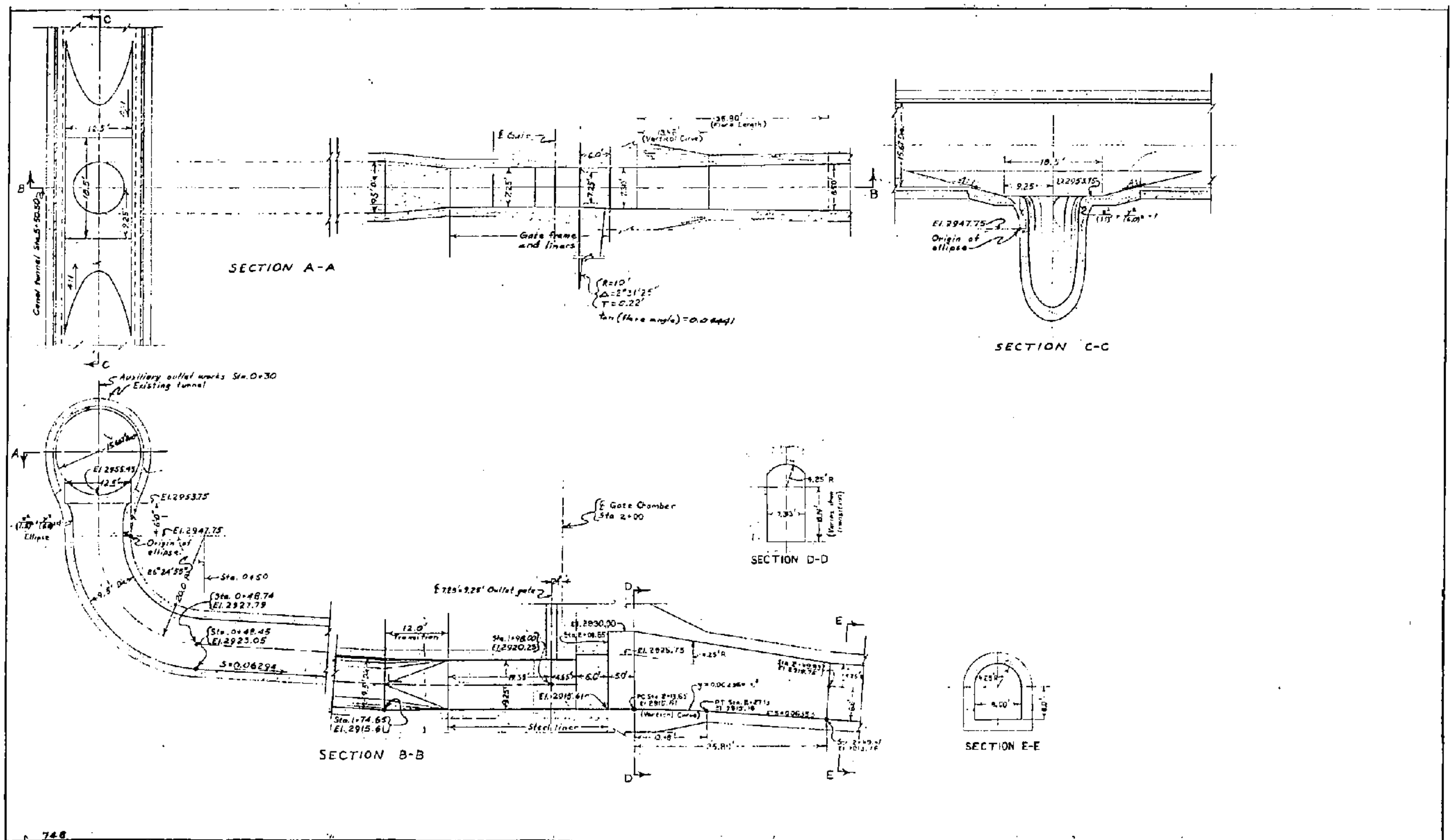


Figure 13. Tiber Dam Auxiliary Outlet Works—Preliminary design.

tunnel through an elliptical tunnel shape 6 feet (1.83 m) long.

Tests showed that the system should be filled very slowly and with the auxiliary outlet works gate closed; otherwise, the flow in the canal outlet works tunnel submerged the vertical drop inlet of the auxiliary outlet works tunnel and trapped air in the near-horizontal portion of the conduit between the vertical drop and the gates. The air accumulated along the crown of the conduit in the form of a bubble and did not move upstream until the buoyant force of the bubble overcame the drag force of the flow. When the bubble reached the vertical bend, it rapidly ascended to the surface and an explosive-type decompression resulted which caused pressure fluctuations and heavy loading on the structure. Several of these bubbles may form, move upstream, and explode before the system fills completely. These tests also showed that, in addition to the air shaft vent in the canal outlet works gate structure (Figure 5), an air vent should be provided in the canal outlet works tunnel to relieve the accumulation of air under pressure. In the first modification the vent was placed at the high point of the tunnel crown at Station 4+83.50 (147.40 m) (Figure 6). In dewatering the system the vent also would relieve the subatmospheric pressure if the outlet gates were opened too rapidly.

When the outlet works was operated during the filling of the system, an unfavorable flow condition over the drop inlet developed. With the gate 25 percent open (Figure 14) hydraulic jumplike flow occurred near the mouth of the drop inlet. As filling progressed and with the gate 50 percent open, the condition became very unstable. Waves traveled downstream from the jump to the dead end of the canal outlet works conduit and were reflected back and submerged the jump. The cycle was repetitious and could, possibly, occur at or near resonance which would place a heavy structural load on the system. Large vortices formed during the cyclic motion carrying air into the system, adding to the instability of the flow downstream from the auxiliary outlet works gate. The vortices persisted up to and including 100 percent gate opening until the tunnel was completely filled. At 70 percent gate opening, pressures along the elliptical surface of the vertical drop inlet reached the cavitation range. The subatmospheric pressures increased still further as the gate opening was increased, indicating that the 90° change in direction of flow over the elliptical curved surface was too abrupt.

The spiral motion of the flow through the drop inlet persisted even after the tunnels were filled; therefore, several antivortex devices were tested at the drop inlet intake, including a number of vertical parallel walls above the inlet, guide vanes in the drop inlet, and a vane deflector on the downstream side of the inlet. The most promising deflector was a curved deflector on the crown of the tunnel above the center of the drop inlet. This was adopted for the modified drop inlet design (Figure 15).

Modified Drop Inlet and Vertical Bend

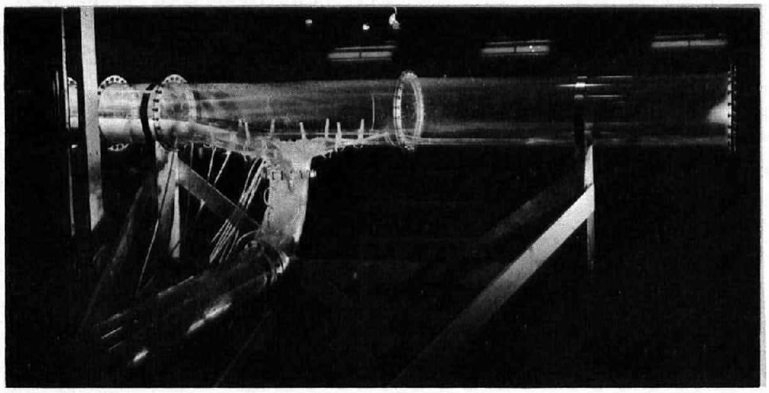
The modified drop inlet design (Figure 15) provided a larger throat diameter and a more gradual change in the direction of the tunnel invert from the horizontal canal outlet works tunnel to the vertical bend of the auxiliary outlet works tunnel. The drop inlet throat elevation and vertical bend centerline radius were not changed, but the diameter of the auxiliary outlet works tunnel was increased from 9 feet 6 inches (2.90 m) to 10 feet 3 inches (3.12 m) to match the increased throat diameter. An air vent was provided at the high point of the crown of the canal outlet works tunnel several feet upstream of the drop inlet, and a deflector-type antivortex device was placed on the crown of the tunnel above the throat of the drop inlet.

Pressure measurements along the drop inlet invert and crown of the vertical bend (Figure 16) showed some unacceptable subatmospheric pressures when head on the structure was relatively low. These pressures could be raised by closing the gates to 97 percent or, preferably, to 95 percent. However, restricting the gate opening was not considered feasible to restrict full capacity prototype operation. Therefore, further modifications to the shape of the drop inlet invert and vertical bend were made.

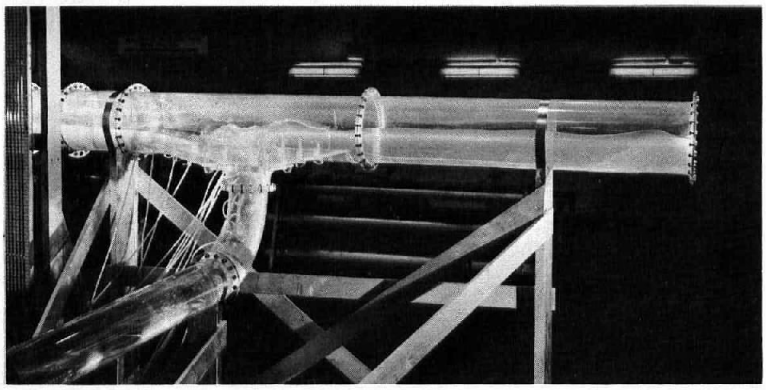
At low reservoir elevations air accumulated along the crown of the canal outlet tunnel upstream and downstream of the antivortex deflector and would not move upstream to the vent at the high point of the tunnel crown because of the drag force of the flow and because of the obstruction caused by the deflector. Therefore, the vent in the crown of the canal outlet works tunnel was moved about 25 feet (8.23 m) farther downstream to a location near the beginning of the drop inlet where the drag force of the flow seemed to maintain the air pocket; and a vent pipe was placed through the deflector near the tunnel crown to allow the air trapped downstream of the deflector to pass to the upstream side.

Recommended Drop Inlet and Vertical Bend

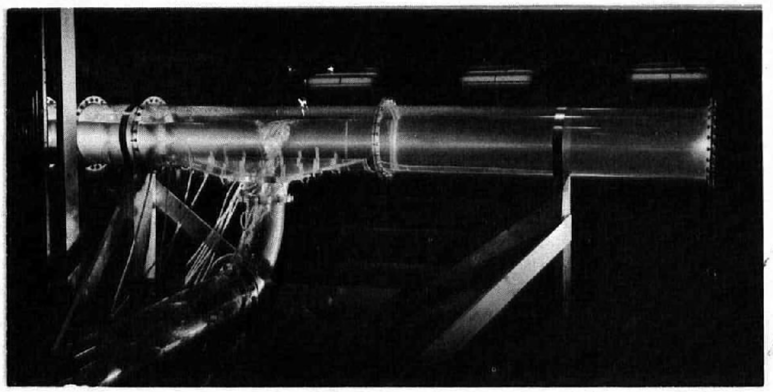
The final or recommended drop inlet and vertical bend design (Figure 6) had a larger throat diameter and a more gradual curvature of the drop inlet invert than



A. Reservoir elevation 2962 (902.82) with outlet works gate 25 percent open during the filling of the system. The flow is unstable with extremely turbulent flow in the drop inlet. Photo P84-D-68076



B. Reservoir elevation 2962 (902.82) with outlet works gate 50 percent open during the filling of the system. The flow is unstable with waves reflecting from the dead end. Photo P84-D-64680



C. Reservoir elevation 2967 (904.34) with outlet works gate 50 percent open during the filling of the system. The flow is unstable with a large vortex extending from the drop inlet and through the downstream gate section. Photo P84-D-64681

Figure 14. Tiber Dam Auxiliary Outlet Works—Preliminary drop inlet discharging—1:17.53 scale model.

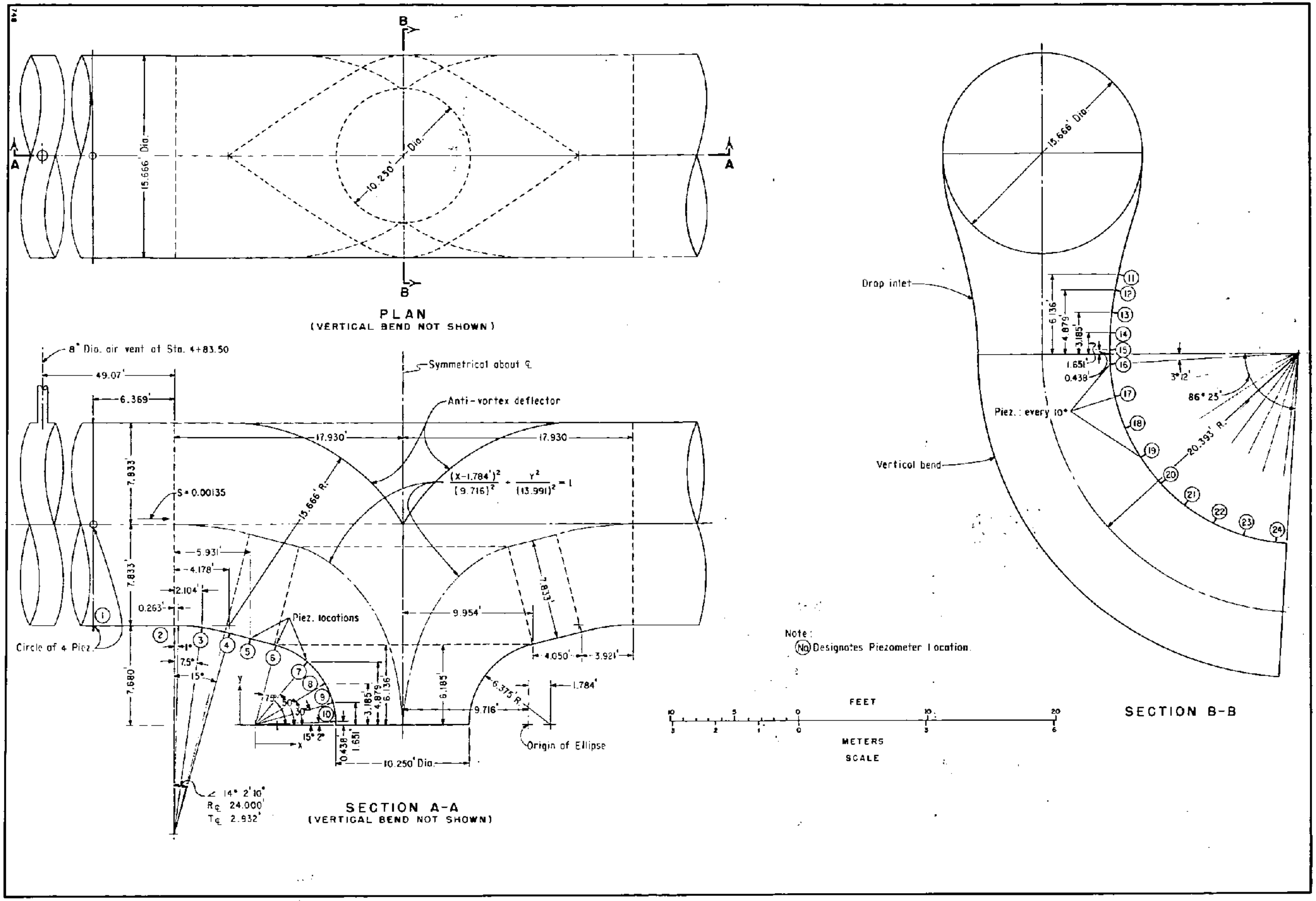
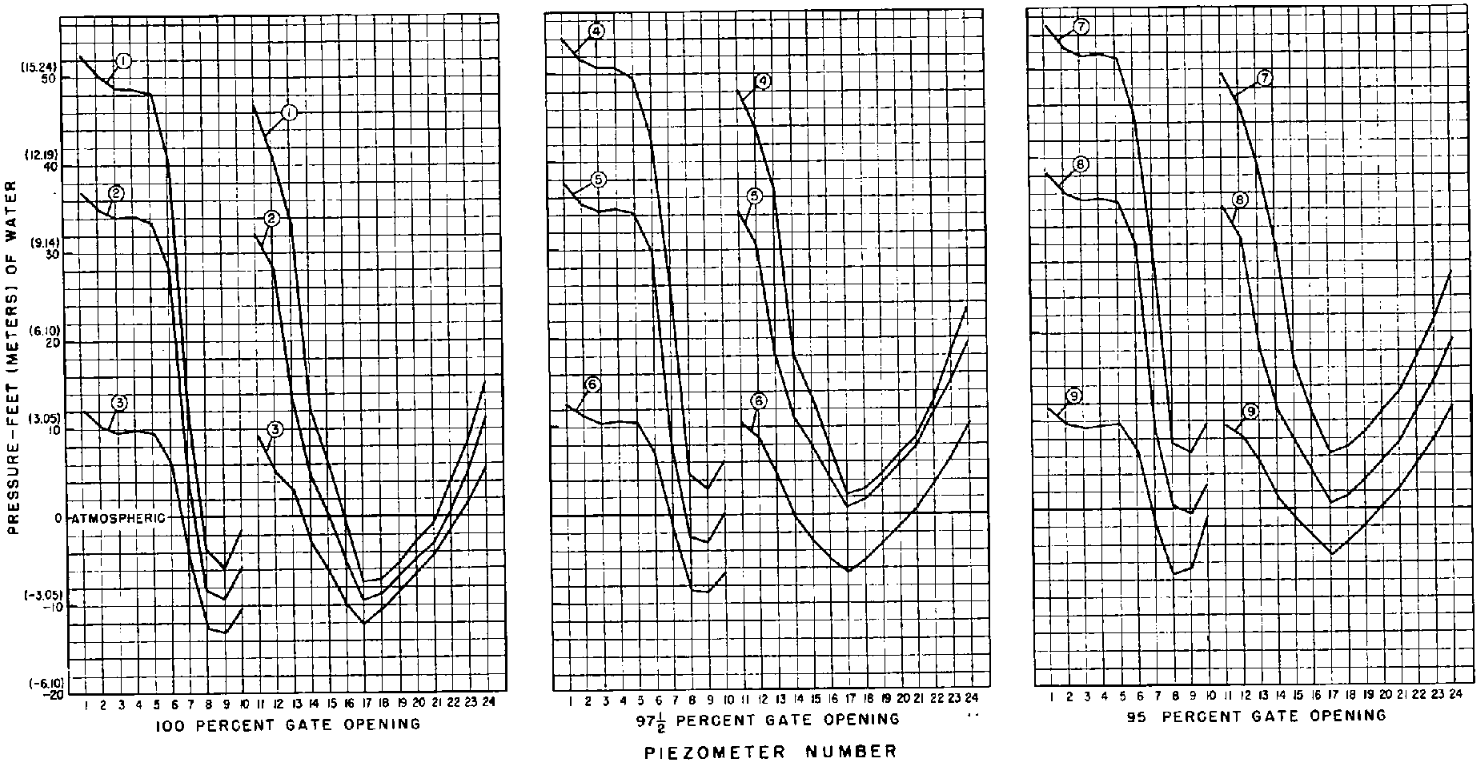


Figure 15. Tiber Dam Auxiliary Outlet Works—Modified drop inlet and vertical bend—1:17.53 scale model.



NOTE:
All pressures fluctuate in unison about 2 feet (0.61 m) ± from values plotted.
See Figure 14 for piezometer locations.

CURVE NO.	RESERVOIR ELEVATION-FEET (METERS)	DISCHARGE CFS (CMS)
1	3014.90 (918.94)	4,280 (121.20)
2	2995.00 (912.88)	3,780 (107.04)
3	2975.00 (906.78)	3,200 (90.61)
4	3014.90 (918.94)	3,990 (112.98)
5	2995.00 (912.88)	3,520 (99.68)
6	2975.00 (906.78)	3,000 (84.95)
7	3014.90 (918.94)	3,860 (109.30)
8	2995.00 (912.88)	3,380 (95.71)
9	2975.00 (906.78)	2,850 (80.70)

Figure 16. Tiber Dam Auxiliary Outlet Works—Modified drop inlet and vertical bend pressure gradients—1:17.53 scale model.

the preceding modification. The throat diameter and the outlet tunnel diameter were increased from 10 feet 3 inches (3.12 m) to 10 feet 9 inches (3.28 m) to reduce the flow velocity and increase pressures in this region and through the vertical bend. The drop inlet invert radius was increased from 6.375 feet (1.94 m) to 12.557 feet (3.82 m) to increase the pressures along the drop inlet invert. To further increase the pressures along the crown of the vertical bend the rate of curvature of the bend was decreased by increasing the centerline bend radius from 20 feet (6.10 m) to 21 feet 4-1/2 inches (6.51 m). The increases in the radii of the vertical bend and drop inlet invert and the increase in tunnel size lowered the invert of the auxiliary outlet works tunnel at its upstream end which changed its slope from 0.06294 to 0.01.

Relocation of the 8-inch (20.31-cm) vent in the crown of the canal outlet tunnel from the high point at Station 4+83.50 (147.37 m) to Station 5+10 (155.45 m) near the beginning of the drop inlet and providing a vent through the deflector as were previously described in the modified design were also included in the recommended design. In addition, about half of the deflector was eliminated by replacing the curved surface on the downstream side of the deflector with a vertical face.

The auxiliary outlet works was calibrated to determine the reservoir elevation needed to maintain full tunnel flow in the canal outlet portion and to provide a minimum pressure of approximately 1 foot (30.48 cm) above atmospheric pressure at the air vent for partial gate openings. In the model it was determined that the auxiliary outlet works gate can be partially opened at reservoir elevation 2972 (905.87), but that the gate must not be fully opened until the reservoir reaches elevation 2981 (908.61) (Figure 17). For the prototype reservoir elevation 2983 (909.22) was specified as the minimum allowed for full gate opening.

Pressures at the piezometers in the drop inlet and vertical bend (Figure 18) for full capacity tunnel flows were above atmospheric pressure for reservoir elevations above 2981 (908.61) (Figure 19).

The need for the antivortex deflector in the recommended design was verified by operating the recommended drop inlet without it. Without it at minimum reservoir elevation 2981 (908.61) the water surface downstream from the air vent was drawn down by a swirling flow pattern through the drop inlet (Figure 20). The swirling flow produced a vortex which extended on an intermittent basis through the gate section and downstream transition. At maximum reservoir no air was taken into the tunnel, but the flow swirled through the drop inlet and tunnel downstream as was evidenced by the swirl of the flow over the crown of the transition downstream of the outlet works gate (Figure 20).

Operation of the recommended drop inlet with the antivortex deflector installed (Figure 21) showed that the canal outlet works tunnel above the drop inlet flows full even at minimum reservoir elevation 2981 (908.61) and that the flow through the gate section and downstream tunnel transition was smooth and straight. Compare Figures 20 and 21. Therefore, the antivortex deflector (Figure 6) is recommended.

Preliminary Tunnel Transitions Downstream of Gate Chamber

Prior to construction of the preliminary designed transition but with the preliminary drop inlet, an offset transition consisting of a semicircular top and bottom with straight, decreasing height, sidewalls (Figure 22) was installed in the model. The offset was 1.75 feet (0.53 m) on the sidewalls and floor with a 3-7/8-inch (9.84-cm) offset horizontally and vertically from the lower corners.

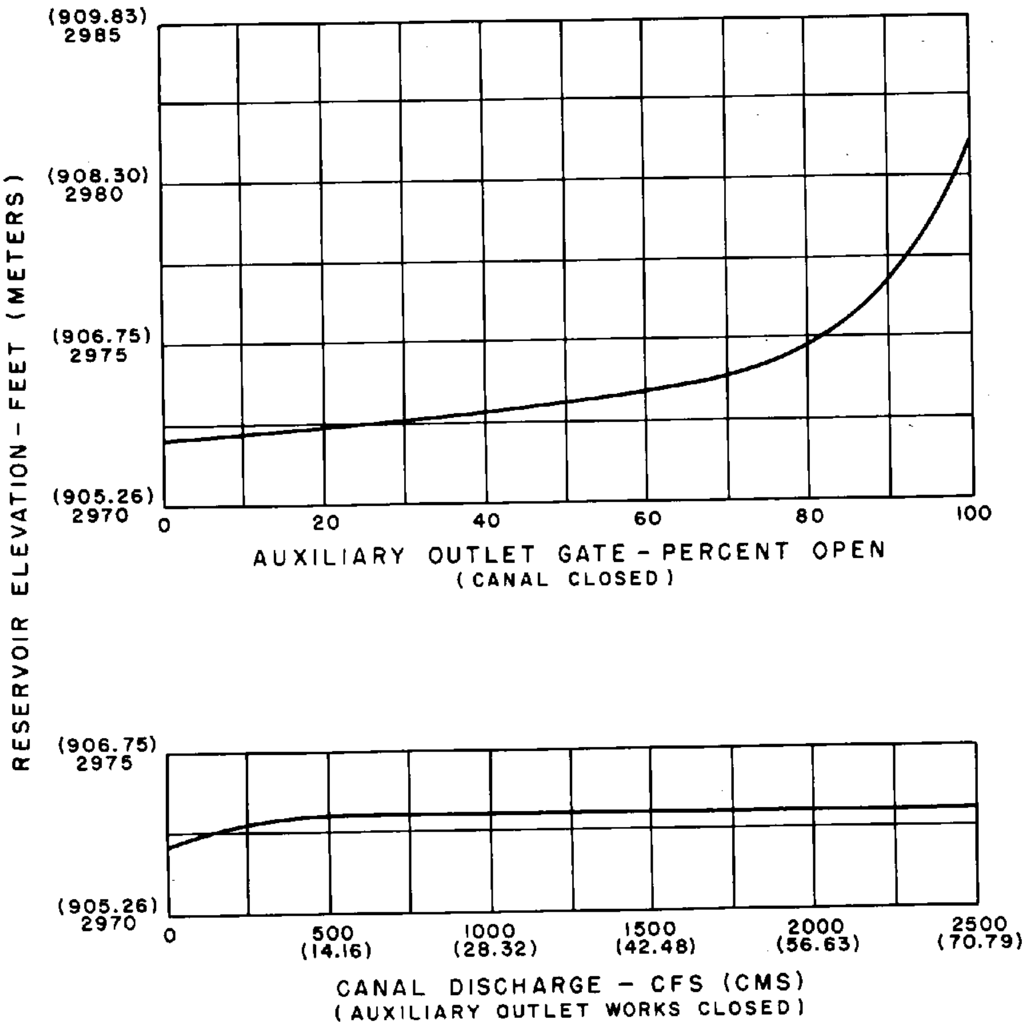
The transition performed satisfactorily up to 60 percent gate opening at which time fins of water formed along the sidewalls downstream from the gate section. The fins climbed the sidewalls and became progressively worse as the gate opening was increased.

The fins tended to fill the 10.75-foot (3.28-m) diameter tunnel above the main flow surface, but this was partially due to the spiraling flow currents from the vortex in the drop inlet.

The offset transition was replaced with the preliminary designed transition (Figure 13) consisting of a flat-bottom, circular-top section at the 7-foot 3-inch (2.21-m) wide gate frame that transitioned to an 8-foot 6-inch (2.59-m) wide by 10-foot 3-inch (3.12-m) high flat-bottom tunnel. The transition to a flat-bottom tunnel rather than to a circular tunnel was intended to aid in straightening the spiraling flow currents that were initiated in the preliminary drop inlet but failed to perform this function.

Modification of Tunnel Transition Downstream of Gate Chamber

Since the flat-bottom tunnel provided no hydraulic advantage, it was decided to develop a transition for use with a circular tunnel. The diameter of the proposed circular tunnel was 10.25 feet (3.12 m) to match the tunnel upstream of the gate. A gradually flaring rectangular-to-round transition (Figure 23) was



NOTE: Reservoir elevations plotted are those required to maintain full pipe flow in the system except for small air pockets which are trapped upstream of the crown vent at Sta. 5+10 (155.45m) but move to the vent with slightly increased head. At this minimum full pipe flow water stands approximately one foot (30 cm) deep in the vent.

Figure 17. Tiber Dam Auxiliary Outlet Works—Calibration for full pipe flow recommended design—1:17.53 scale model.

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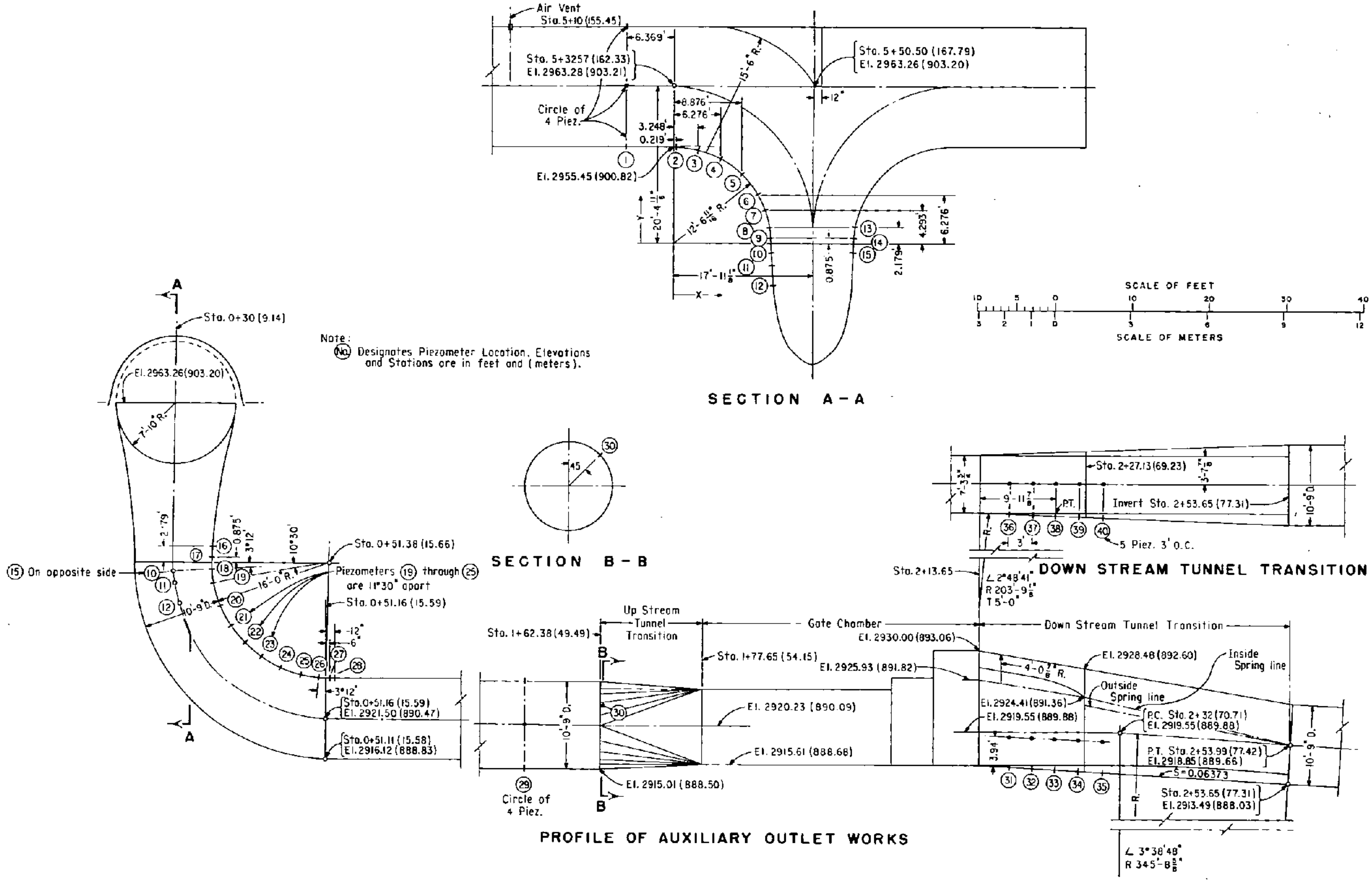
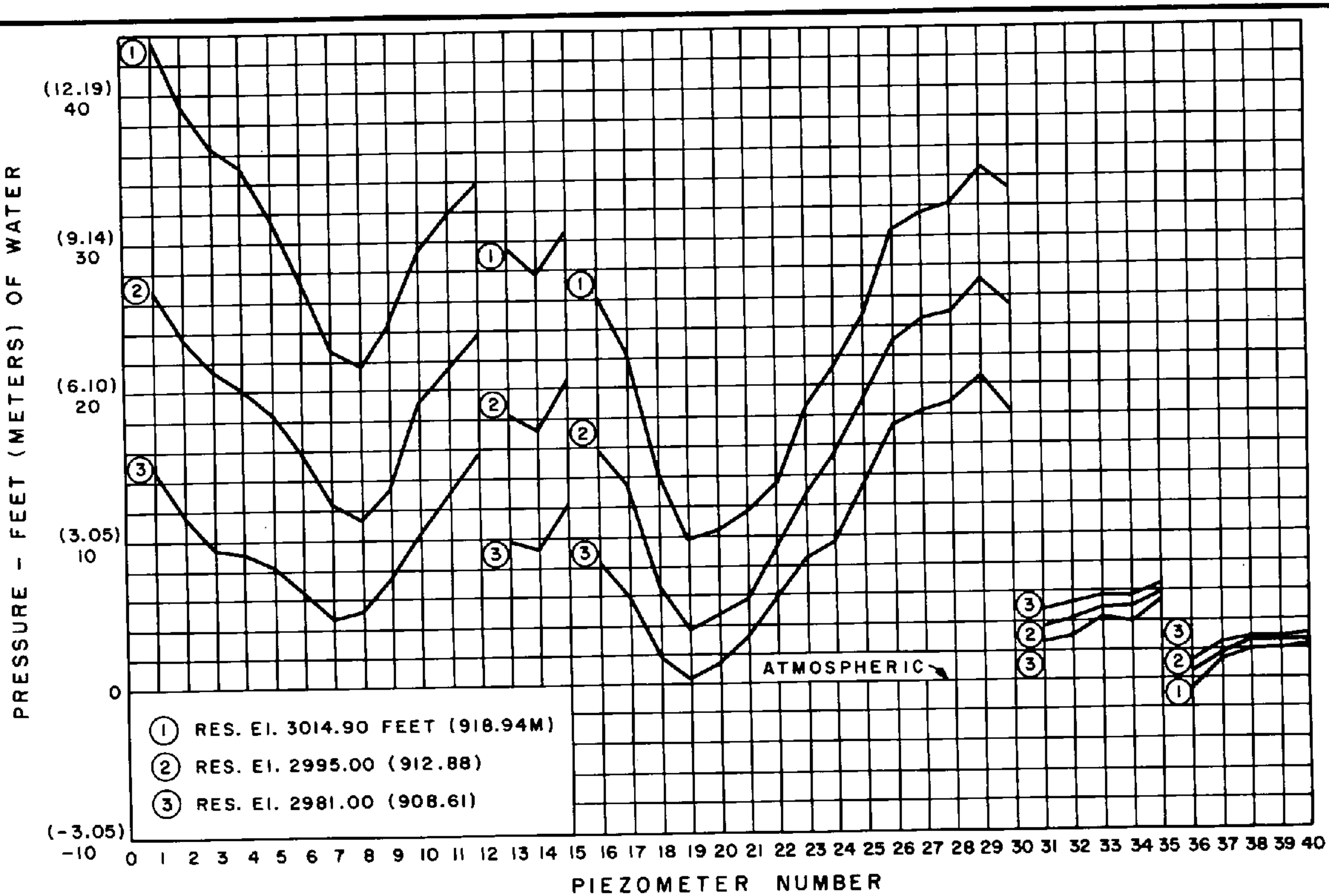
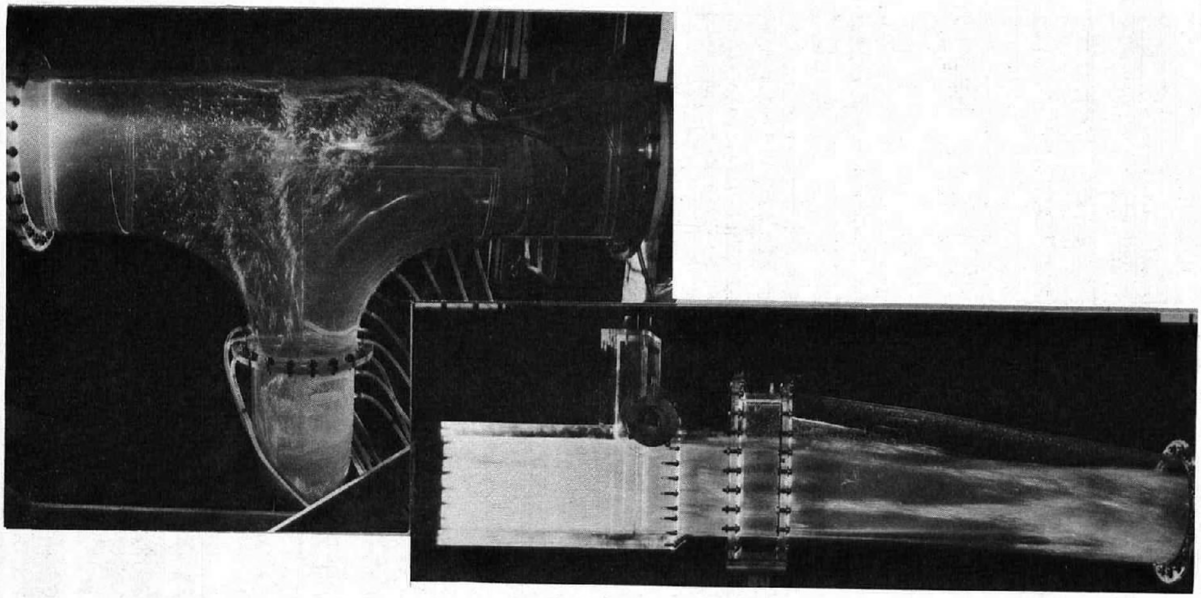


Figure 18. Tiber Dam Auxiliary Outlet Works—Piezometer locations in the recommended design—1:17.53 scale model.



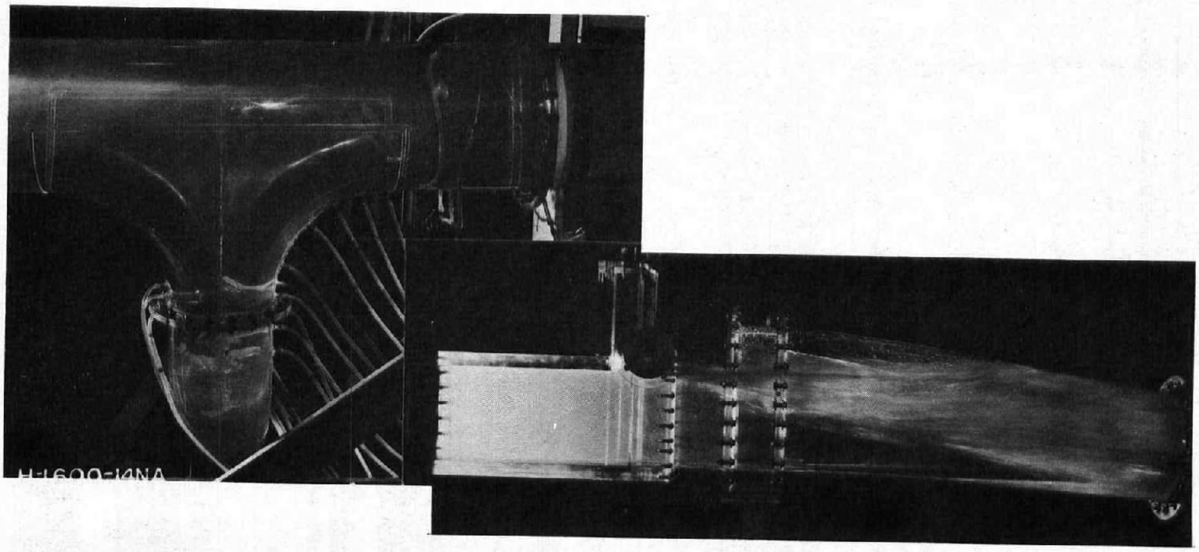
NOTE: All pressures fluctuate in unison about 2 feet (0.61m) ± from values plotted. See Figure 17 for Piezometer locations.

Figure 19. Tiber Dam Auxiliary Outlet Works—Recommended drop inlet, vertical bend, tunnel, and transition pressure gradients—1:17.53 scale model.



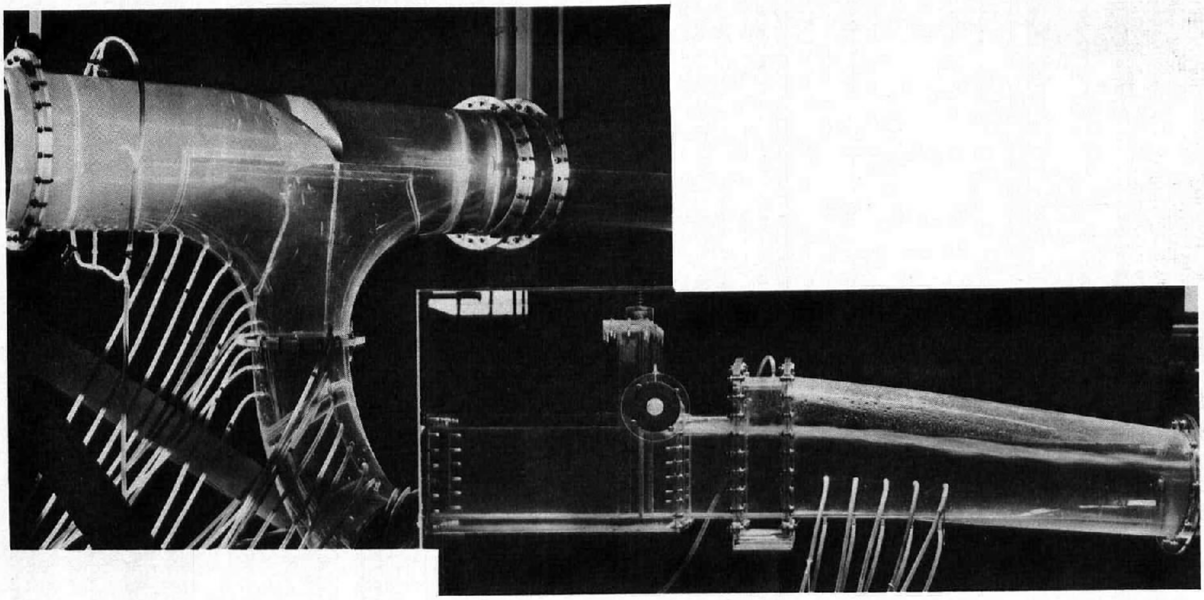
Reservoir elevation 2981 (908.61) with the outlet works gate fully open. Photo P84-D-64686.

Note the air entrainment and swirling flow pattern extending from the drop inlet through the transition downstream of the gate section.

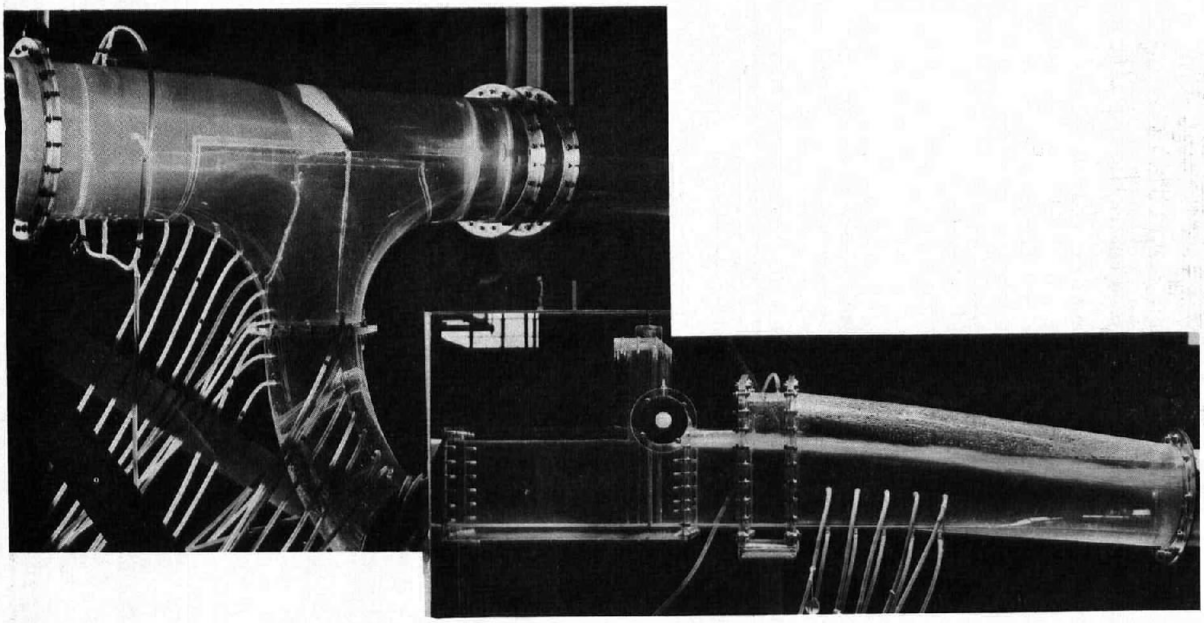


Reservoir elevation 3014.9 (918.94) with the outlet works gate fully open. Photo P84-D-68082.

Figure 20. Tiber Dam Auxiliary Outlet Works—Flow through drop inlet and transition without deflector—1:17.53 scale model.



Reservoir elevation 2981 (908.61) with the outlet works gate fully open. Left Photo P84-D-64687. Right Photo P84-D-64688.



Reservoir elevation 3014.9 (918.94) with the outlet works gate fully open. Left Photo P84-D-68085. Right Photo P84-D-68086.

Note the deflector at the crown of the drop inlet and the smooth flow that extends from it and through the transition downstream of the gate section.

Figure 21. Tiber Dam Auxiliary Outlet Works—Flow in recommended drop inlet and transition—1:17.53 scale model.

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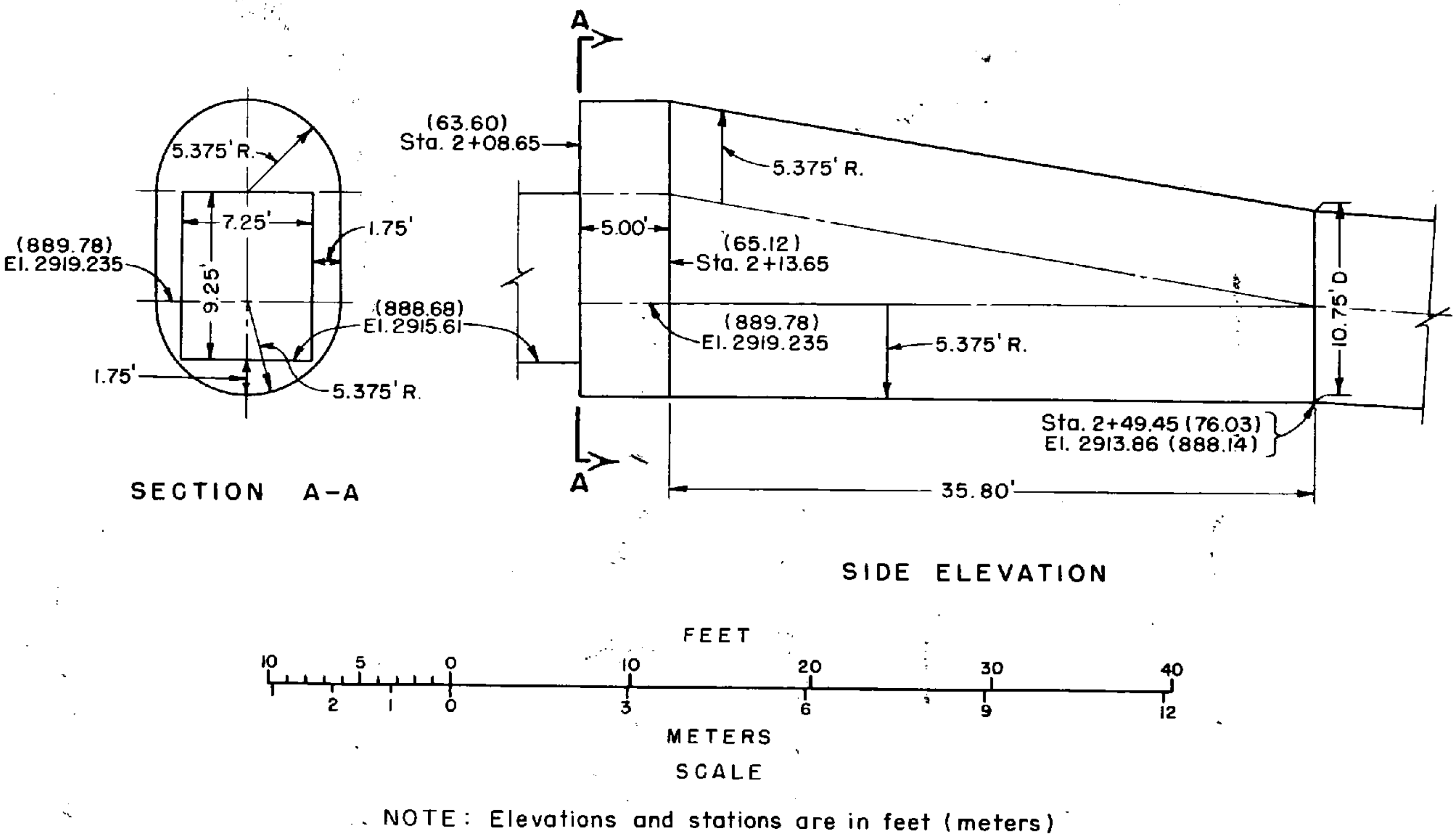


Figure 22. Tiber Dam Auxiliary Outlet Works—Gate chamber off-set transition.

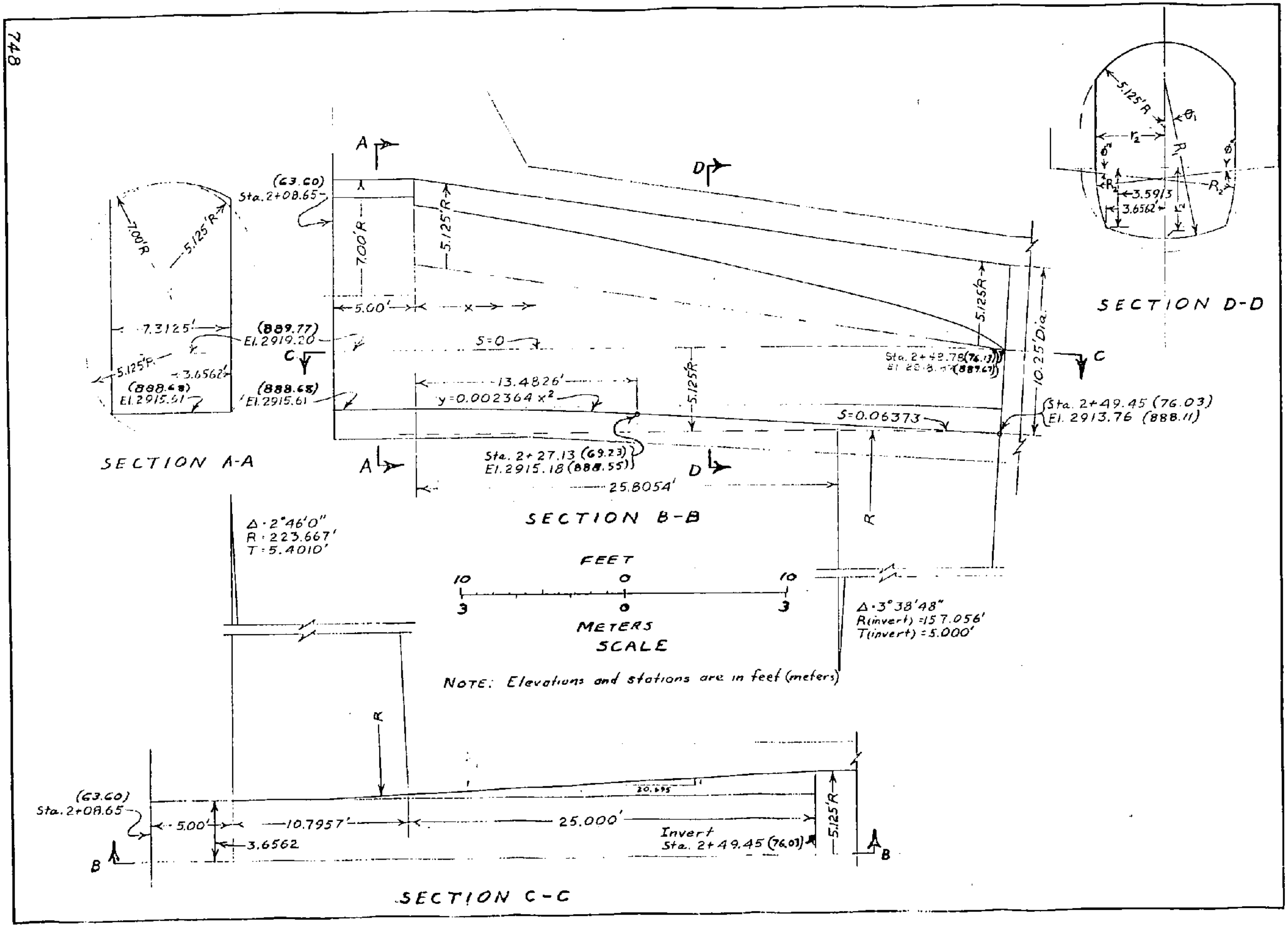


Figure 23. Tiber Dam Auxiliary Outlet Works—Gate chamber transition modification.

designed and tested, first with the modified drop inlet and antivortex deflector.

This transition, along with the modified drop inlet design, was more satisfactory than any of the previous designs tested. However, the depth of flow in the tunnel at the downstream end of the transition was about 0.8 of the diameter and was expected to be even deeper at the downstream portal. Therefore, the tunnel diameter was increased to 10 feet 9 inches (3.28 m) in the recommended design, the same as the diameter of the throat of the recommended drop inlet and tunnel upstream of the gate section.

Recommended Tunnel Transition Downstream of Gate Chamber

The transition was modified to fit the recommended increase in tunnel diameter. Further refinements were also adopted in the recommended transition as the result of observing small fins that formed along each wall where the flow passed over the breakline between the round top and vertical sides in the preceding transition. It was decided to eliminate this breakline in the downstream two-thirds of the transition and allow the top radius to become tangent to the vertical sides (Figure 7).

Performance of this recommended transition with the recommended drop inlet (Figure 21) was very good. The water surface was level throughout and well below the crown of the tunnel. The flow appeared to be very straight with negligible fins with the antivortex deflector installed in the drop inlet.

Pressures were measured along the invert and sidewalls of the transition at carefully chosen locations where critical subatmospheric pressures were most likely to occur (Figure 18).

All observed pressures were near atmospheric pressure or above (Figure 19). However, because of the high velocities of flow in this structure, it is important that the flow surface be made smooth since small irregularities, particularly those protruding into the flow, could cause local subatmospheric pressures great enough to cause cavitation erosion.

The possibility of dropping the invert of the transition and downstream tunnel 2 feet (0.61 m) and providing vents through this offset to aerate the undernappe downstream from the gate frame was investigated (Figure 24). At 100 percent gate opening, operating at either minimum reservoir elevation 2981.00 (908.60) or maximum reservoir elevation 3014.90 (918.94), the air demand was not sufficient to vent the undernappe. At minimum reservoir elevation it was necessary to close the auxiliary outlet works gate 10 percent to provide enough air demand to vent the undernappe. At maximum reservoir elevation, it was necessary to close the gate only 3 percent.

Lowering the invert as tested here did not appear to be necessary and would be quite difficult to incorporate into this design. However, for future installations the idea appeared to be quite feasible and desirable.

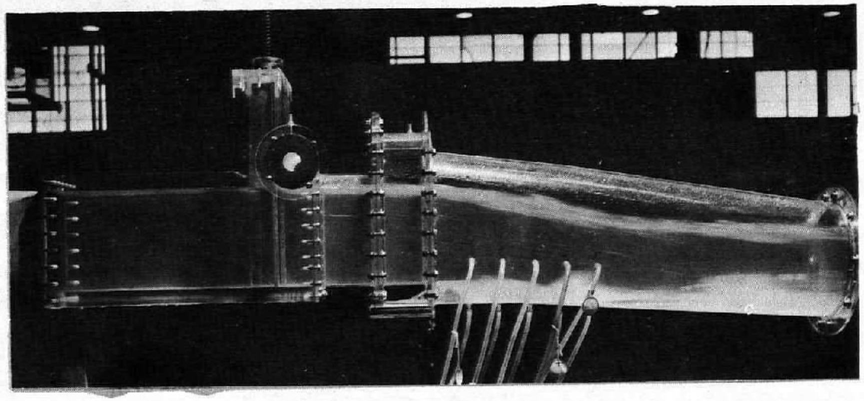
Auxiliary Outlet Works Operating Procedure and Calibration

Since the invert of the intake structure (Figure 4) is at elevation 2957.25 (901.37 m), the system can be filled by opening the canal outlet works gates when the reservoir rises above this elevation. By keeping the auxiliary outlet works gate closed until the reservoir rises to elevation 2962 (902.82), the auxiliary outlet works tunnel to the gate will be filled and will remain filled as the reservoir rises further if the auxiliary outlet works gate is opened no more than is specified by the limiting discharge elevation curve in Figure 9. This curve was derived by offsetting the free-flow discharge curve 300 cfs (8.49 cu m/sec) to the left of its computed location, to insure that control of the flow is at the auxiliary outlet works gate (rather than first at the intake weir crest then shifting to the drop inlet at reservoir elevation 2968 (904.64 m) and, finally, to the auxiliary outlet works gate at approximately elevation 2981 (908.61). Thus, the possibilities of unstable shifting control operations at these critical elevations and the air bubble explosions that are likely to occur when the control is at the drop inlet are eliminated.

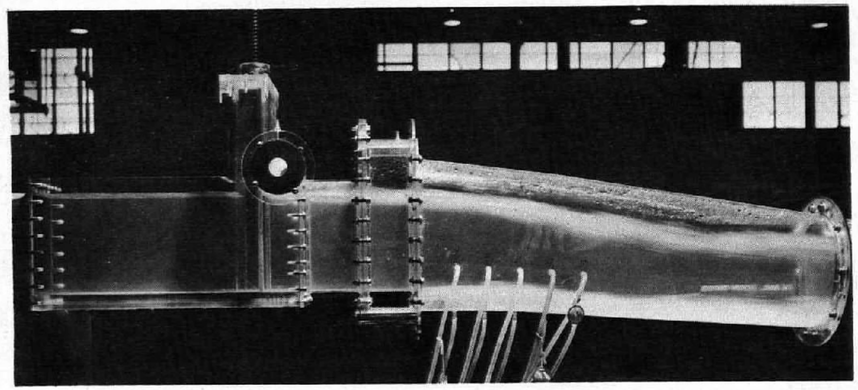
Normally, the system will be operated with sufficient head to provide full tunnel flow conditions throughout the system and with the auxiliary outlet works gate fully open. Reservoir elevation 2981 (908.61 m) will be required for this operating condition (Figure 19).

At reservoir elevation 2972 feet (905.87 m) (Figure 19) the auxiliary outlet works gate could begin to be opened while still maintaining full tunnel flow operation and in accordance with the curve in Plot A of Figure 19, the gate could be opened further as the reservoir rises.

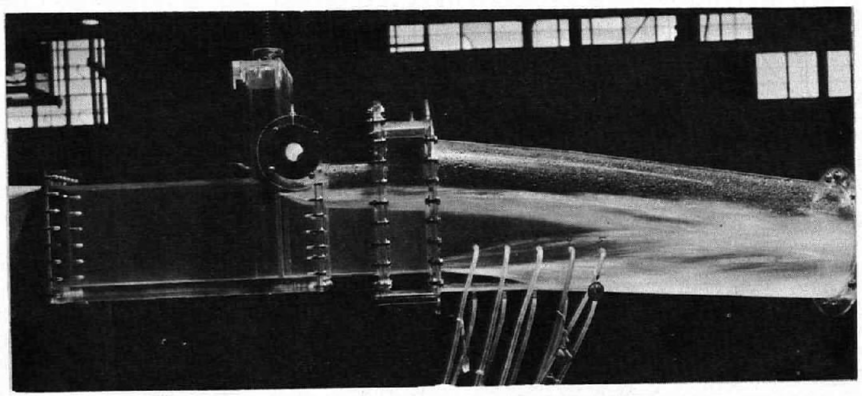
Precise calibration of the gate-controlled flows was not possible in the model since friction losses and the gate were not exactly represented in the model. However, a few discharge measurements made at gate openings of 95, 97-1/2, and 100 percent were found to be slightly more than the computed values. Considering the inadequacies of the model, the agreement with the computed values in Figure 9 was very good and on the side of safety. For example, at reservoir elevation



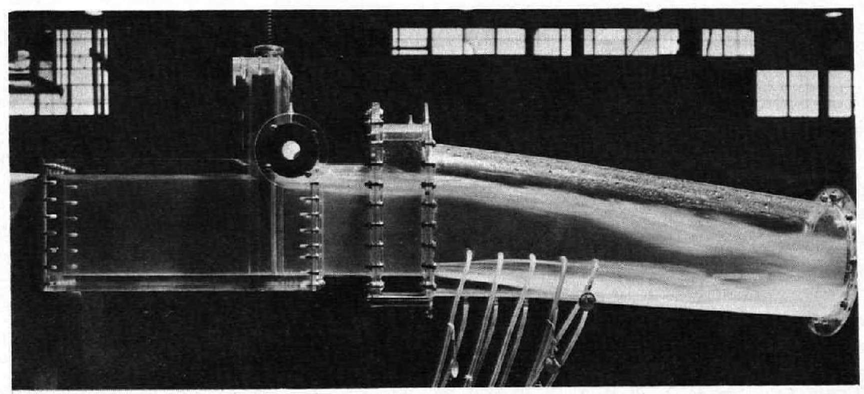
Reservoir elevation 2981 (908.61)
Gate open 100 percent
Compare with Figure 20. Photo P84-D-68087



Reservoir elevation 3014.9 (918.94)
Gate open 100 percent
Compare with Figure 20. Photo P84-D-64682



Reservoir elevation 2981 (908.61)
Gate open 90 percent. Photo P84-D-68089



Reservoir elevation 3014.9 (918.94)
Gate open 97 percent. Photo P84-D-64683

NOTE: The offset is vented at the upstream end through four 4-3/8 inch (111.12 mm) round openings.

Figure 24. Tiber Dam Auxiliary Outlet Works—Operation with transition off-set—1:17.53 scale model.

3014.9 (918.94 m), the average measured value was approximately 4,275 cfs (120.98 cu m/sec) as compared to the computed value of 4,125 cfs (116.78 cu m per sec) in Figure 9, and at reservoir elevation 2981 (908.61), the model measurement was 3,350 cfs (94.81 cu m per sec) as compared to 3,250 cfs (91.97 cu m per sec) on the plot.

Dewatering the System

Dewatering the system with the reservoir at or above the crown of the canal outlet works tunnel was not considered to be a normal operating condition, but conceivably could be necessary. In this case, it would be best to first close the auxiliary outlet gate, then close the canal outlet gates, after which the auxiliary outlet works gate can be reopened slowly being sure all vents to the tunnel system are open. Tests showed that the air vent and the 4-inch (10.15-cm) vent pipe through the deflector (Figure 6) plus the air shaft in the gate structure (Figure 5) to be adequate in venting the system as the auxiliary outlet gate was opened to dewater the system. Nevertheless, the gate should be very slowly opened for the first 5 percent and then in 5 and 10 percent increments pausing a minute or two between increments.

Operation of the Canal Irrigation System

This section is for use only when and if an irrigation system will be installed from the dead end of the existing canal outlet works. When in use, the existing canal outlet control gates will be fully opened at all times while the flow to the irrigation system will be controlled by one or more gates at or near the existing dead end. A slide gate was installed in the model at the dead end of the existing canal outlet works to simulate release of water to an irrigation system. The minimum operational pool level for irrigation use is anticipated to be at reservoir elevation 2967 (904.34) which is about 3 inches (7.62 cm) below the crown of the intake tunnel and about 4 feet (1.22 m) below the crown of the canal outlet tunnel at the drop inlet (Figure 6). At this reservoir elevation the irrigation control canal gate at the dead end can be opened sufficiently to discharge the design flow of 2,400 cfs (67.92 cu m/sec) to the irrigation system with no hydraulic problems occurring over the drop inlet or any other place in the tunnel.

As the reservoir rose and filled the tunnel, air was evacuated through the vent upstream of the deflector (Figure 6). If the irrigation control gate at the dead end remained closed until the reservoir reached elevation 2971 (905.56) which is at the crown of the canal outlet tunnel at the drop inlet, all of the air will be evacuated from the tunnel except for two very small pockets of air: One along the crown upstream of the vent at Station 5+10 (155.45) which will move to the vent when the irrigation control gate is opened and the flow begins; the other is along the crown of the tunnel downstream of the deflector above the elevation of the vent through the deflector. Calibration test (Figure 19) showed that at elevation 2973 (906.17) the canal irrigation gate can be opened to release up to the design flow of 2,400 cfs (67.92 cu m/sec) with the tunnel remaining full under a slight pressure, with no hydraulic problems.

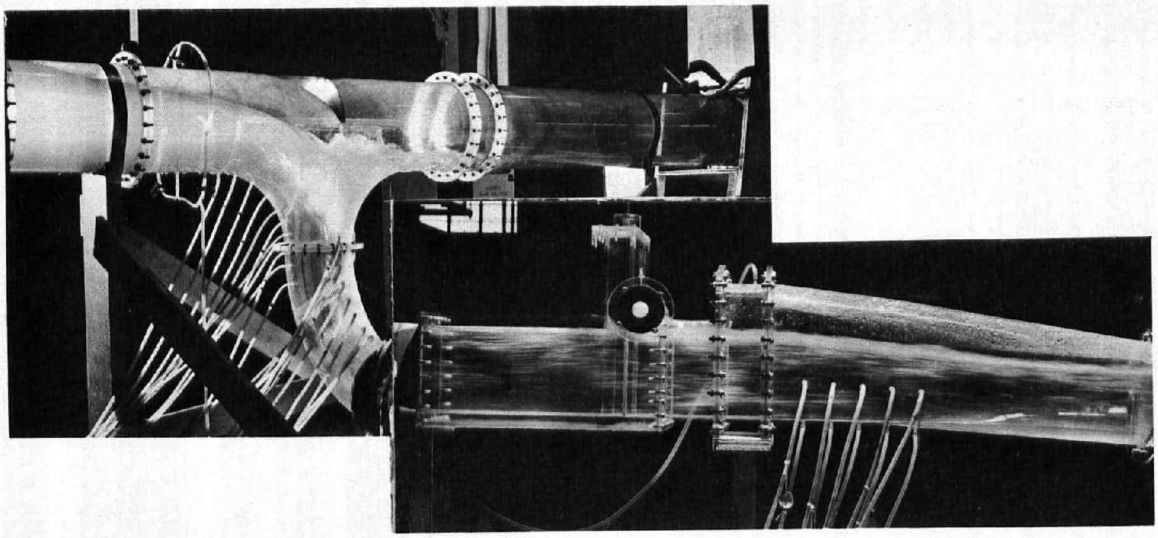
If the irrigation water control gate was partially opened before the reservoir reached elevation 2971 (905.56), the air pocket became trapped between the deflector and the gate. As the reservoir rose, this air pocket became pressurized and moved downstream away from the deflector vent by the drag force of the flow. It remained on the downstream side of the deflector until the irrigation control gate at the dead end was either closed or nearly closed.

Some thought was given to providing a vent in this region of the tunnel crown and connecting it into the vent upstream of the deflector. However, it was decided that the canal irrigation gate at the dead end could be closed for a few minutes to eliminate the drag force of the flow and allow the buoyant force of the air bubble to move it upstream to the vent through the deflector. The irrigation control gate could then again be opened to discharge up to 2,400 cfs (67.92 cu m/sec) with no further accumulation of air as long as the reservoir remained at elevation 2973 (906.17) or above and the outlet gate was not opened.

Simultaneous Operation of the Outlet Works and the Irrigation Canal System

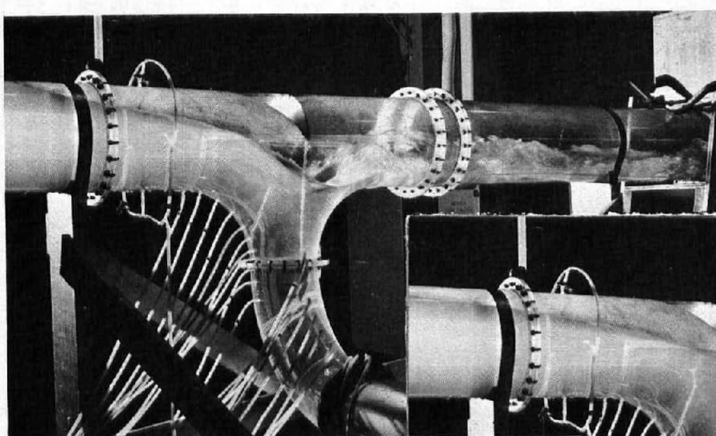
Various combinations of reservoir elevations and outlet works gate openings with the irrigation canal gate 100 percent open were investigated (Figures 25 and 26). Some operating conditions were more turbulent and less desirable than others in the tunnel between the drop inlet and the gate.

It was recommended that simultaneous operation of the two systems be used only while the canal outlet tunnel is flowing full and that flow through the auxiliary outlet works gate be controlled to prevent the canal outlet tunnel from becoming only partially full at irrigation flows of 2,400 cfs (67.92 cu m/sec), or less. For this type of operation, the outlet works discharge and the permissible auxiliary outlet works gate openings that will maintain a full tunnel to the canal irrigation gate were determined from the model and plotted in Figure 27 for a range of irrigation canal

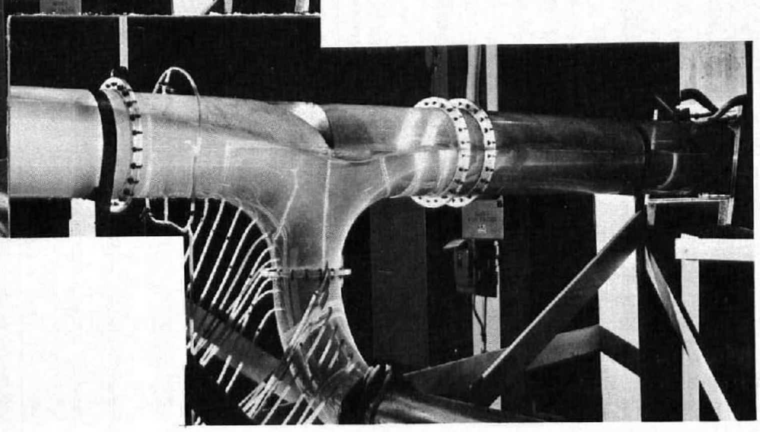


Reservoir elevation 2978 (907.69)
Discharging 3200 cfs (90.62 cu m/sec)
Both canal gate and
outlet works gate open 100 percent
Photo P84-D-68091

Note the air entrainment from the drop inlet and through the transition section.

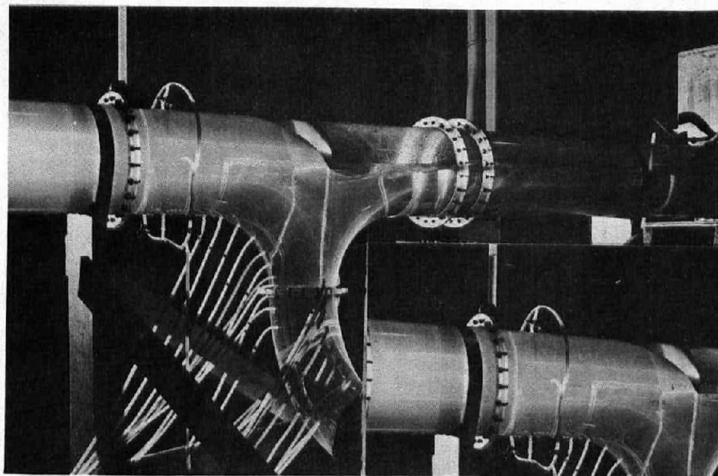


Reservoir elevation 2978 (907.69)
Discharging 3200 cfs (90.62 cu m/sec)
Canal gate open 100 percent
Outlet works gate open 70 percent
Photo P84-D-68094

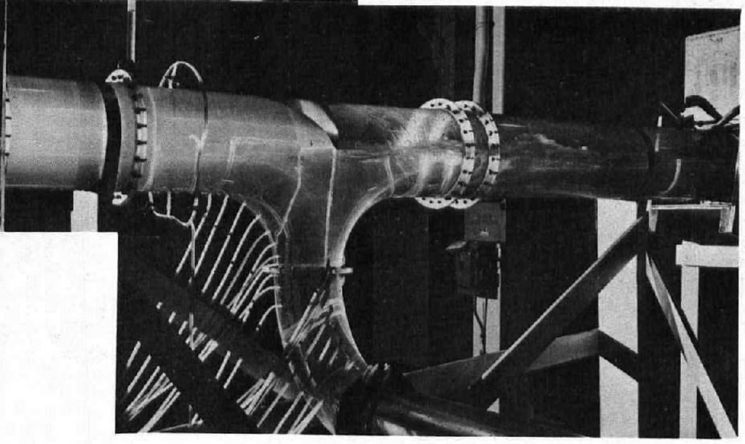


Reservoir elevation 2978 (907.69)
Discharging 3200 cfs (90.62 cu m/sec)
Canal gate open 100 percent
Outlet works gate open 20 percent
Photo P84-D-68094

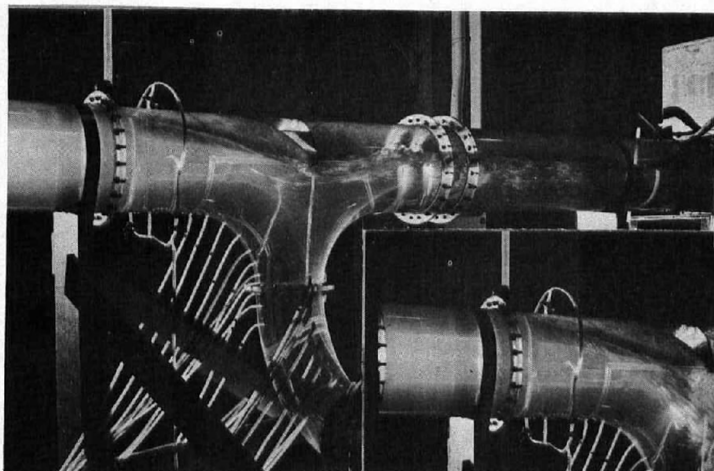
Figure 25. Tiber Dam Auxiliary Outlet Works—The outlet works and irrigation system operating simultaneously—1:17.53 scale model.



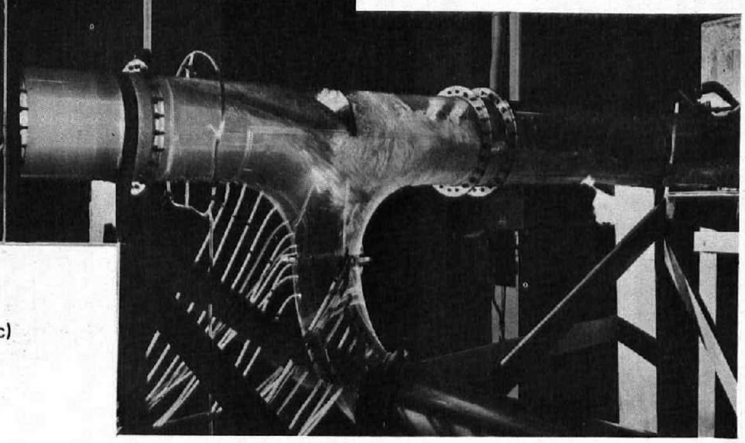
Reservoir elevation 2982 (908.91)
Discharging 3200 cfs (90.62 cu m/sec)
Canal gate open 100 percent
Outlet works gate closed
Photo P84-68095



Reservoir elevation 2996 (913.18)
Discharging 4280 cfs (121.21 cu m/sec)
Canal gate open 100 percent
Outlet works gate closed
Photo P84-D-68096

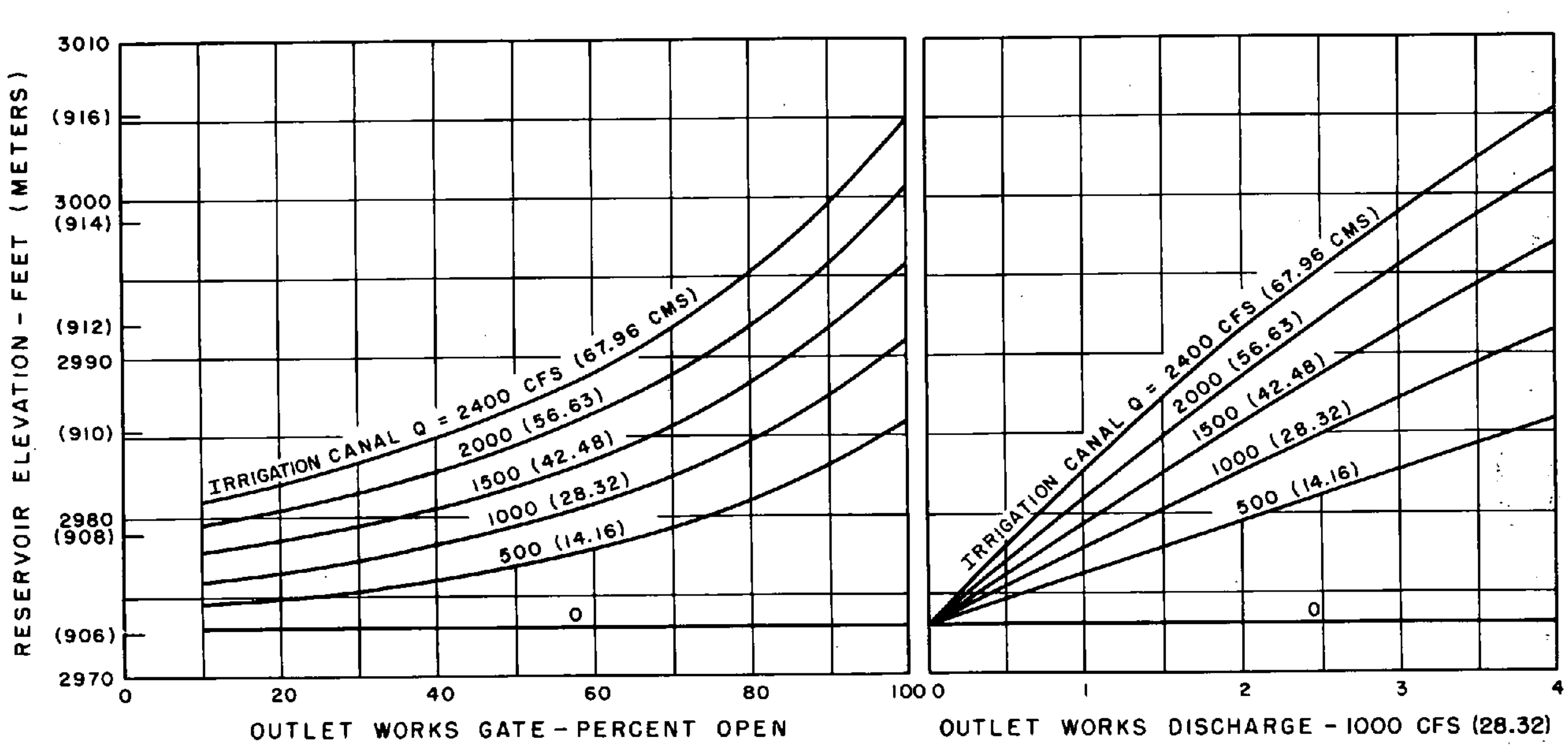


Reservoir elevation 2983 (909.22)
Discharging 4280 cfs (121.21 cu m/sec)
Canal gate open 100 percent
Outlet works gate open 45 percent
Photo P84-D-68097



Reservoir elevation 2984 (909.52)
Discharging 4300 cfs (1217.62 cu m/
Canal gate open 100 percent
Outlet works gate open 100 percent
Photo P84-D-68098

Figure 26. Tiber Dam Auxiliary Outlet Works—The outlet works and irrigation system operation simultaneously—1:17.53 scale model.



NOTE : The curves show for a given reservoir elevation the maximum permissible auxiliary outlet works gate opening and approximate discharge to maintain the tunnel system flowing full.

Figure 27. Tiber Dam Auxiliary Outlet Works—Permissible operation of the outlet works discharge with flow in the irrigation systems—1:17.53 scale model.

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flows. For example, if at reservoir elevation 2980 (908.30) the canal discharge is to be 2,000 cfs (56.62 cu m/sec), then the auxiliary outlet works flow should not exceed approximately 900 cfs (25.48 cu m/sec). Figure 27 is only approximate and should be used with discretion.

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03*	Square centimeters
	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	946.358*	Cubic centimeters
	0.946331*	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985 x 10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582 x 10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873 x 10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482 x 10^{-5}*	Dynes

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.092903*	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

ABSTRACT

The existing canal outlet works tunnel at Tiber Dam, Mont, is used as an intake and as the upstream portion of an auxiliary outlet works designed to provide additional reservoir release capacity. The existing 17-ft-dia horseshoe free flow tunnel is converted to a 15-ft 6-in.-dia pressure tunnel and is connected to a new 10-ft 9-in.-dia tunnel by a drop inlet and vertical bend. The smaller tunnel is equipped with a 7.25- by 9.25-ft slide gate and terminates in a stilling basin in the river channel. A 1:17.53 scale model was used to develop the hydraulic design of the auxiliary outlet works including: the drop inlet and vertical bend from the existing canal outlet works tunnel, and the transition in the tunnel downstream from the gate chamber. Details of the model testing and recommended modifications to the preliminary design prompted by the testing are presented.

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REC-OCE-70-44
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DESCRIPTORS–/ *outlet works/ *hydraulic models/ slide gates/ irrigation systems/ *model tests/ tunnels/ *vents/ velocity/ vortices/ canals/ air/ calibrations/ bends/ pressure/ pressure tunnels/ operations/ transitions (structures)/ hydraulic design

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