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HYDRAULIC MODEL STUDIES — RIDGWAY DAM OUTLET WORKS

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16. ABSTRACT

Hydraulic model studies, on a 1:12 scale model of Ridgway Dam outlet works, were conducted to evaluate flow conditions in the multilevel inclined outlet conduit. The model investigations centered on identifying areas of potential cavitation damage at the intersections of the high-level and midlevel tees with the inclined conduit and the wye branch-mitered bend intersection for the low-level intake. Determination of vortex potential over the intakes and a discharge rating for the intakes operating as overflow weirs were also investigated. The studies revealed that the high-level intake would experience subatmospheric pressures capable of producing cavitation damage if operated alone at 100 percent open below reservoir elevation 6871. The midlevel intake tee and low-level wye branch would not require operating restrictions to prevent cavitation damage. When the three intakes operate simultaneously, no subatmospheric pressure zones occur. Operating criteria to prevent vortex formations over the intakes are presented. A discharge curve for the intakes operating under weir flow is also included in the study.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. *DESCRIPTORS*--/ hydraulic models/ cavitation/ outlet works/ vortices/ wye branch/ high velocity flow/ tees/ mitered bends

b. *IDENTIFIERS*--/ Ridgway Dam, Dallas Creek Project, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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K.W. Frizzell, Hydraulic Engineer, K.A. Sayer, Civil Engineer, J.R. Fitzwater, civil engineering technician, and T.W. Hoefler, engineering aid, assisted in this study.

CONTENTS

TABLE

FIGURES

PURPOSE AND APPLICATION

This report summarizes the results of the hydraulic model study of the inclined selective level intake structure for the Ridgway Dam outlet works. The model study was conducted to determine if subatmospheric pressures capable of producing cavitation damage would occur in the intake structure.

The results apply to the Ridgway Dam structure. However, flow conditions at the multilevel tee intersections and in the 170° mitered bend at the base of the inclined intake structure may be applicable to similar structures.

INTRODUCTION

Ridgway Dam is on the Uncompahgre River, approximately 20 miles south of Montrose, Colorado (fig. 1). The reservoir will have a capacity of 80,000 acre-feet increasing usable water supplies for irrigation, municipal, and industrial uses in Montrose, Olathe, Delta, and surrounding rural communities in west-central Colorado.

Ridgway Dam will be a rolled-earth fill structure with a height of 227 feet above streambed. The dam crest, at elevation 6886, will be 2,430 feet long and 30 feet wide. An uncontrolled concrete morning glory inlet serves as the spillway. The 42-foot-diameter spillway crest reduces to a 16.5-foot tunnel in the right abutment. A stilling basin will dissipate the 8,660-ft^3/s design discharge for the spillway.

To provide suitable temperatures for the downstream fishery, several outlet structures were considered for the dam — a high- and low-level outlet, a three-level outlet, and a single low-level outlet. This report covers the model investigation for the three-level inclined outlet structure shown on figure 2.

Seismic analysis of the area indicated the vulnerability of a vertical intake tower and resulted in the selection of an inclined tower design placed on the upstream slope of the embankment. Due to the uniqueness of the design and the potential for subatmospheric pressures in the inclined conduit, a 1:12 scale model of the outlet works was constructed and tested in the Bureau's hydraulic laboratory.

CONCLUSIONS

1. When the three intakes were operated simultaneously to deliver the design discharge of 1,380 ft^3/s, no localized subatmospheric zones occurred in the Ridgway inclined intake structure. This is due to the high ambient pressure at the tees and wye branch caused by the head loss through the 770 feet of 64-inch-diameter steel pipe downstream from the gate chamber (fig. 3).

2. For the high-level intake, local pressures in the tee become subatmospheric when the intake operates alone and 100 percent open at or below reservoir elevation 6871 (Q = 1,190 ft^3/s). The pressure drops to approximately 20 feet subatmospheric at reservoir elevation 6839 (Q = 1,105 ft^3/s). This is due to high velocity flow in the tee when the high-level intake operates alone.

3. For the midlevel intake, local pressures in the tee become subatmospheric when the intake operates alone and 100 percent open at or below reservoir elevation 6807 (Q = 1,022 ft^3/s). The pressure drops to approximately 4.5 feet subatmospheric at reservoir elevation 6800 (Q = 1,000 ft^3/s). The midlevel intake could operate in this range without experiencing damage to the tee.

4. Under all operating conditions, local pressures at the low-level intake are well above atmospheric. The lowest measured pressure was approximately 30 feet.

5. Intake vortex formation is a function of intake discharge and submergence. The high-level intake required approximately 34 feet of submergence to suppress vortex formation for maximum discharge of 1,120 ft^3/s at 100 percent gate opening. The low-level intake required approximately 25 feet of submergence to suppress vortex formation at the maximum discharge of 900 ft^3/s at 100 percent gate opening. The trashrack structure was not modeled, and it is not known to what degree it would have suppressed vortex formation.

THE MODEL

The 1:12 scale model represented a 70-foot-wide, 430-foot-long section of the upstream slope of the Ridgway dam embankment and reservoir, figure 3. The three bellmouth intakes, rectangular elbows, 5- by 6-foot high-pressure gates, and the transition sections were made of sheet metal. The 6.5-foot-diameter tees, 6.5-foot inclined conduit, and 170° mitered elbow were made of plastic. The model also included the 6.5- to 9.0-foot-diameter transition immediately downstream of the mitered elbow and approximately 320 feet of the 9-foot-diameter outlet conduit. A gate valve was placed at the downstream end of the model conduit to control releases and simulate head losses through the remainder of the prototype outlet works system. Seventy-three piezometers were installed in areas where subatmospheric pressures were likely to occur. The location and elevation of the piezometers are summarized on figure 4 and table 1. Although the intake trashrack structures were not simulated, the sheet metal bellmouths were placed at the specified crest elevations on the 3:1 sloping floor of the model, figure 5. Water was supplied to the model through the permanent laboratory supply system and was measured by one of a bank of venturi meters installed in the laboratory.

MODEL INVESTIGATIONS

The model investigations emphasized three areas: identifying areas of potential cavitation damage, determination of vortex potential over the intakes, and discharge rating for the intake structure. As perceived in the multilevel inclined intake structure concept, the intakes could be operated separately or in various combinations to achieve the desired discharge and temperature. Figures 6 and 7 illustrate the calculated reservoir elevation-discharge relationships for the intakes operated separately and in combination. It was anticipated that a maximum discharge of 1,380 ft^3/s could be released through the outlet structure if the three inlets discharge simultaneously at a reservoir elevation of 6879.9. For individual intake operation, the respective maximum discharges would be 1,220, 1,235, and 1,368 ft^3/s for the high-level, midlevel, and low-level intakes with a reservoir elevation of 6879.9.

Areas of Potential Cavitation Damage

In hydraulic structures, cavitation is associated with high velocity flow separation from surfaces where water vapor cavities form in the flowing water. The cavities form when water vaporizes in zones of low pressure where the vapor pressure-temperature limits of water are exceeded. As these cavities move out of the low-pressure zones, they immediately implode producing

Table 1. — *Piezometer locations and elevations*

(see fig. 4)

	Description	Location	Elevation (ft)
High level	First row	U11 and U15	6786.94
		U12 and U14	6787.60
		U13	6787.84
	Second row	U21 and U25	6786.39
		U22 and U24	6787.05
		U23	6787.29
	Crotch	U1 and U5	6787.34
		U2 and U4	6787.78
		U3	6787.94
Midlevel	First row	M11 and M15	6748.78
		M12 and M14	6749.00
		M13	6749.08
	Second row	M21 and M25	6747.66
		M22 and M24	6748.32
		M23	6748.56
	Third row	M31 and M35	6747.11
		M32 and M34	6747.77
		M33	6748.01
	Crotch	MC1 and MC5	6748.06
		MC2 and MC4	6748.50
		MC3	6748.66
Low level	First row	L11 and L15	6695.46
		L12 and L14	6694.85
		L13	6694.63
	Second row	L21 and L25	6692.63
		L22 and L24	6692.20
		L23	6692.05

Table 1. — *Piezometer locations and elevations — Continued*

(see fig. 4)

Description	Location	Elevation (ft)
Third row	L31 and L35	6686.77
	L32 and L34	6686.72
	L33	6686.70
Fourth row	L41 and L45	6684.59
	L42 and L44	6684.81
	L43	6684.89
Fifth row	L51 and L55	6683.05
	L52 and L54	6683.27
	L53	6683.35
Crotch	LC1 and LC5	6693.34
	LC2 and LC4	6695.17
	LC3	6695.82
Nine-inch downstream pipe piezometer — 2 sides 6672.70		
top 6677.20		

extremely high-pressure fluctuations. If cavitation occurs close to a flow surface, the pressure fluctuations may be strong enough to damage the surface. Piezometers were therefore installed in the areas where low pressure resulting from flow separation was expected to occur. Water manometer and pressure cell data were recorded. In general, the water manometer measurements were similar to the average instantaneous pressure measurements. For purposes of this study, water manometer measurements representing local pressures 5 feet subatmospheric or lower will be considered in the cavitation damage zone. Pressure — in this report — refers to water manometer data unless otherwise defined.

The three areas where potential cavitation could occur are the intersection tees for the high-level and midlevel intakes and the wye branch-mitered bend intersection for the low-level intake. As can be seen on figure 8, the high-level and midlevel intakes have a very sharp 90° entrance to the inclined conduit. The wye branch and mitered bend intersection at the low-level intake also have several potential low-pressure zones.

Figure 9 shows the hydraulic gradeline for the inclined outlet structure at the design discharge of 1,380 ft^3/s through all three outlets. The invert elevation of the inclined conduit, mitered bend, and downstream outlet conduit from the upper tee through the downstream control house are also shown. With the three gates 100 percent open, approximately 295 ft^3/s will pass through the high-level intake, 485 ft^3/s through the midlevel intake, and 600 ft^3/s through the low-level intake. The vertical dashed lines indicate the lowest water manometer pressures found in each of the three zones. As a result of the high ambient pressure created by the downstream frictional losses in the 64-inch-diameter outlet conduit, these localized minimum pressures are well above atmospheric pressure. Although a similar test was not conducted at reservoir elevation 6839 (minimum level for use of the high-level intake), it is evident from figure 9 that the hydraulic gradeline would be well above the elevation of the inclined conduit.

High-Level Intake

Figure 10 illustrates the hydraulic gradelines and water manometer pressures measured for discharges (through the high-level intake only) of 1,213 ft^3/s (test 4) and 1,120 ft^3/s (test 7A). These discharges are for respective reservoir water surface elevations of 6879.9 feet (maximum) and 6839 feet (minimum to prevent a vortex). When the upper gate is fully open, the most critical area is in the vicinity of the high-level intake tee, as shown on the figure. Because the slope of the inclined conduit is greater than the slope of the hydraulic gradeline, the ambient pressure increases along the incline conduit from the high-level intake to the mitered elbow. Thus, the high-level intake has a lower ambient pressure and is more subject to subatmospheric pressures than the other two intakes. For a discharge of 1,213 ft^3/s at maximum reservoir elevation, the minimum pressure was approximately 6.0 feet (6793-6787). For a discharge of 1,120 ft^3/s near the minimum reservoir elevation when operating the high-level intake (El. 6839), the minimum measured pressure was approximately 24.0 feet subatmospheric (6763-6787).

Figure 11 graphically shows the local pressure drop at the high-level tee for a 100 percent gate opening. Tests No. 4, 7A, and 9 are plotted on the graph. The model tests were set fairly close to the reservoir elevation expected for various discharges.

As the reservoir elevation decreases from 6879.9 to 6839.0, the flow rate also decreases. However, the decrease in reservoir elevation results in a decrease in the ambient pressure (indicated by the hydraulic gradeline) which produces local zones of subatmospheric pressure in the crown of the tee once the local pressure falls below 6787.0, the average elevation of the high-level tee.

The coefficient, Cp, defines the local pressure drop in the tee and is used to draw the lower curve on figure 11.

$$Cp = \frac{h_1 - h_0}{V^2/2g}$$

where h_1 = local pressure (ft) in tee (minimum pressure)

h_0 = pressure (ft) along the hydraulic gradeline extension

V = velocity (ft/s) in the 78-inch inclined conduit

The pressure drop coefficient, Cp, for the high-level tee is approximately -1.81. The pressure drop coefficient was derived from measured data collected on the model. The zone of subatmospheric pressure shown on figure 11 identifies the reservoir elevation range where 100 percent gate opening could result in cavitation damage. This zone extends from reservoir elevation 6871 (Q = 1,190 ft^3/s) to 6839 (Q = 1,105 ft^3/s) and the cavitation damage potential becomes more severe as the reservoir elevation drops below 6866 for the full gate opening. As stated previously, the cavitation damage zone is defined as the zone where the water manometer pressure is 5 feet subatmospheric or less.

Midlevel Intake

Figure 12 illustrates the hydraulic gradeline and local pressures measured for flow through the midlevel intake only, for discharges of Q = 1,177 ft^3/s (test 12) and Q = 906 ft^3/s (test 17A). These discharges are less than Q = 1,235 ft^3/s and 1,000 ft^3/s which represent respective reservoir elevations of 6879.9 (maximum) and 6800.0 (minimum) when the midlevel intake is fully open.

The inclined conduit above the midlevel tee is essentially a large piezometer when the high-level conduit is closed. The static water level in the inclined intake and air vent seeks the level of the hydraulic gradeline at the midlevel tee. From figure 12, it is evident that even the local pressures are well above atmospheric for Q = 1,177 ft^3/s, representative of a high reservoir level. The minimum pressure occurs at the midlevel tee, but is 52 feet (6800-6748). For the lower reservoir elevation of 6800 feet and discharge of Q = 906 ft^3/s, the minimum local pressure is 7 feet (6755-6748), considerably below 52 feet but still above atmospheric. Figure 13 illustrates the reservoir elevation, hydraulic gradeline, and local pressure drop for the midlevel tee for a 100 percent gate opening. Tests 11, 12, 13A, and 17A are plotted on figure 13. Comparing figures 13 and 11, it is evident that the potential for subatmospheric pressure is much greater for the high-level tee (fig. 11) than for the midlevel tee. The lower elevation of the midlevel tee (6748.0) ensures a higher local pressure distribution than at the high-level tee. For the maximum discharge of 1,235 ft^3/s at reservoir elevation 6879.9, the local pressure in the tee would be approximately 47 feet (6795-6748). For the minimum operational reservoir elevation at the midlevel intake (6800 feet) representing a discharge of 1,000 ft^3/s, the average minimum pressure would be approximately 4 feet subatmospheric (6744-6748).

The pressure drop coefficient, Cp, for the midlevel tee is approximately -1.63. The zone of subatmospheric pressures for the midlevel tee is quite small. The midlevel intake can operate in this range without experiencing damage to the tee.

Low-Level Intake

The hydraulic gradeline and measured local pressures for flow through the low-level intake only are shown on figure 14. For the maximum reservoir elevation of 6879.9 feet, the low-level intake can discharge up to 1,368 ft^3/s. The upper hydraulic gradeline on figure 14 represents the test data for test 21A at a discharge slightly higher (1,379 ft^3/s) than design. The lower curve represents test data for test 20 with a discharge of 953 ft^3/s at reservoir elevation 6750. The water level in the inclined conduit fluctuates around elevation 6734.

The hydraulic gradeline and local pressure drop are plotted on figure 15 as a function of reservoir elevation and corresponding discharge for 100 percent gate opening of the low-level intake. When the low-level intake is operating alone, the flow approach conditions at the wye branch are good and, as a result, the local pressure drop is minimal. In all cases, the local pressures are well above atmospheric with the minimum, test 20, approximately 30 feet (6725-6695). The pressure drop coefficient, Cp, for the low-level intake operating alone is approximately -0.3.

Piezometric Pressures in the Low-Level Wye

It is instructive to study the piezometric pressures at the miters in the low-level wye for flow in the inclined conduit with no flow through the low-level intake. Figure 16 illustrates these pressures in the first (22.5°) and third (45°) miters and along the pipe invert from piezometer rings No. 1 through 5 at the start of the elbow, figure 4. Although well above atmospheric, it is interesting that the lowest pressures for the low-level wye occur at piezometers L31 and L35 (third miter), 45° off the invert on both sides of the pipe centerline (fig. 4). The high pressure for the third miter was on the invert at L33. Miter No. 1 was opposite with the highest pressures 45° off the invert at L11 and L15. Piezometric pressures along the invert were lowest at L13 increasing to the highest values at L53. However, the lowest values are still at L31 and L35, 45° off the invert.

The pressure drop coefficient, Cp, for the low-level wye with no flow through the low-level intake is approximately -2.0. If the hydraulic gradeline through the wye was on the order of 25 feet instead of 125 feet and the flow velocity was 36 ft/s, the pressure drop in the area of piezometers L31, L35, and L13 would be 40 feet or an average pressure of 15 feet subatmospheric, capable of producing cavitation and the associated damage. This further illustrates the advantage of the high ambient pressure at the midlevel and low-level intakes.

Vortex Potential Over the Intake

As mentioned earlier, the intake trashrack structures and local geometry were not modeled. However, the intake bellmouths were located in the model as shown on figure 5. Figure 17 illustrates a typical intake design with the modeled portion darkened. It is important to recognize the difficulty in modeling a prototype vortex. Normally, the model discharge has to be increased disproportionately to create a vortex; therefore, a vortex may occur in the prototype although it does not occur in the model. Conversely, if a vortex occurs in a model, a similar one can be expected in the prototype under like geometric and flow conditions.

Vortices that occurred on the Ridgway model were associated with the transition zone where the intake flow regime changes from crest control to pipe control. Vortices were also associated with discharge. Vortex formation was more prevalent over the high-level intake (Q = 1,120 ft^3/s) than the low-level intake (Q = 900 ft^3/s) given the same degree of submergence (note discharge curves on fig. 6). Figure 18 illustrates the model vortex over the high-level intake with a submergence of 18 feet and a flow discharge of 1,130 ft^3/s.

The operating criteria for the three-level intake structure stated that a minimum submergence of 25 feet would be required for operation of the high-level and midlevel intakes. Results of the model study indicated that 34 feet of submergence would be required to prevent vortex formation at the high-level intake (flow discharge was approximately 1,120 ft^3/s). It is not known to what degree the trashrack structure could have controlled vortex formation.

At the low-level intake, 25 feet of submergence proved adequate to prevent vortex formation (flow discharge was approximately 900 ft^3/s).

Discharge Rating for Intake Structure

A series of tests was conducted on the midlevel intake to determine the discharge rating for the intakes operating as overflow weirs. Under normal operating criteria, the high-level and midlevel intakes would only operate under pipe control (minimum of 25- to 35-foot submergence) to prevent air entrainment in the flow and/or vortex formation at the intake. The low-level intake, however, would operate down to the sill elevation of 6720.

Figure 19 illustrates the discharge characteristics of the intakes up through a discharge of 868 ft^3/s. Once the intake discharge exceeds 700 ft^3/s, the flow regime enters a transition zone between crest control and pipe control. At these low discharges, the trashrack structure will not affect the head-discharge relationship.

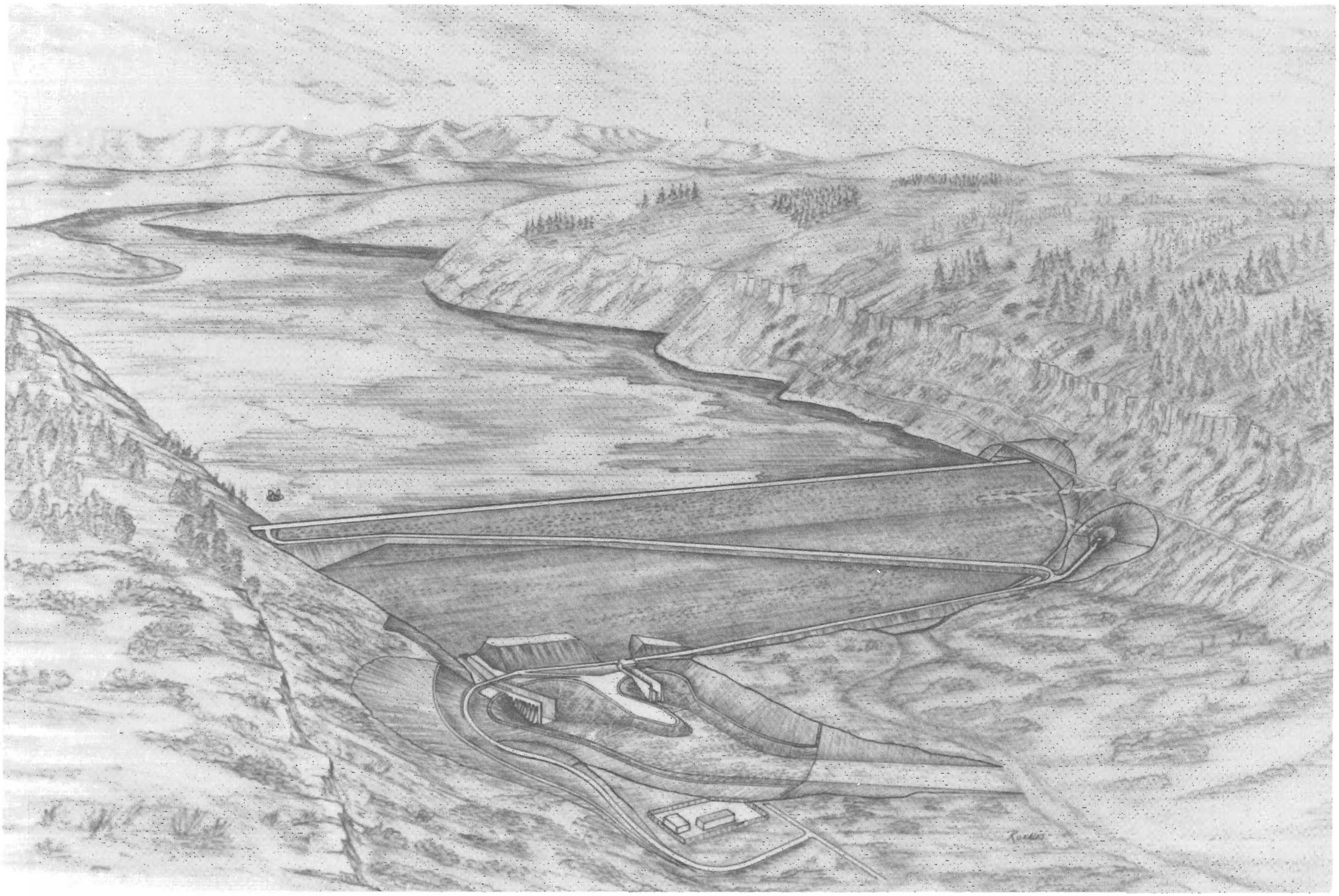

Figure 1. — Artist's conception of Ridgway Dam. P801-D-80762

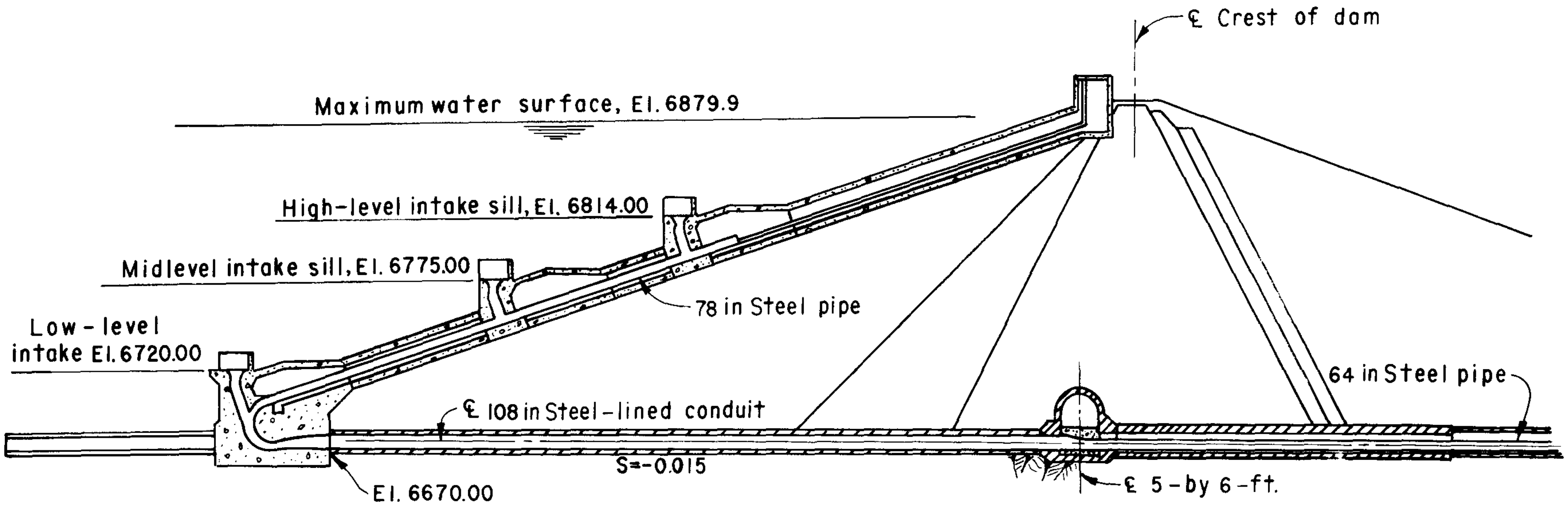

Figure 2. — Ridgway Dam inclined multilevel outlet structure.

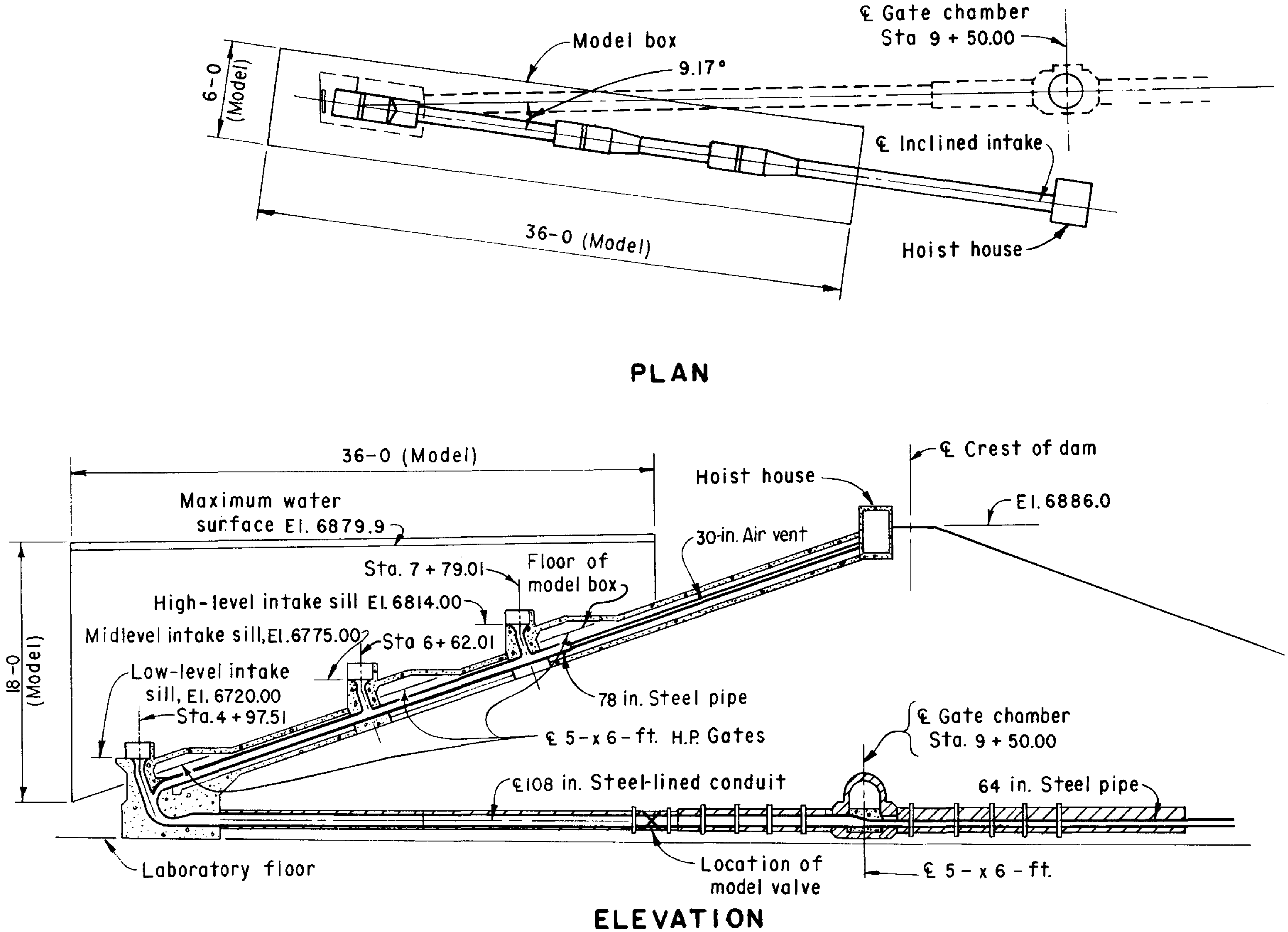

Figure 3. — Extent of Ridgway outlet works model.

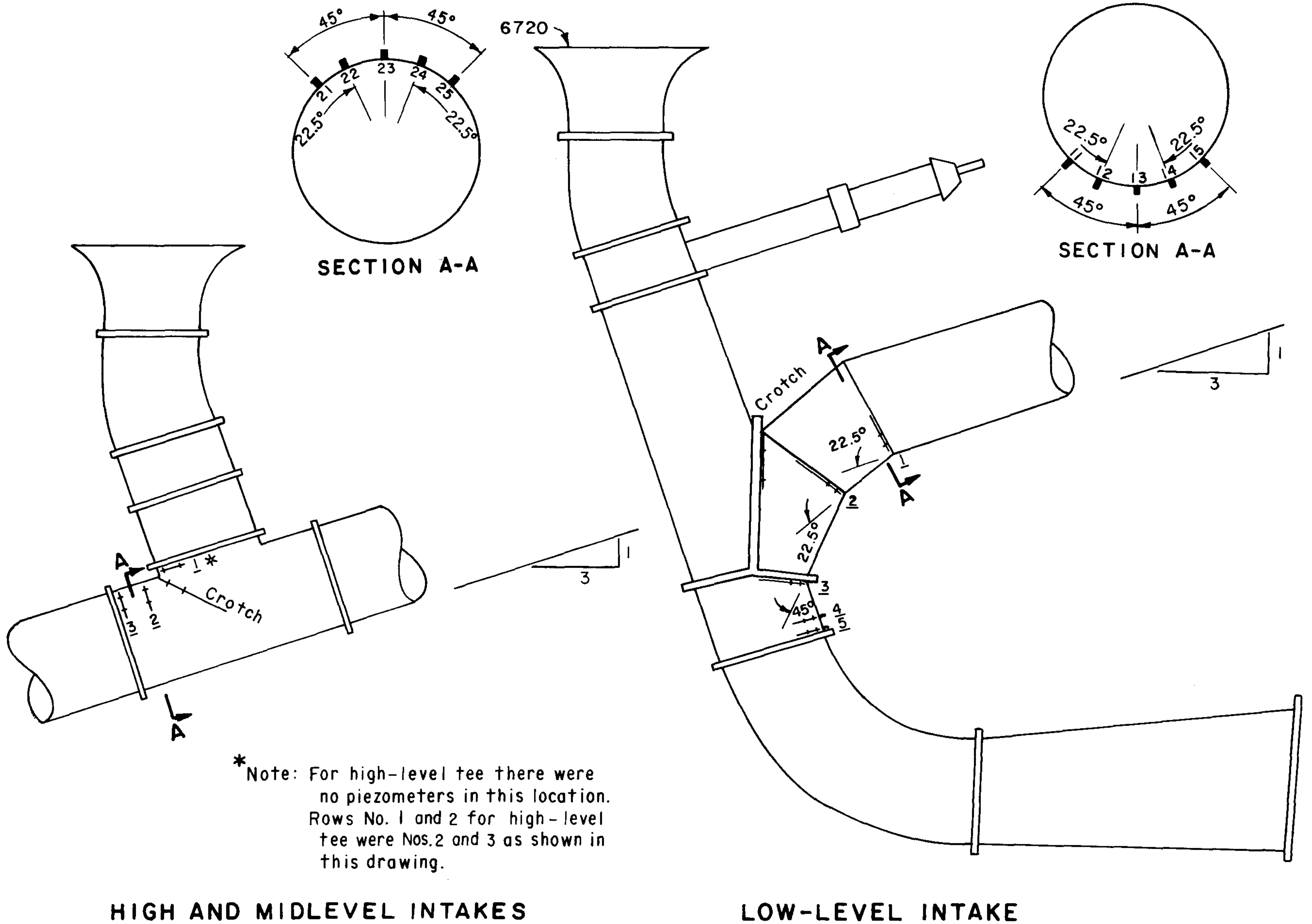

Figure 4. — Piezometer locations for Ridgway multilevel outlet conduit (see table 1).

Figure 5. — View of high-level intake on Ridgway model. P801-D-80763

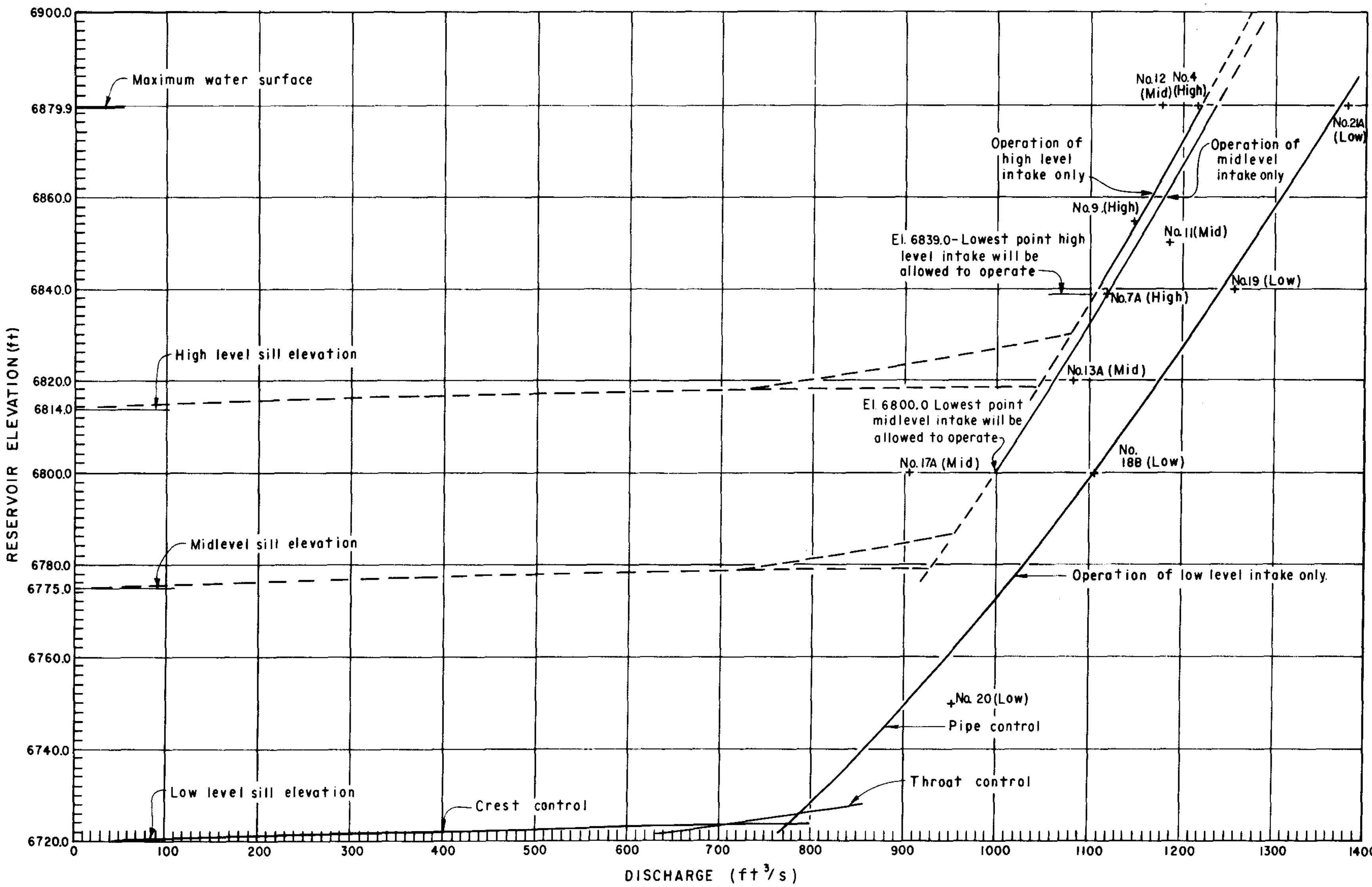

Figure 6. — Ridgway outlet works discharge curve — separate operation.

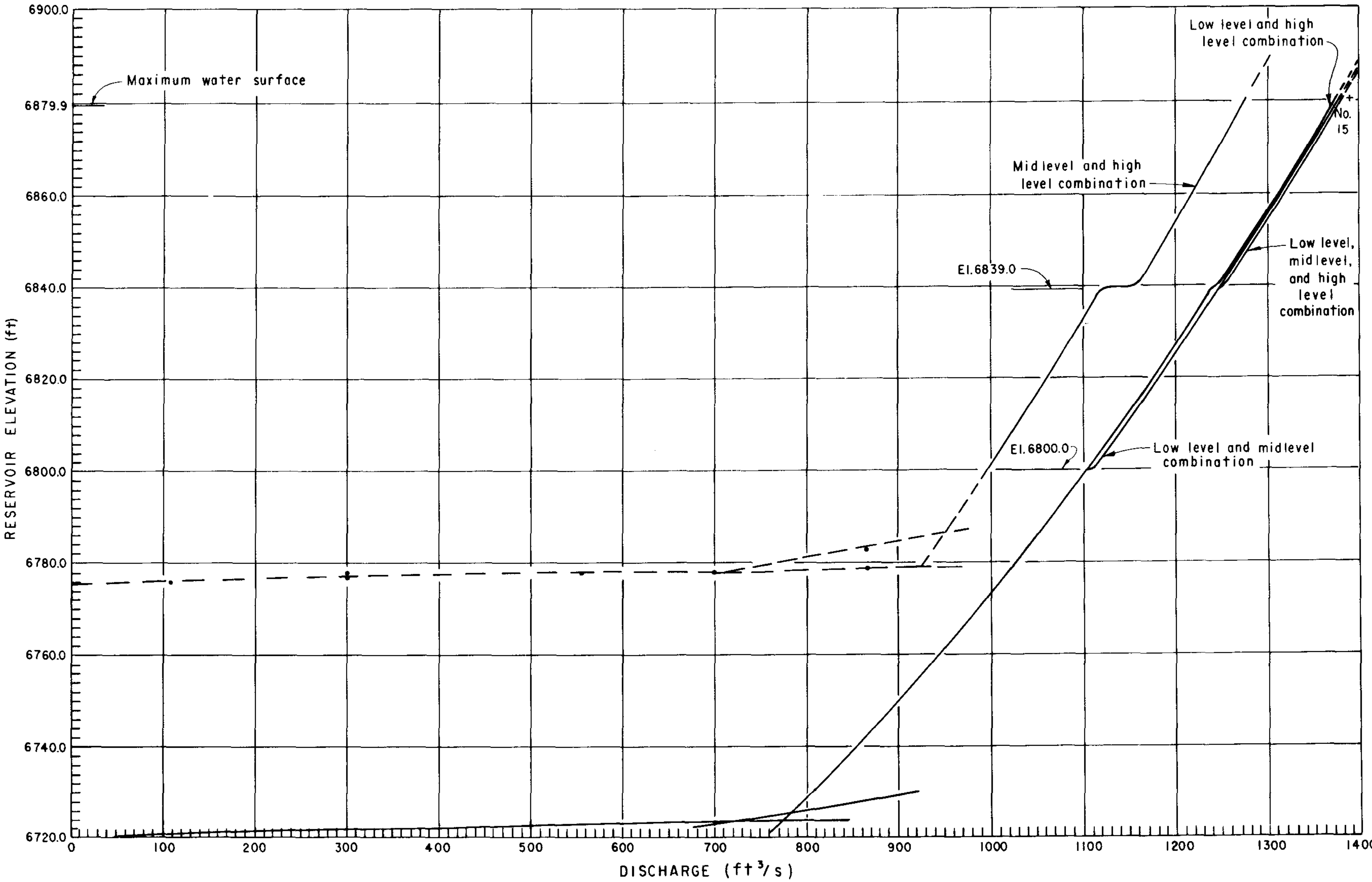

Figure 7. — Ridgway outlet works discharge curve — combined operation.

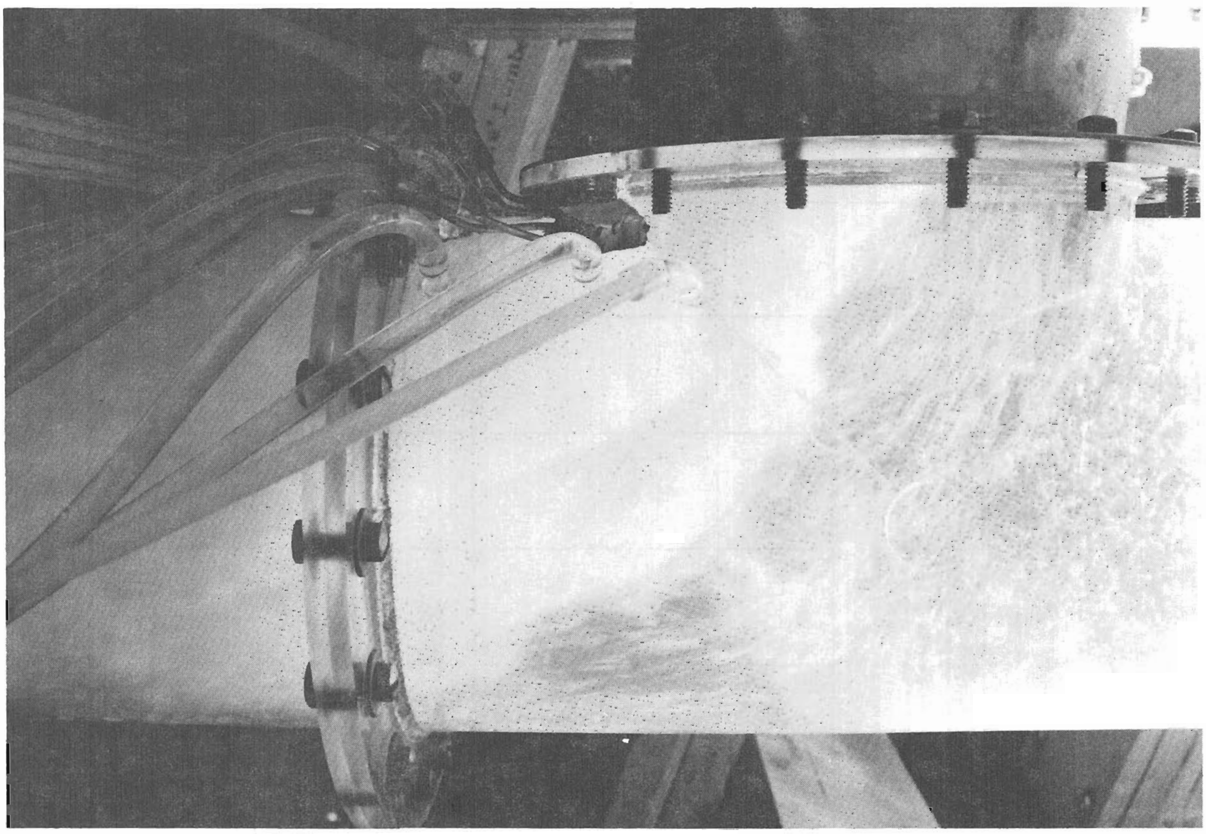

Figure 8. — View of high-level tee with vortex formation over intake structure. P801-D-80764

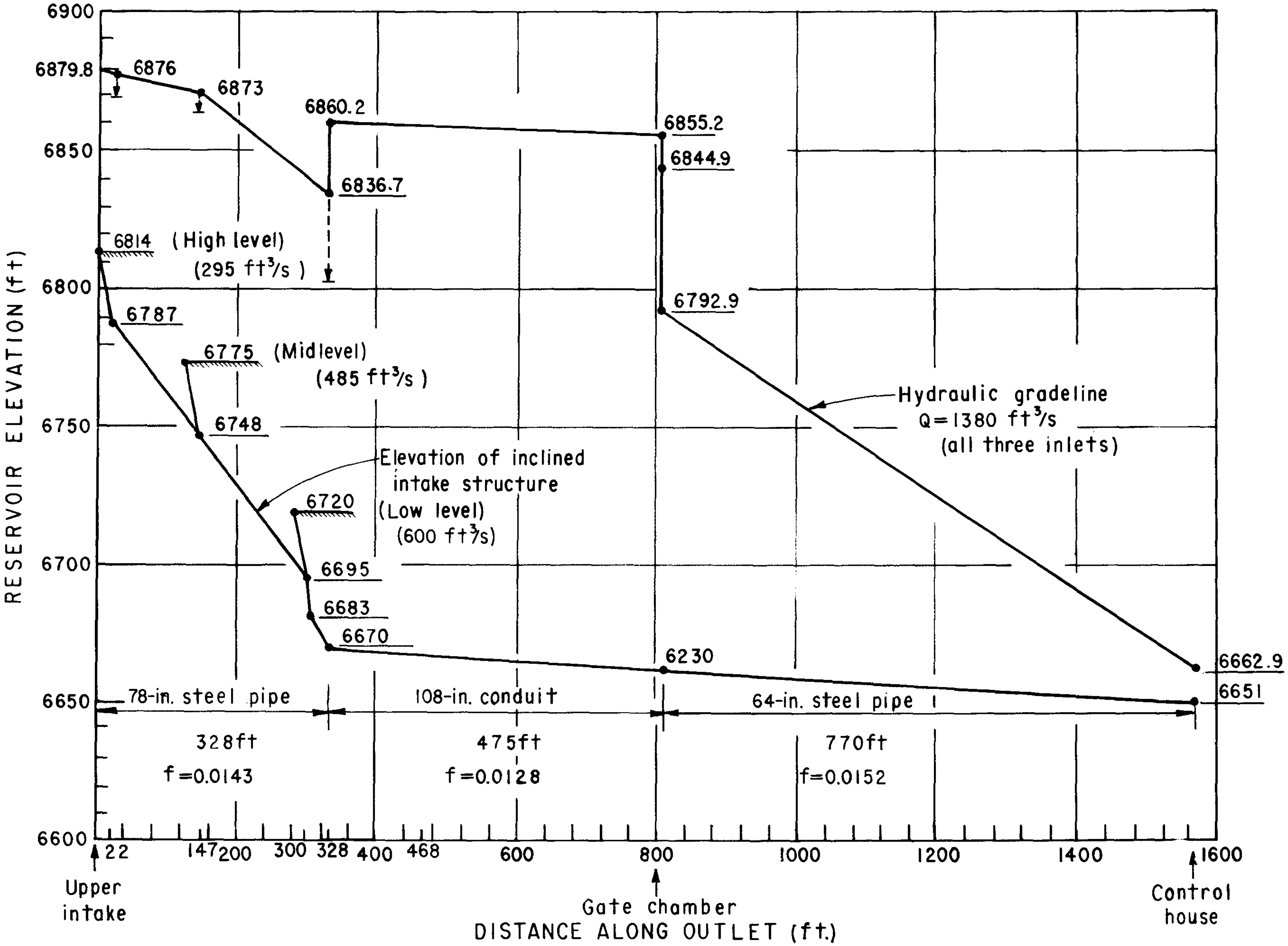

Figure 9. — Hydraulic gradeline along inclined outlet structure — release of 1,380 ft³/s.

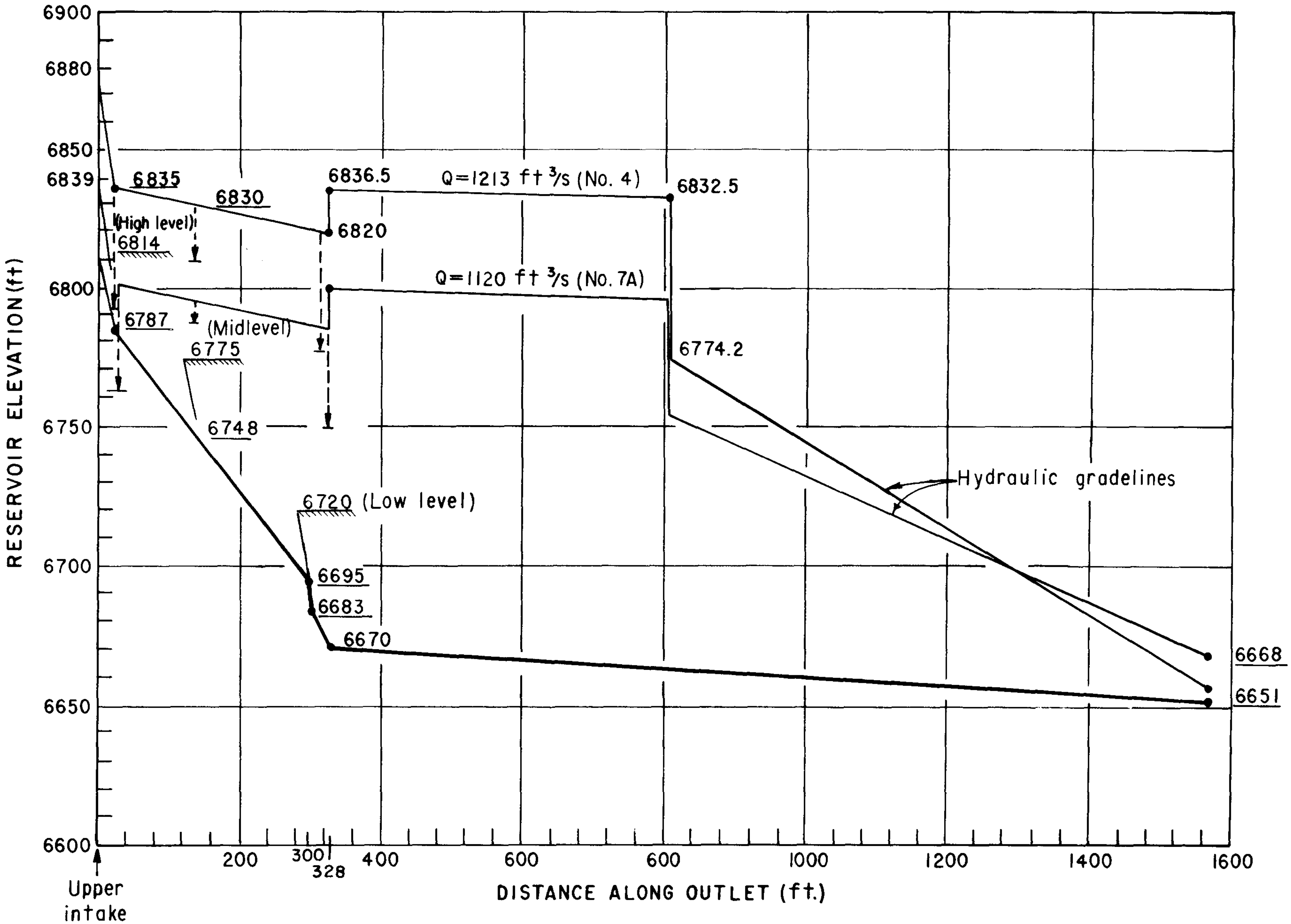

Figure 10. — Hydraulic gradelines along inclined outlet structure — high-level intake releases.

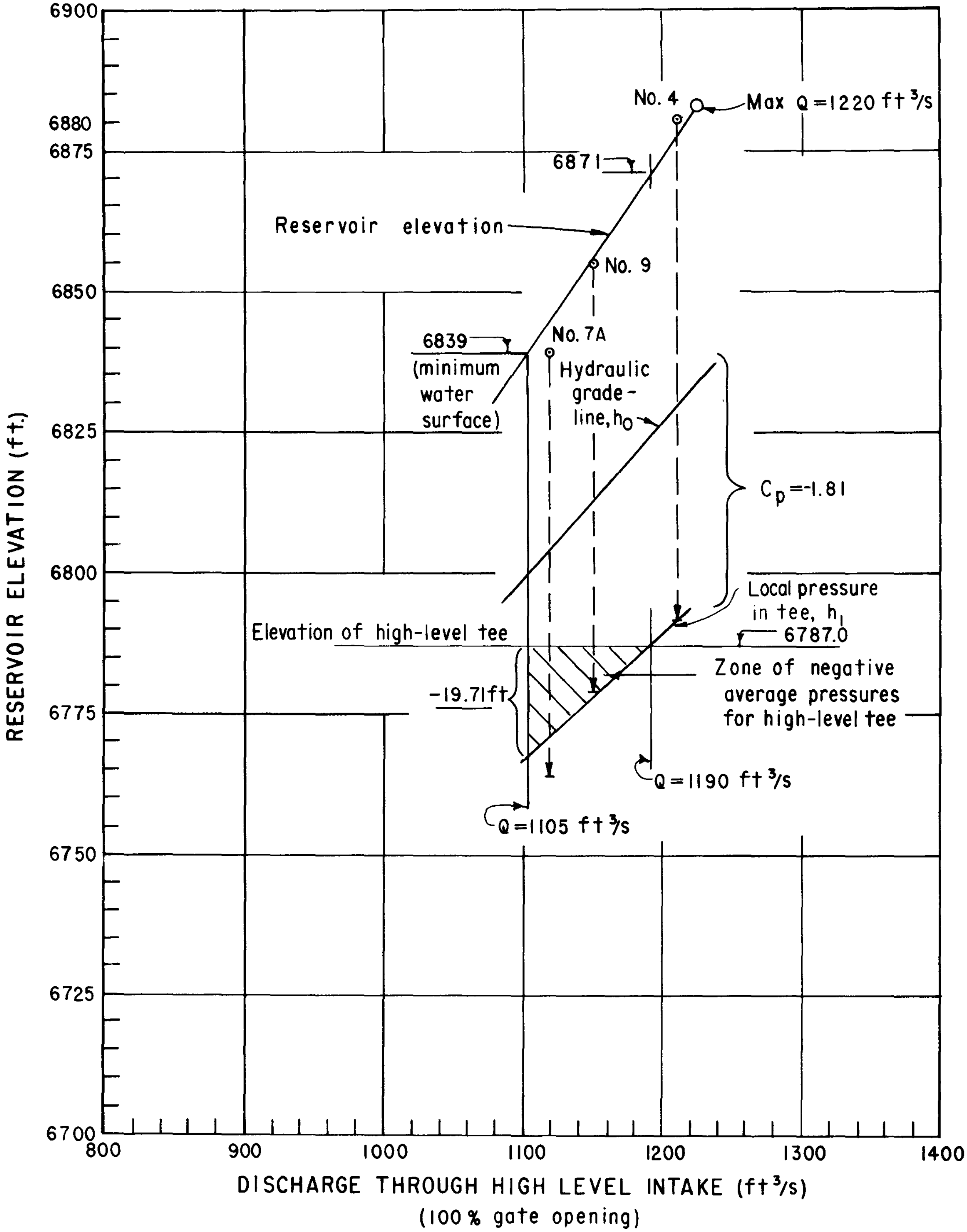

Figure 11. — Local pressure drop for high-level tee.

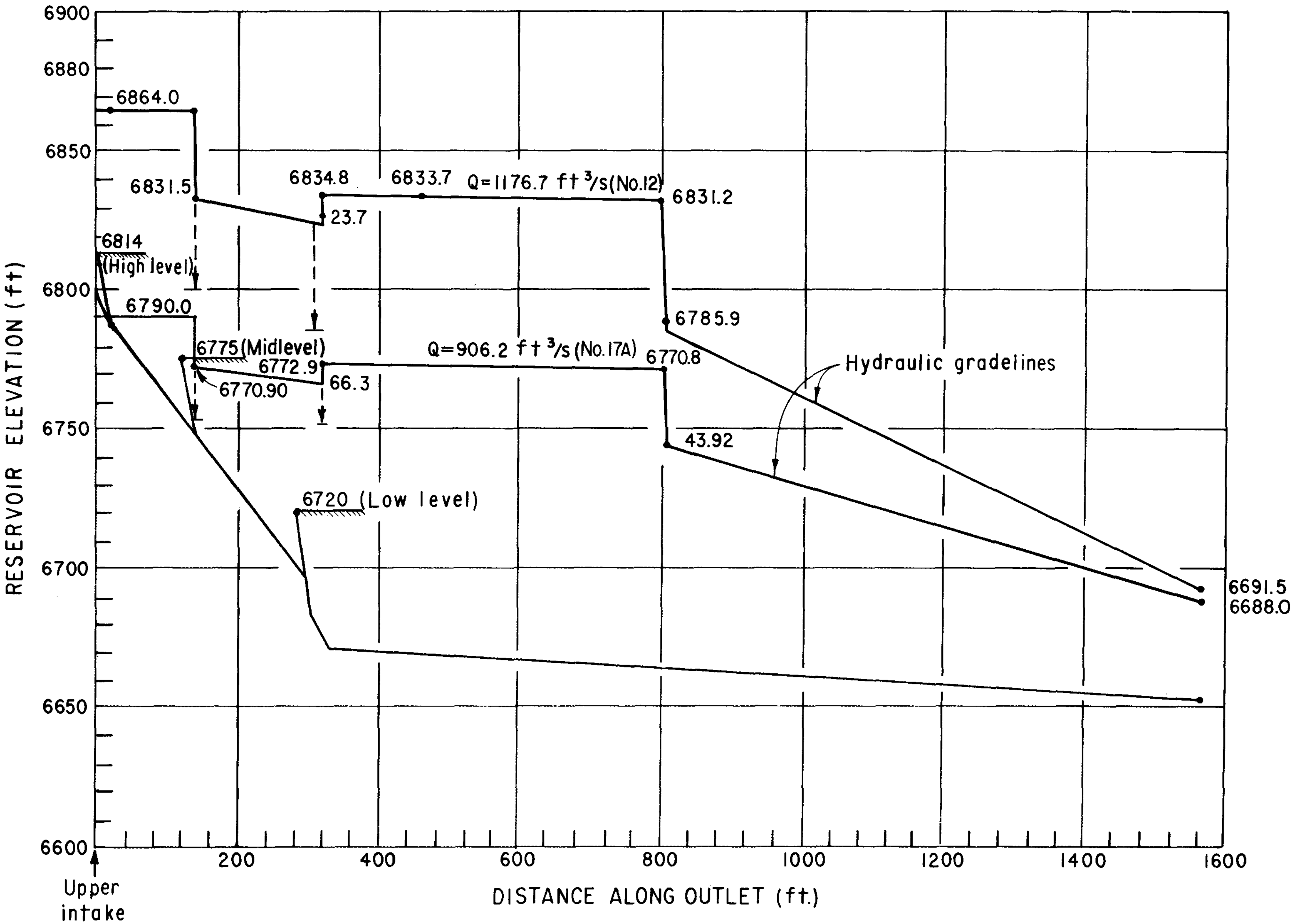

Figure 12. — Hydraulic gradelines along inclined structure — midlevel intake releases.

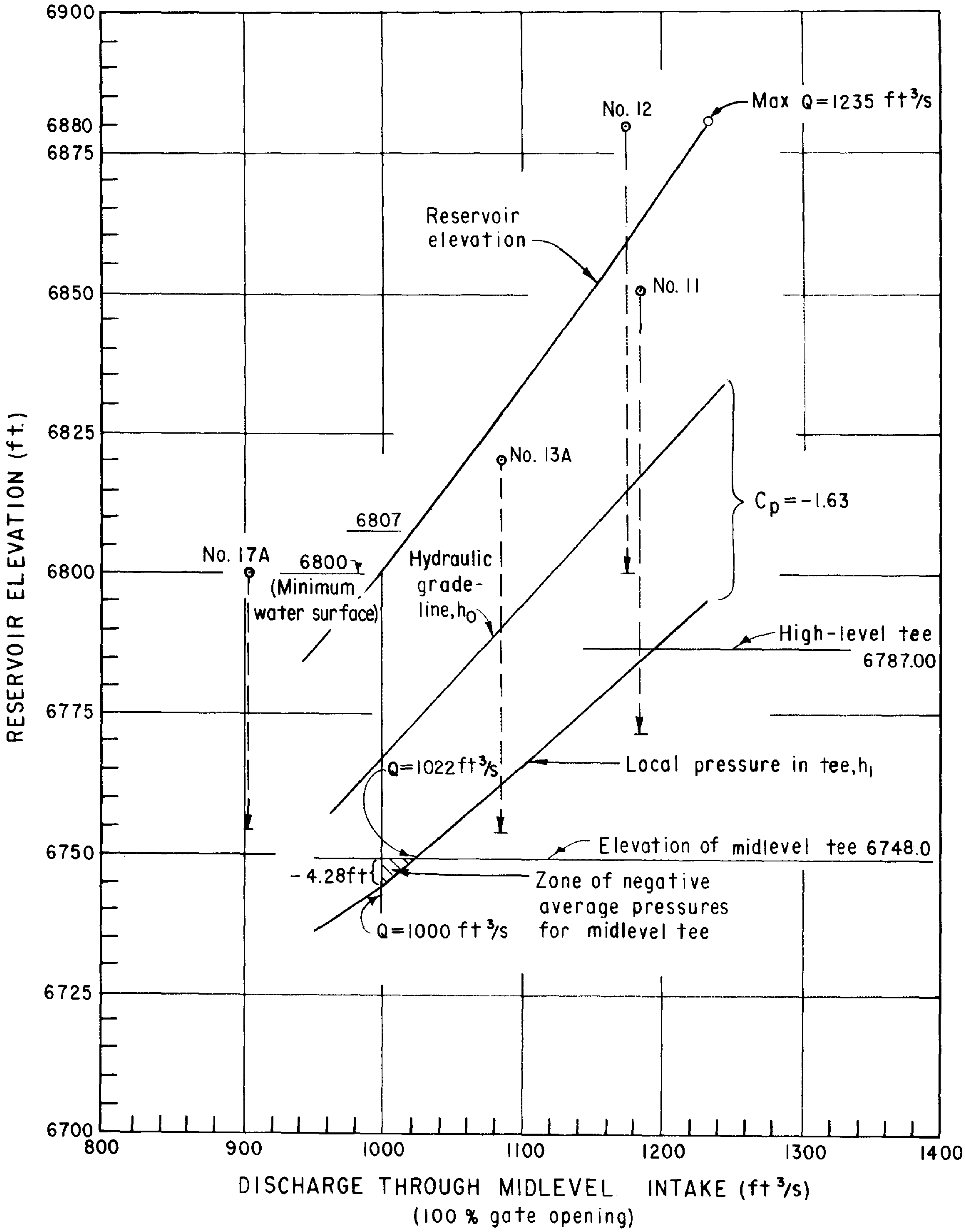

Figure 13. — Local pressure drop for midlevel tee.

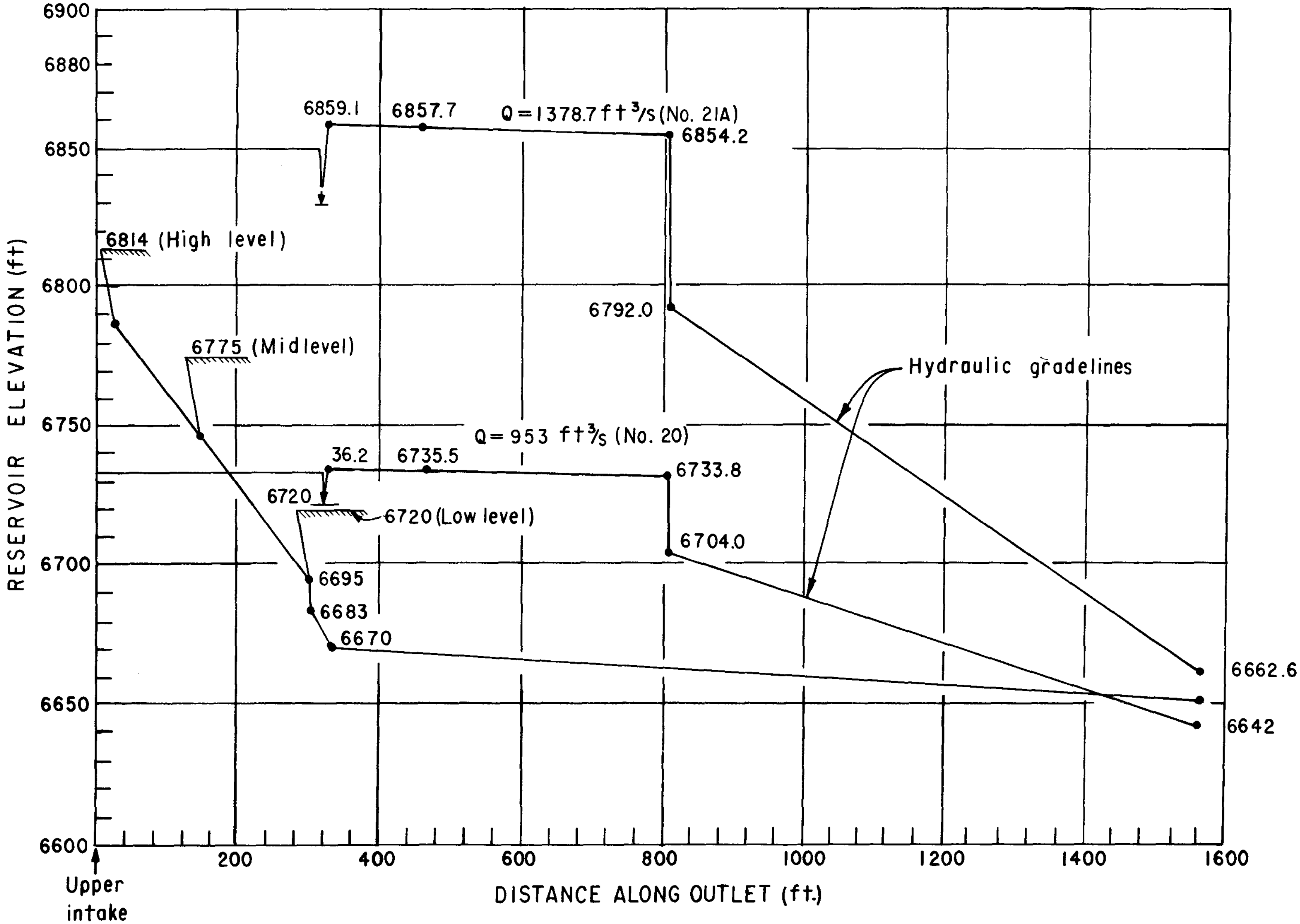

Figure 14. — Hydraulic gradelines along inclined outlet structure — low-level intake releases.

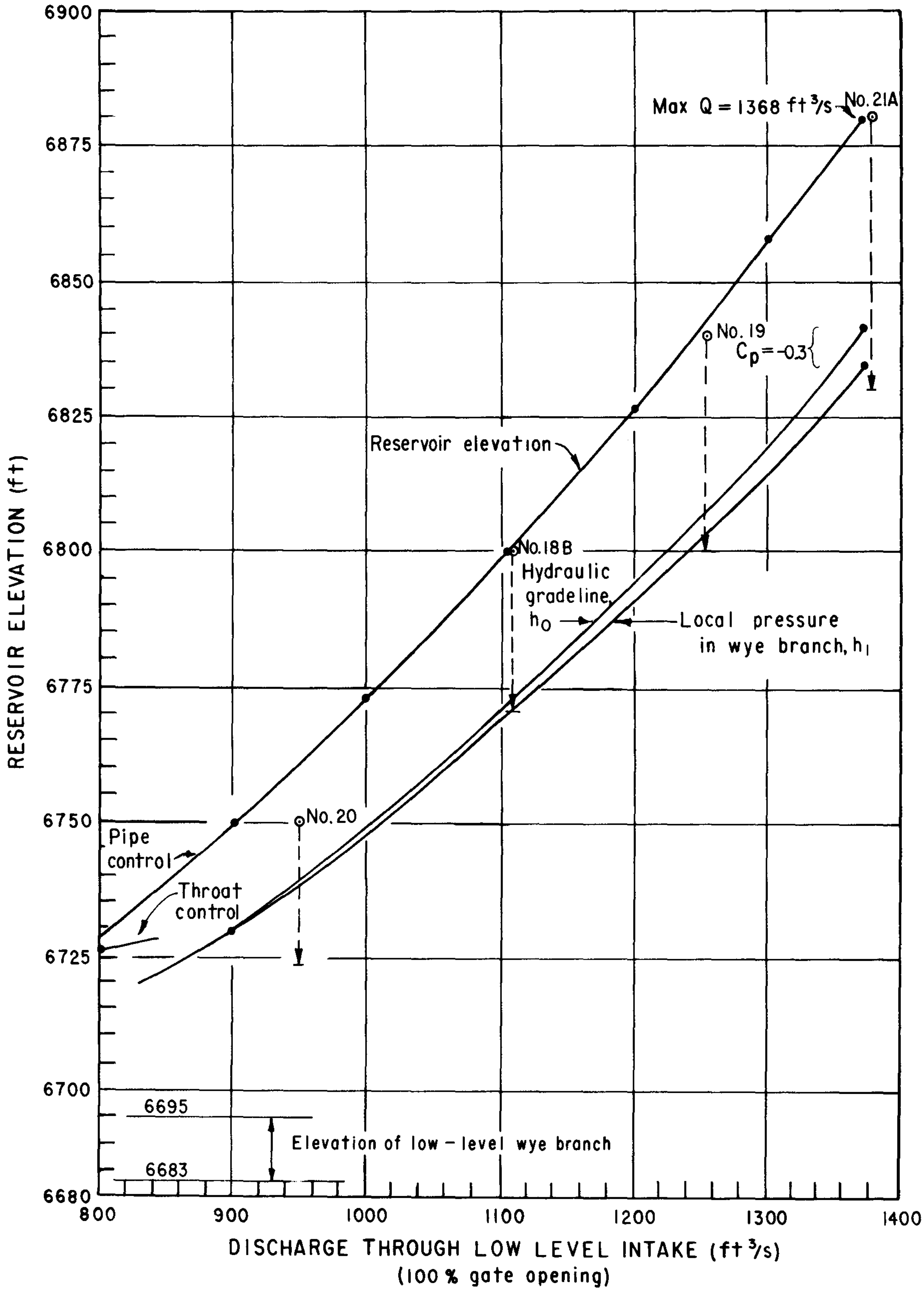

Figure 15. — Local pressure drop for low-level intake.

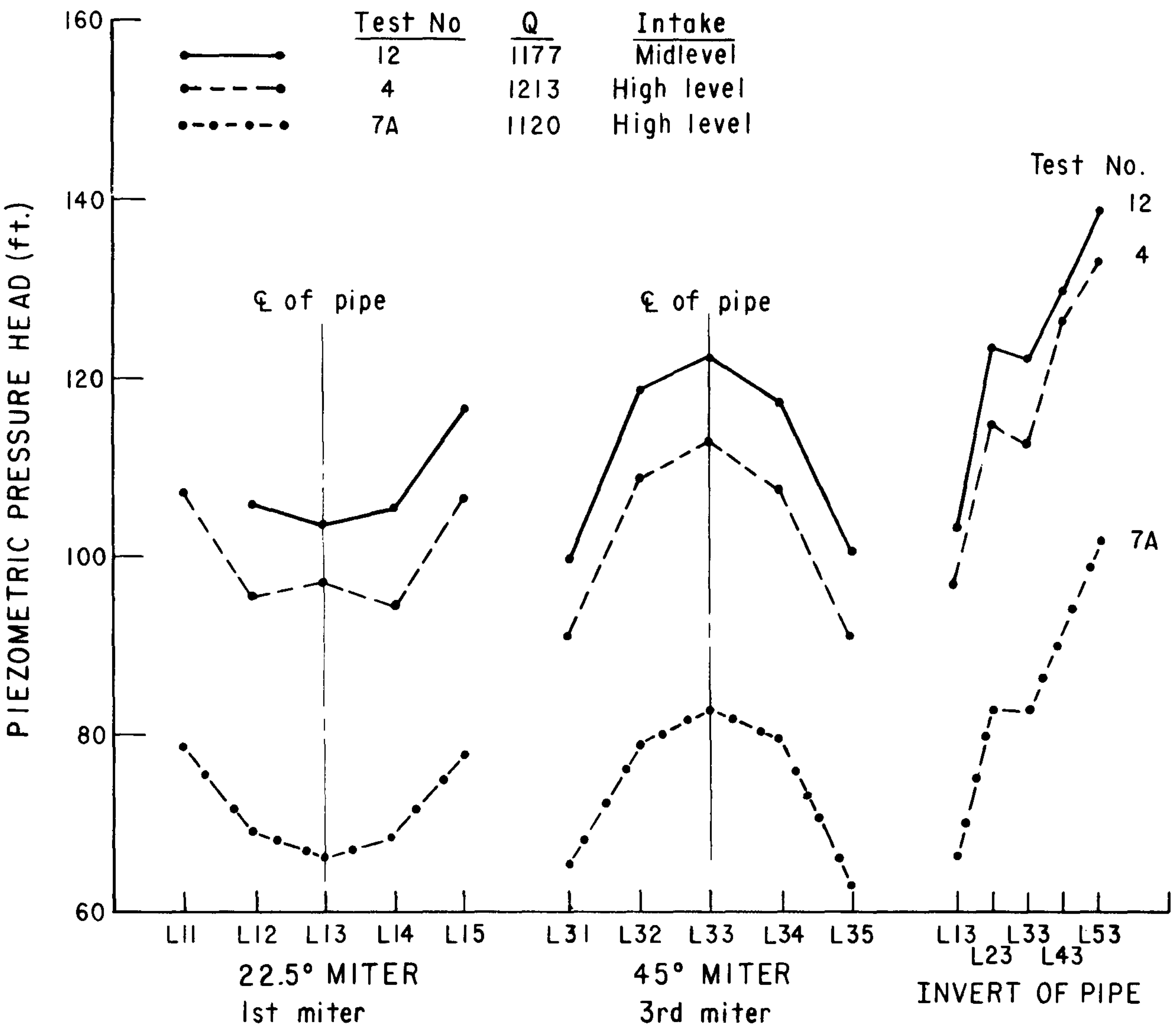

Figure 16. — Piezometric pressures in low-level wye.

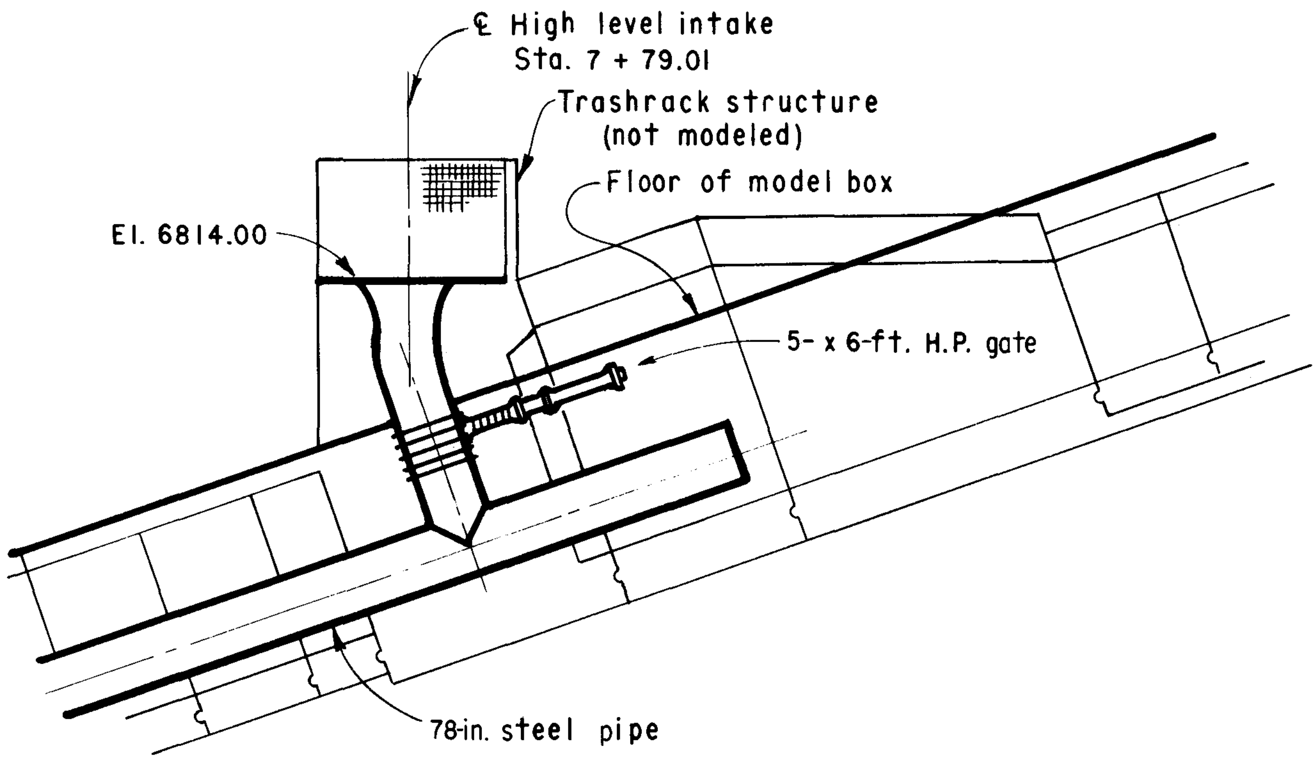

Figure 17. — Ridgway multilevel outlet conduit — high-level intake.

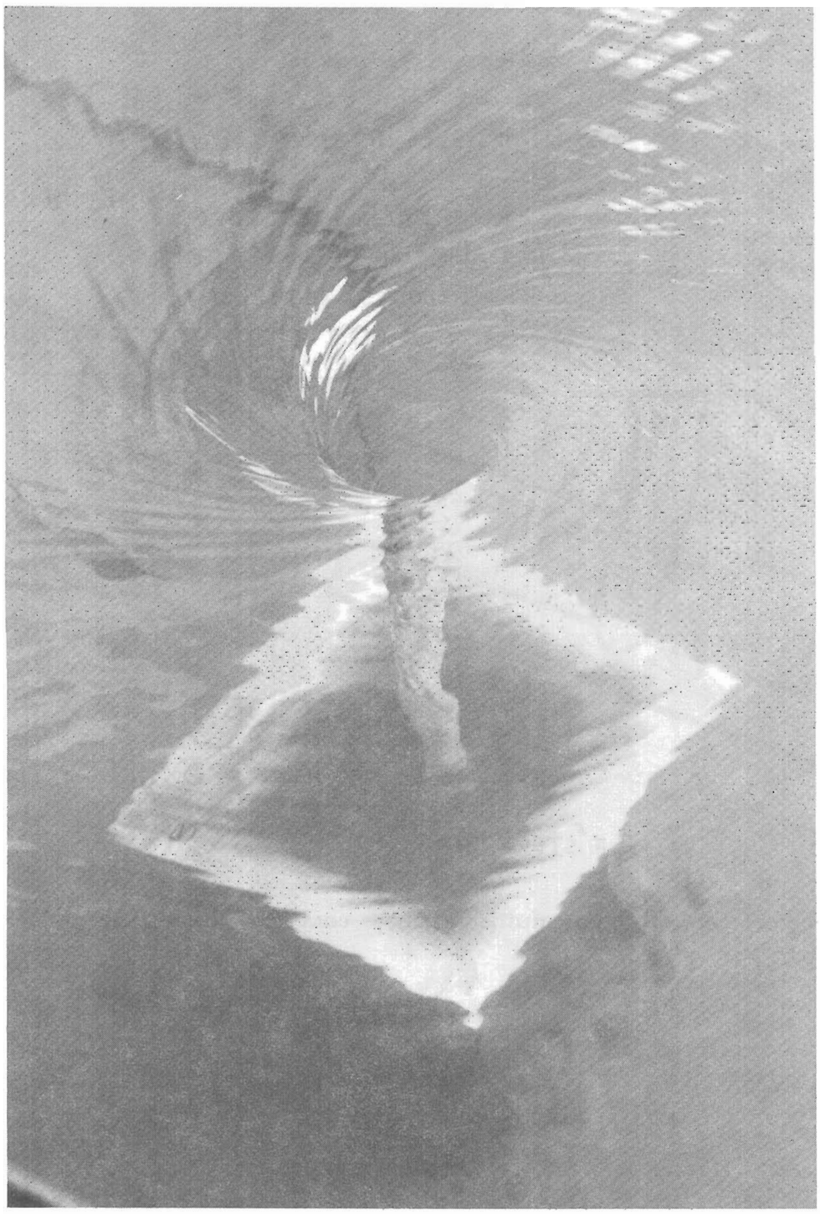

Figure 18. — Model vortex over high level intake Q = 1,130 ft^3/s, submergence is 18 feet. P801-D-80765

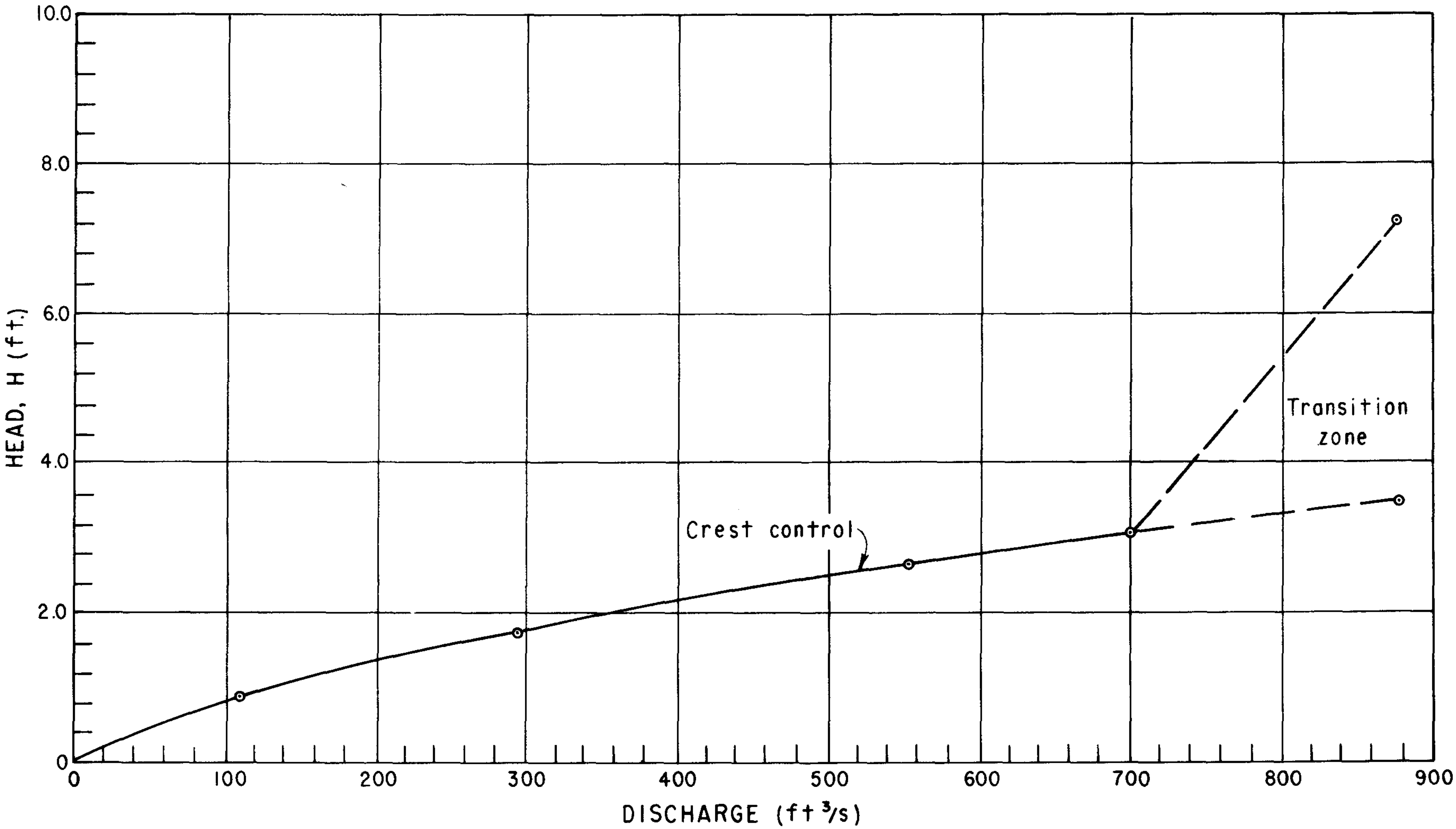

Figure 19. — Calibration for intakes at low head.

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.