GR-82-15

LAKE SHERBURNE DAM MODEL STUDY

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16. ABSTRACT

Hydraulic model studies, on a 1:15 scale model of Lake Sherburne Dam, were conducted to evaluate flow conditions in the spillway and outlet works tower structure during the passage of the IDF (inflow design flood). Model tests on the existing structure revealed two areas where pressures were consistently negative, and a third area where intermittent roller vortices occurred during submerged spillway flows. A crown flow constriction was placed in each tunnel, downstream of the low-pressure areas, in the hydraulic model. The constrictions were designed in conjunction with downstream air venting. The shape and location of these constrictions were changed several times to determine the discharge capacity versus localized upstream pressure recovery. Nonsymmetric crown flow constrictions provided sufficient back pressure to raise the consistently low-pressure areas to acceptable levels during the design discharge. Roller vortices occurred due to a 90° square-edged flow boundary on each side of the tower structure. Large radius fillets were placed in the 90° corners to eliminate the vortex action.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- /hydraulic models/ spillway capacity/ spillways/ cavitation/ tunnel hydraulics/ tunnel pressures/ air admission/ air bubbles/ air chambers/ air demand

b. IDENTIFIERS-- Sherburne Lake Dam, Montana, Milk River Project

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LAKE SHERBURNE DAM
MODEL STUDY

by
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Hydraulics Branch
Division of Research
Engineering and Research Center
Denver, Colorado
September 1983

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SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR   *   BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

The original work was done using inch-pound units and converted to SI units.
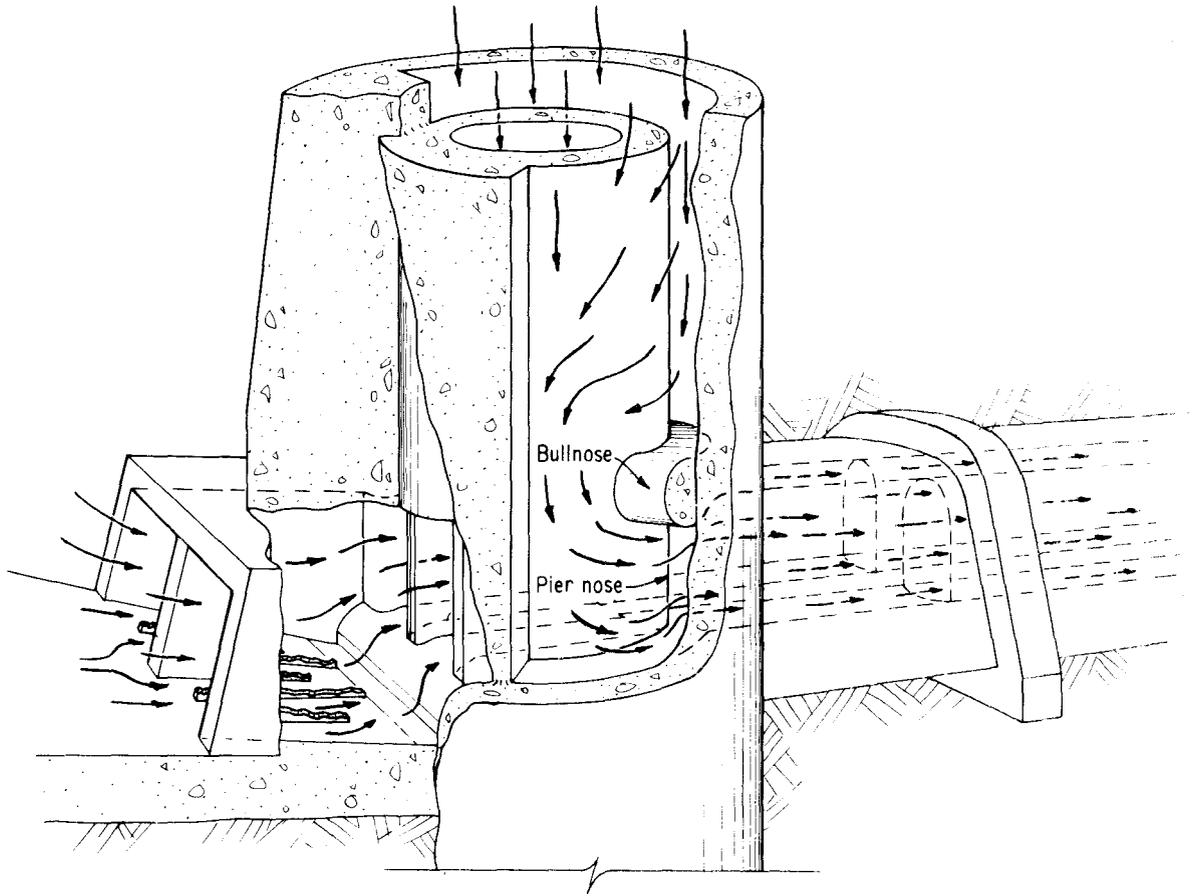
Frontispiece. – Lake Sherburne Dam spillway and outlet works.

CONTENTS

FIGURES

CONTENTS – Continued

INTRODUCTION

In 1981, a proposal was made to raise the Lake Sherburne Dam crest elevation (fig. 1) to increase the reservoir flood detention capabilities to meet IDF (inflow design flood) criteria. The discharge capacity of the existing tower structure under increased reservoir heads was determined. The model tests were conducted to aid in design modifications for Lake Sherburne Dam. Although the structure is unique, the inherent problems of increasing spillway-outlet capacity to comply with IDF requirements are not unique. Results of the model study are to be used in part to determine the new height of Lake Sherburne Dam crest. The methods used in this study add to the general base of information for future rehabilitation projects.

Lake Sherburne Dam is a homogeneous earthfill structure 32.9 m high with a crest length of 366 m located on Swiftcurrent Creek in north-central Montana. The dam was put into service in 1921. The reservoir has a storage capacity of 84 000 x 10^3 m^3.

The original spillway was abandoned because of the instability of underlying glacial debris. A temporary wood flume was built to serve as the spillway. Reservoir control was achieved using two cylinder gates within the outlet works intake tower. Twin tunnels carry flows from the intake tower to the downstream stilling basin.

A rehabilitation of the spillway and outlet works was conducted in 1960. The cylinder gate intake structure was modified to a combined spillway and outlet works (fig. 1). The existing cylinder gates were replaced by two 1220- by 1520-mm, high-pressure slide gates. A weir-type overflow spillway in the left abutment was backfilled with compacted earth and replaced by a modified morning glory spillway added to the intake tower. Spillway and outlet works flows are merged (fig. 2) near the tower base and passed through the existing tunnel structures.

CONCLUSIONS

1. Water manometer data which yielded prototype pressures less than −2.0 m were considered unacceptable for this study. Three low-pressure regions with cavitation potential were present for spillway flows in the existing structure: (a) The outer vertical walls forming the transition from the tower base to the outlet tunnels are subjected to low pressure at reservoir elevations above 1460 m, (b) Similar flows also created transverse roller vortices along the wall and adjacent floor near the upstream corners of the tower annulus, and (c) Increasing the reservoir elevation to 1460.3 m created a third area of low pressure on the lower portions of each bullnose (fig. 9).

2. To meet IDF criteria at the established maximum reservoir pool elevation of 1465.8 m, the combined spillway and outlet works structure must convey 114.7 m^3/s under acceptable hydraulic conditions.

3. Installation of a tunnel crown constriction 5.07 m downstream of the gate centerline raised tunnel-entrance-wall and bullnose pressures to acceptable levels for design discharge (Q_{max} = 114.7 m^3/s, EL_{max} = 1465.8). The tunnel sections were constricted to a flow area of 3.42 m^2. Air vents were installed to relieve the pressure downstream of each constriction.

4. The spillway flow passage at the junction of the upstream tower wall and floor was converted from a square corner on either side of the tower to a 2.43-m radius vertical fillet transition. This modification eliminated the steady vortex roller action.

5. Passing 114.7 m^3/s through the modified structure produced maximum average tunnel pressures of 6.8 m of water downstream from the constriction. Peak dynamic pressures ranged from 1.0 to 3.0 m of water above the average pressure.

2

6. Hydraulic conditions in the modified structure were unacceptable for outlet gate settings less than 100 percent during spillway operation at reservoir elevations above 1460.5 m.

THE MODEL

The study was conducted using a 1:15 scale model designed (and results analyzed) as a Froude law model. The spillway outlet works tower and tunnels, including the spillway tower, crest, gated outlets, access bridge, air vents for crest and outlet gates, tunnels, and flip bucket outlet structure, were modeled (figs. 3, 4, and 5). Trashracks were not modeled on either the intake or spillway structures. The tower base and tunnels were constructed of clear plastic; the spillway tower from sheet metal. Polyurethane was milled to form the spillway ogee crest. The model was placed in an elevated 3.65- by 3.05-m headbox. Tunnels were run on a 0.005 slope into a 2.44- by 1.83-m tailbox.

Discharge was measured using a permanent laboratory venturi bank. Pressures were measured using both water column manometers and pressure transducers. Transducers were utilized in areas where manometers showed low average pressures.

MODEL INVESTIGATIONS

The model study was conducted to determine if the spillway and outlet could be operated simultaneously without producing cavitation problems in the intake tower; to determine the head-discharge capacity of the intake tower; and to identify areas of poor hydraulic performance.

Unmodified Structure

Model tests of the existing structure were conducted for equal high-pressure, slide-gate positions from 100 to 0 percent in 20 percent increments, and at a range of reservoir pool

elevations from 1459 to 1468 m for each gate setting. Uncontrolled spillway flows occurred above reservoir pool elevation 1459 m. Model test data obtained for selected reservoir elevations included total discharge, tailwater elevation, and pressure heads from which discharge curves were developed for the unmodified structure (fig. 6).

Initially, pressures were measured on the right bullnose, left and right pier noses, and adjacent downstream tower floor (fig. 7). Following initial testing, visual observations indicated the need for pressure data along the outside vertical wall in the tunnel entrance transitions. Pressure taps were installed along a vertical line on the tunnel entrance wall (fig. 8), and in the downstream tunnel. The pressure taps were installed in the tunnel to obtain hydraulic loading on the tunnels when operating as pressure conduits. Pressures shown are average pressures determined by water column manometers (figs. 9, 10, 14, 16, 18, 22, and 23).

Pressures were positive on the gate pier noses and adjacent floor for discharges at reservoir elevations up to 1467.5 m when the spillway was discharging in conjunction with fully open outlet gates. Negative pressures developed on the pier noses (piezometers 1R, 3R, 11L, and 13L) during outlet works operation below 50 percent gate opening and reservoir elevations above 1461.2 m. The reduction in outlet works flow decreased tunnel pressures, allowing the high velocity spillway flow to separate from the pier nose radius.

Negative pressures occurred on the spillway bullnose (fig. 9) and on the outer vertical wall of each tunnel entrance transition, piezometer locations 26 through 36 (fig. 10). Pressures were positive near the top of the wall but dropped sharply at lower levels.

High negative pressures occurred on the outer tunnel entrance walls during all spillway flows exhibiting throat control or submerged crest conditions (reservoir elevation $\geq$ 1460 m). At reservoir elevations below 1460 m (crest control) spillway flow entered the tunnels, as well-mixed froth flow. Wall pressures were not measured during froth flow conditions.

4

Two areas of poor hydraulic performance were observed. During spillway operation, horizontal roller vortices formed intermittently at the junctions of the tower floor and upstream tunnel walls (fig. 11). The vortices resulted from poor flow conditions imposed by the abrupt 90° vertical turn in flow direction as flow approaches the tower floor. The vortices appeared strong enough to expect subatmospheric pressures at the point of attachment to the upstream tower wall.

The second area observed occurred in the tunnels while operating as pressure conduits (Q(total) > 85 m^3/s). During pressurized flow, the tunnels were subjected to a strong swirl along the entire tunnel length (fig. 12). The swirl was initiated by the abrupt change in horizontal angle between the spillway annulus and the tunnel entrance. Significant pressure fluctuations attributed to the swirl were observed in the tunnels during steady-state operation.

A maximum reservoir elevation of 1465.8 m was selected based on test results of the unmodified structure. To pass the IDF within the maximum reservoir limit, the combined spillway and outlet works must pass 114.7 m^3/s under acceptable hydraulic conditions.

Modification to Upstream Tower Wall

The 90° vertical corner along the upstream tower floor was streamlined by adding a vertical fillet transition between the upstream vertical wall and the floor. Fillet radii of 2.43 and 4.26 m were tested in the model. The 2.43-m fillet proved effective in preventing steady transverse vortex action from forming and improved the low pressures present on the downstream tunnel wall transition (fig. 13). Based on pressures recorded while the 2.43-m fillet was installed, a 4.26-m radius fillet was installed. The larger fillet provided similar flow conditions in the area of the fillet; however, the larger fillet provided no additional improvement in tunnel wall pressures.

Tunnel Modifications

Two methods of modifying the tower structure to reduce subatmospheric pressures were considered. One option centered on treating the bullnose and tunnel transition wall with a significant modification to the tower to streamline flow passages. The other was to increase the ambient pressure on each side of the spillway outlet works structure by inducing a constriction head loss within each tunnel section downstream of the areas of subatmospheric pressure.

Model tests were initiated to investigate the addition of tunnel crown constrictions and their effect on improving local pressures versus loss of discharge capacity. The crown constrictions were designed to minimize the influence of the constriction during normal outlet works operation.

The initial constriction area was estimated, assuming the constriction acted as a partially closed, vertical-lift slide gate:

$$Q_T = A_T (1 - x) \ C_c (2gH)^{0.5}$$

where:

Q_T = design discharge per tunnel, 58 m^3/s

A_T = tunnel area downstream of transition, 3.92 m^2

x = constriction area as percent of tunnel area

C_c = estimate of contraction coefficient, 0.75

g = acceleration of gravity, 9.8 m/s^2

H = total head available, 26 m (reservoir EL 1465.8 minus tunnel centerline 1439.8 m)

Segment constriction.-A tunnel crown segment constriction blocking 0.54 m² or about 14 percent of the tunnel area (fig. 14) was tested in two locations (1) Immediately downstream of the entrance to the tunnel transition section, and (2) At the exit of the tunnel transition section. Placing the constriction near the entrance pressed the high velocity jet entering the tunnel toward the tunnel floor. The pressure gradient over the vertical tunnel wall steepened without significant low pressure improvement (fig. 14). Bullnose pressures were improved and rose to positive pressure levels.

Moving the constriction 7.32 m downstream of the gate centerline to the start of the uniform tunnel section provided a flatter pressure gradient over the tunnel wall. The tunnel wall and bullnose pressures showed approximately a 2-m improvement over the unmodified structure. Although this back pressure on the structure created some improvement, pressures remained below desired levels.

Arch constriction.-Results of segment constriction tests indicated the constriction should be placed amid the tunnel entrance transition section. The 14 percent segment constriction was replaced by an arch-shaped constriction with a frontal area equal to 16 percent of the uniform tunnel area (fig. 15). The arch-shape design increased the contact area between the tunnel and the constriction, thus simplifying prototype installation. The constriction was designed to cover the full length of the tunnel crown radius. The constriction was installed 5.07 m downstream of the gate centerline. Piezometer taps were placed on the upstream side of the left tunnel constriction and on the downstream side of the right tunnel constriction. Differences between the upstream and downstream pressures were used to determine structural loading.

Tunnel wall and bullnose pressures are shown for $Q = 117.4$ m³/s (fig. 16). The arch constriction raised the worst average subatmospheric pressure to −2.4 m and eliminated the strong swirl which occurred during pressurized tunnel flows in the unmodified structure.

7

Air venting downstream of constriction.—Model tests were conducted to determine the air demand required to vent the tunnel downstream of the constriction. Air vents were sized by developing a series of air demand curves from model tests. Ports were drilled in the tunnel crown immediately downstream of the constrictions. Thin plate metal orifices placed over the ports were used in the model to establish air demand. Air demand was calculated using the standard orifice equation.

$$Q_{air} = A_o \ C_d \ [2g \ (HD_R)]^{0.5}$$

where:

Q_{air} = air demand per tunnel, m^3/s

A_o = area of model orifice plate, m^2

C_d = coefficient of discharge

g = acceleration of gravity, m/s^2

H = pressure drop across the orifice measured by water manometer, m

D_R = density of ratio of air to water

Piezometer tap 43 located on the downstream side of the constriction at the tunnel centerline (fig. 15) was used to determine the pressure drop across the orifice plates. Air velocity data taken with an air velocity meter were used to randomly check air demand readings calculated from orifice plate pressures.

Nonsymmetric arch constriction.—Initial tests with the crown constriction indicated design discharge could not be achieved in combination with the required level of air venting. The constrictions were trimmed from 16 to 14 percent of the tunnel area by shortening the length on the outside tunnel wall (fig. 17). The constriction area adjacent to the inside wall was left intact to break up the high-velocity spillway jet linked to the previously strong tunnel swirl. The constriction reduced the tunnel transition area beneath the constriction to 3.42 m^2. The response of low-pressure areas on the bullnose and in the tunnel entrance

8

transition to the constriction with four rates of air supply were recorded (fig. 18). Observation showed full air coverage over the length of the constriction and tunnel crown (fig. 19). Crown flow downstream of the constriction was fully mixed with entrained air. The 14 percent nonsymmetric constriction produced acceptable pressure levels and rates of air demand at design discharges. Results of tests indicated an optimum prototype air supply of 1.65 m^3/s per tunnel at maximum reservoir allows passage of design discharge with acceptable hydraulic conditions within the intake tower structure. Prototype air vent design should provide a head loss of about 1240 m of air to limit prototype air supply to 1.65 m^3/s. Air velocities within the vent system should be limited to less than 90 m/s to avoid compressibility.

Tests were conducted to develop a combined set of a spillway and gated outlet works discharge curves for the modified structure with tunnel air vents. Discharge curves apply for air vents designed to provide 1.65 m^3/s airflow at design reservoir discharge (figs. 20 and 21).

Hydraulic loading of the constrictions.–Average pressure distributions for design flow indicated that the highest pressures occur on the upstream center of the constriction. On the downstream side, lowest pressures occur near the ends of the constriction. Pressure differential across the constriction was nearly constant over the range of air discharge tested (fig. 22). Constriction pressure differentials for the air demand range correspond to average pressure loads of 194 kPa (Q_{air} = 1.05 m^3/s) to 186 kPa (Q_{air} = 1.90 m^3/s).

Tunnel Pressures

Tunnel pressures were monitored downstream of the constriction during pressurized flow conditions. Highest pressures were recorded 10.55 m downstream of the gate centerline on piezometers 37 and 38. A transducer was installed on piezometer 38 to measure dynamic pressure response. Frequently occurring peak maximum and minimum dynamic pressures and average manometer pressures are given (fig. 23).

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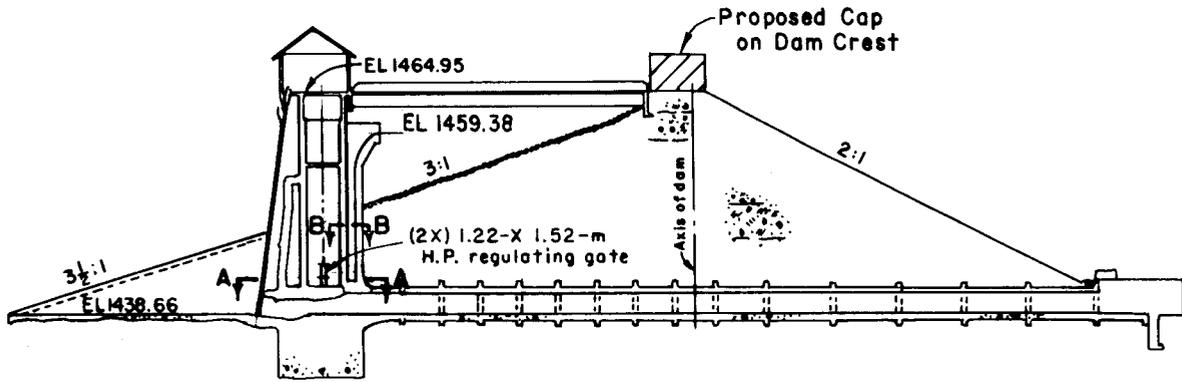
ELEVATION
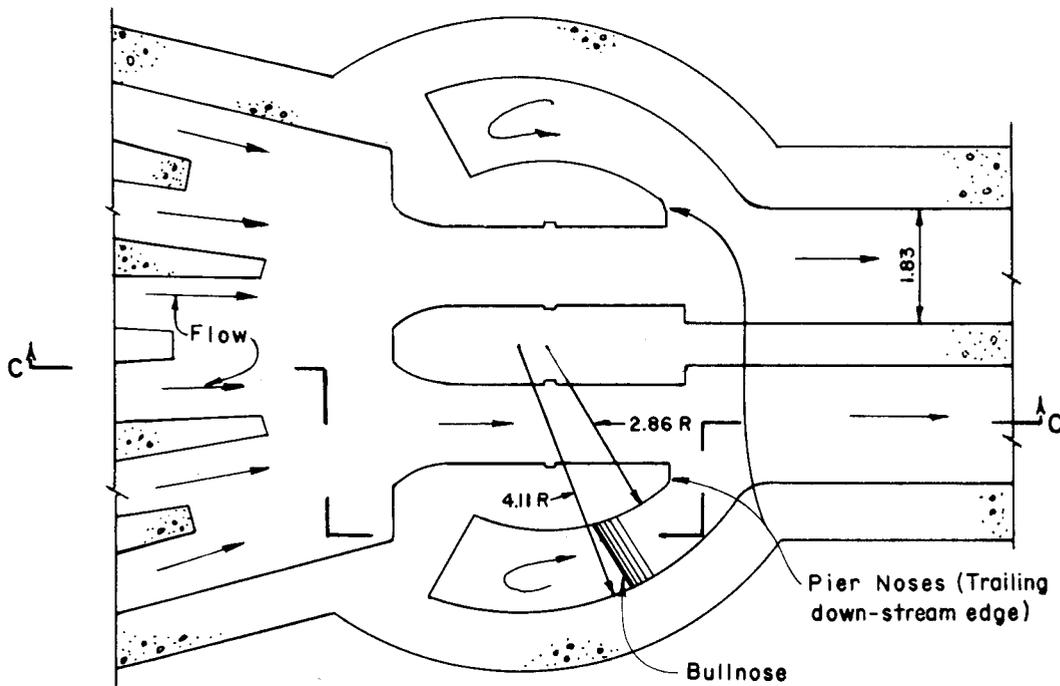
SECTION A-A

Figure 1.—Lake Sherburne Dam spillway and outlet works, elevation and section.

11

SECTIONAL ELEVATION C-C

€ inner shaft
and gates

Flow

Bullnose

EI. 1442.31

EI. 1441.10

Pier nose
(trailing edge)

Flow

1.52

2.44

SECTION B-B

Floor EL 1438.66

Bullnose

Top of concrete
EL 1442.31

SECTION D-D

EL 1442.31

1.22

2.44

Spillway flow

EL 1438.66
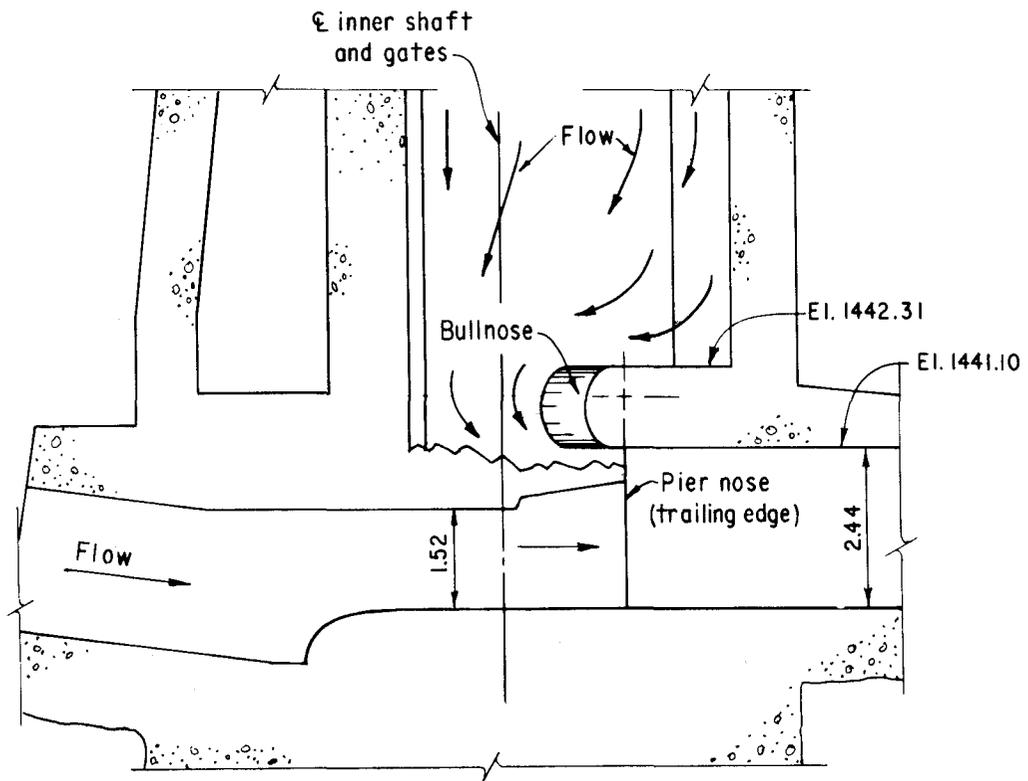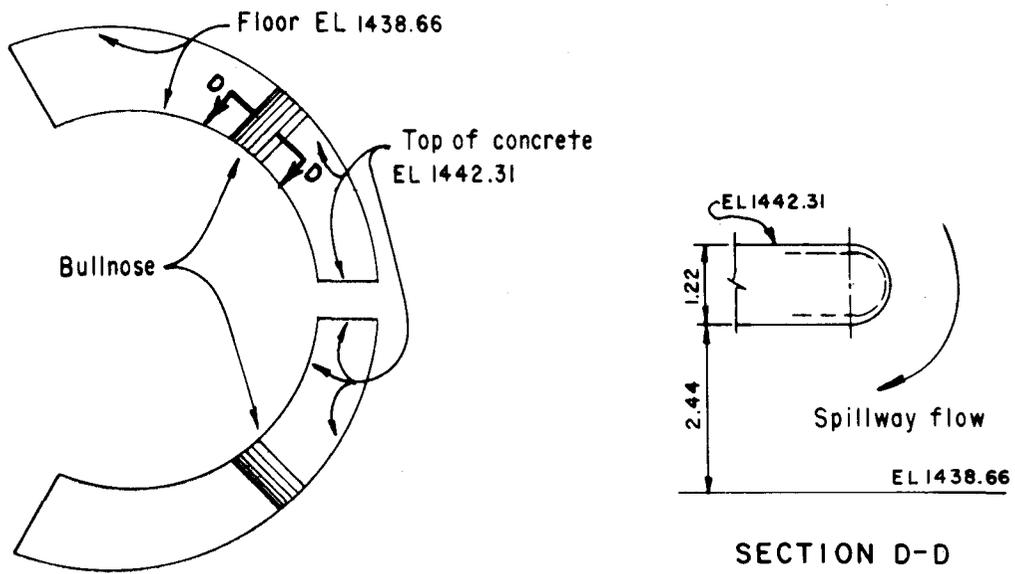
Figure 2.—Lake Sherburne Dam spillway and outlet works, sections (see fig. 1).
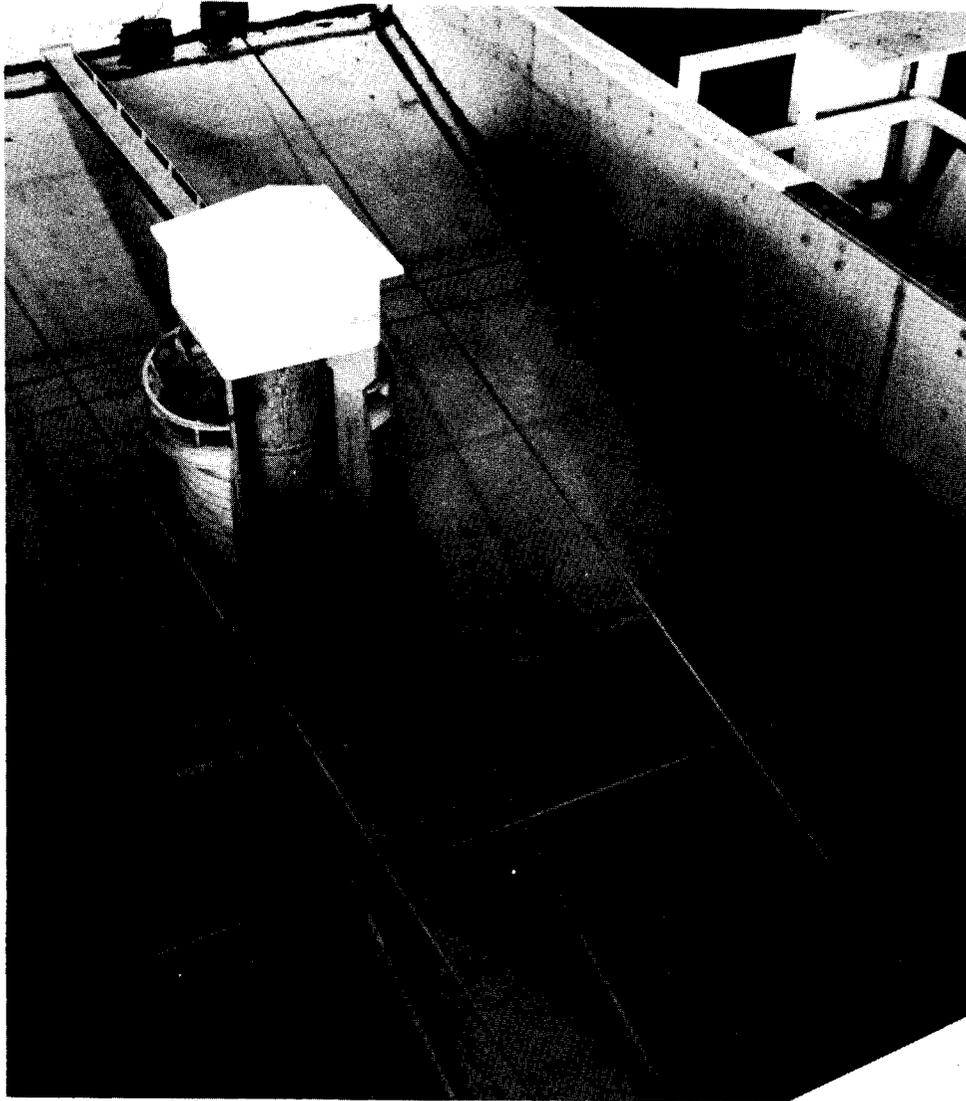
Figure 3.—Intake tower, bridge, spillway crest, and outlet works intake. Photo 80303
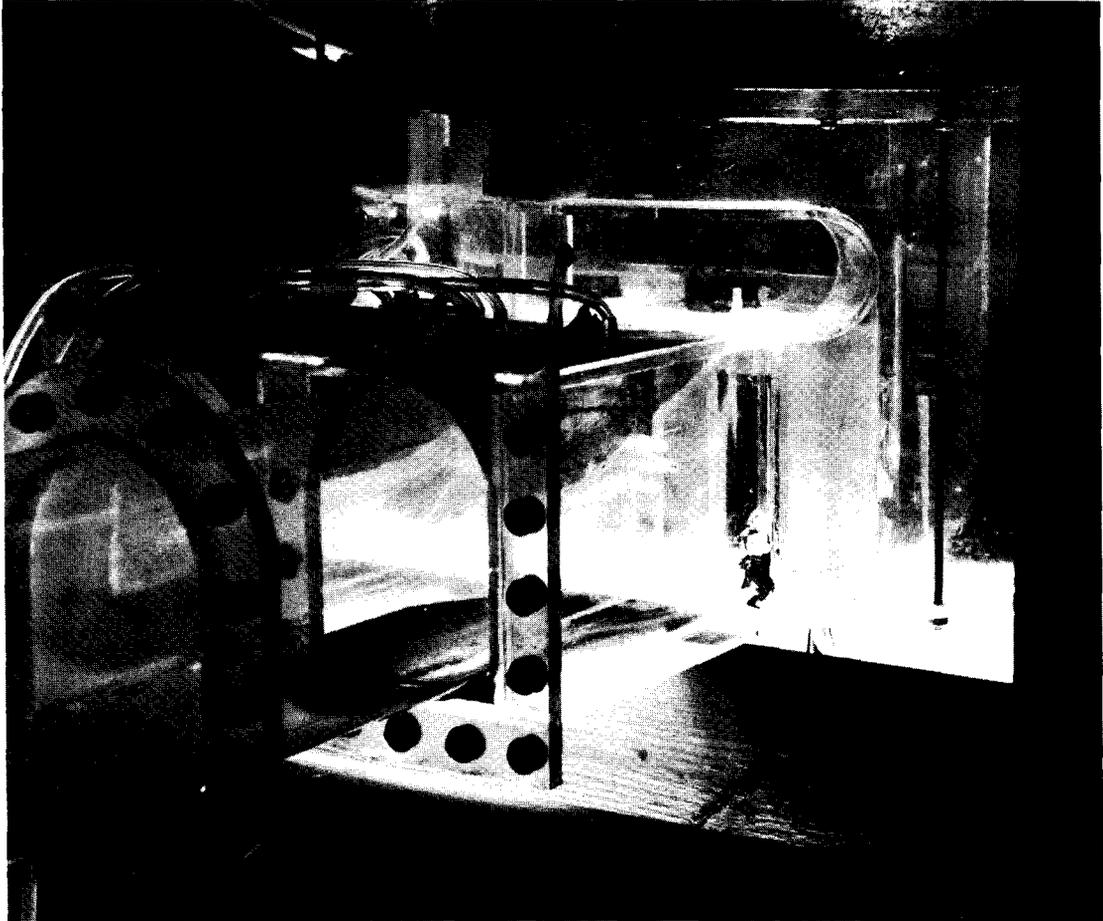
Figure 4.—Intake tower base and tunnel entrances. Photo 80304
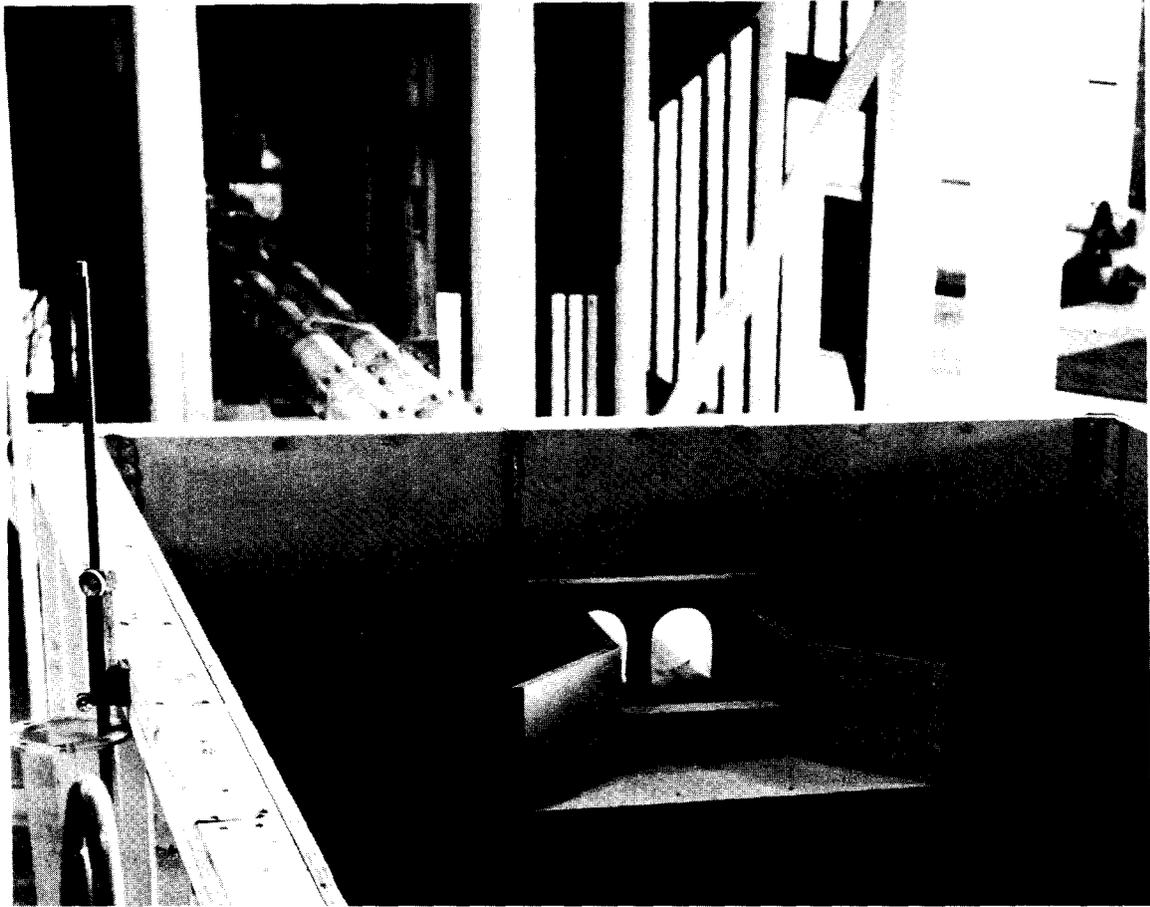
Figure 5.—Tunnel outlets, flip bucket, and tailbox. Photo 80305
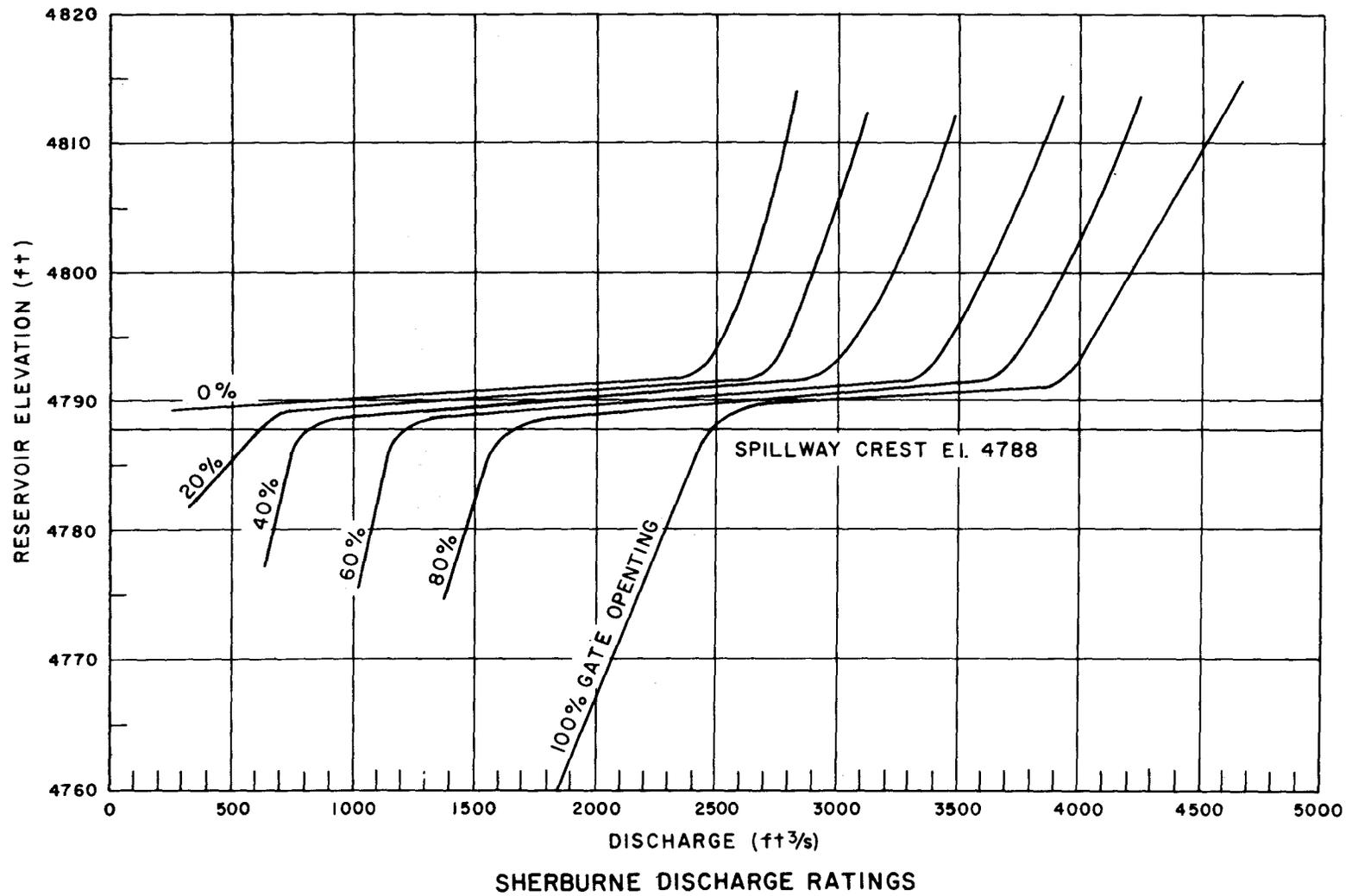
Figure 6.—Unmodified structure, discharge rating curves (inch-pound units).

GATED FLOW

165mm

SPILLWAY FLOW

210mm

8R,18L

9R,19L

15°

10R, 20L

20°

SECTION A-A

Spillway flow

450mm

El. 1442.31

21

22

45°

23

R=0.61 m

24

25

El. 1441.09

Spillway flow

El. 1442.31

21

22

23

24

25 Piezometer numbers

1.22 m

225 mm

FRONT VIEW
Bullnose elevation

A

A

1R, 11L
3R, 13L
5R, 15L
7R, 17L

FLOW

TOWER FLOOR

EL 1438.65

4 R, 14L
6R, 16L

ELEVATION
Downstream trailing edge pier nose

PIEZOMETER
NUMBERS | ELEVATION (m)

PIEZOMETER NUMBERS		ELEVATION (m)
1	11	1439.67
2	12	1438.77
3	13	1439.64
4	14	1438.73
5	15	1439.61
6	16	1438.70
7	17	1439.57
8	18	1438.65
9	19	1438.65
10	20	1438.65
	21	1442.31
	22	1442.00
	23	1441.70
	24	1441.40
	25	1441.09

PIEZOMETER LOCATIONS

Figure 7.—Piezometer tap locations on gate pier noses, bullnose, and tower floor.

PLAN

1.22-x 1.52-m high-pressure slide gate

Tower ℄

Outlet works intake

Tunnel ℄

Gate pier nose

Piez 26–36

0.609-m Tunnel entrance radius

Bullnose

Spillway flow

ELEVATION

Spillway flow

Bullnose

Piezometer 26 to 36

Tunnel ℄

Gated flow

26

36

3.24 m   7.31 m   18.38 m

Gate ℄   Pier nose

TOWER BASE AND TUNNEL SECTION
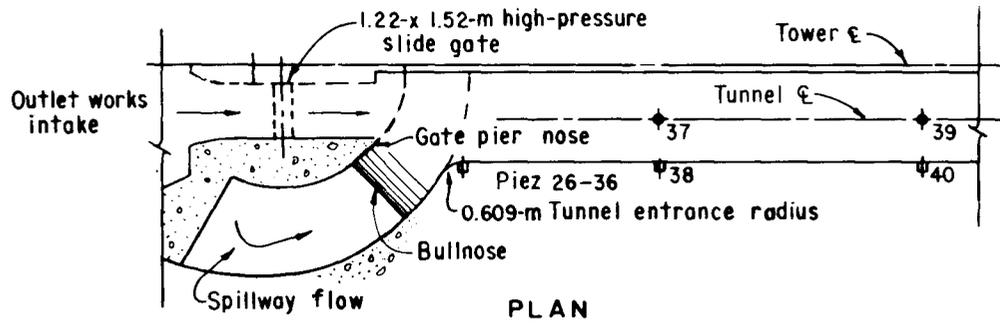
PIEZOMETER NUMBERS	ELEVATION (m)
26	1440.75
27	1440.56
28	1440.37
29	1440.18
30	1439.99
31	1439.80
32	1439.61
33	1439.42
34	1439.22
35	1439.04
36	1434.84
37	1441.03
38	1439.85
39	1440.96
40	1439.64

Figure 8.—Piezometer tap locations on outlet tunnels.
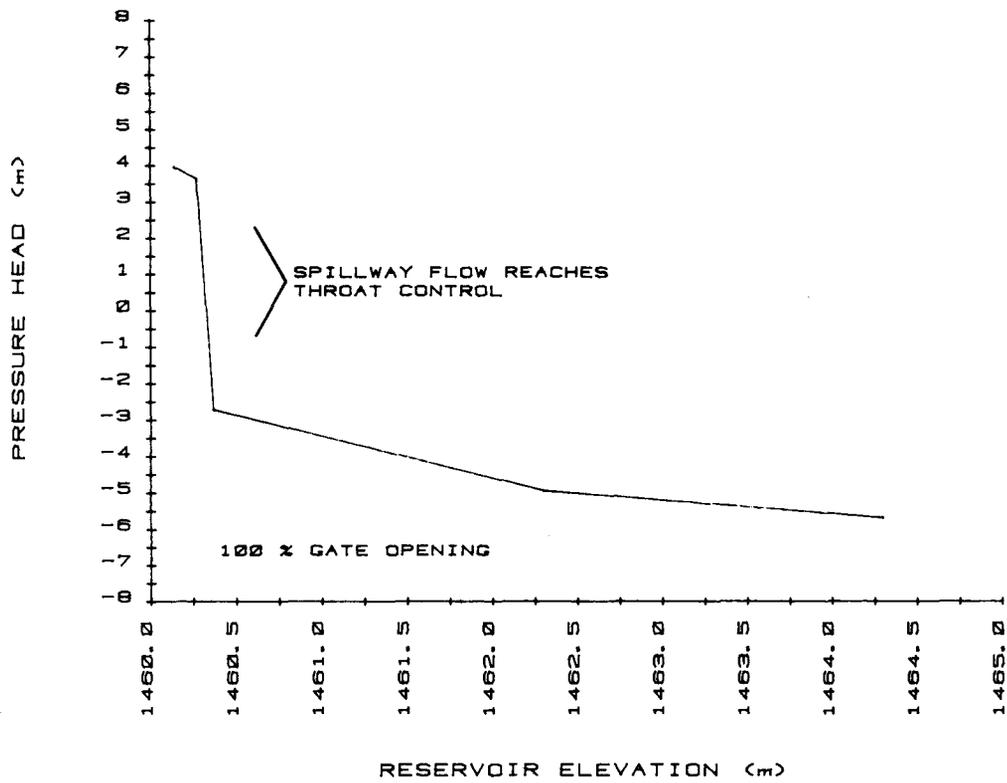
Figure 9.—Pressures on spillway bullnose (piezometer 24).
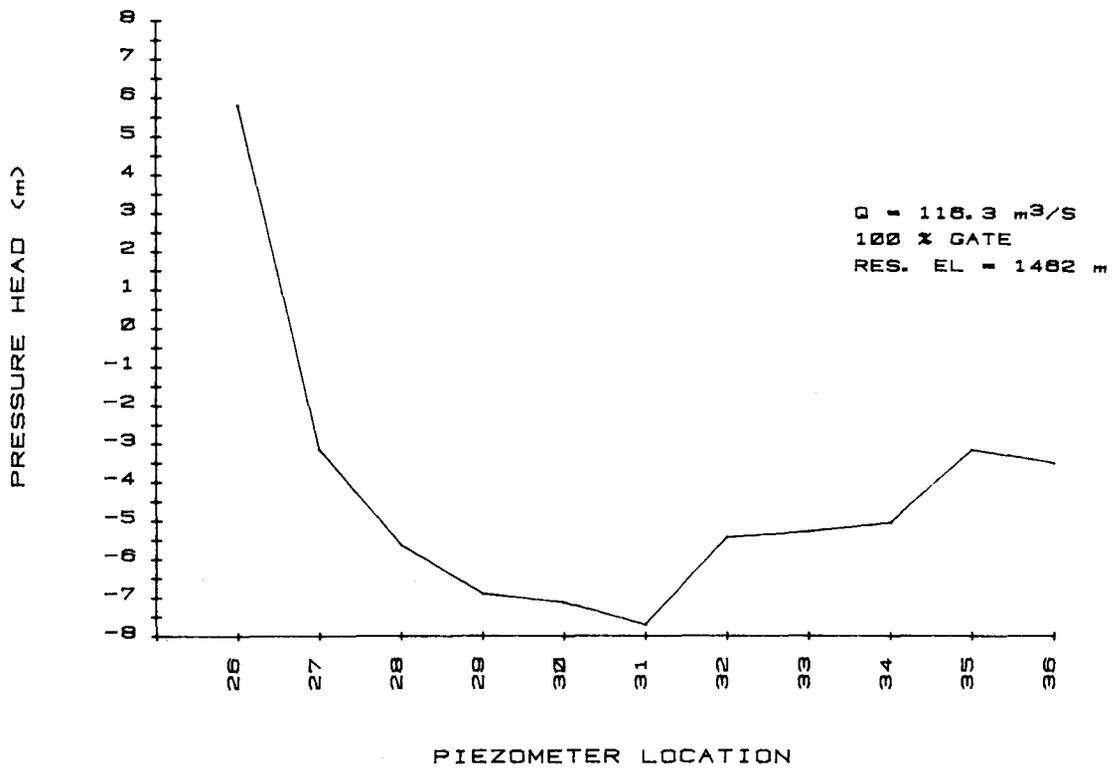
Figure 10.—Pressure profile of the vertical wall downstream of tunnel entrance in the unmodified structure.

20
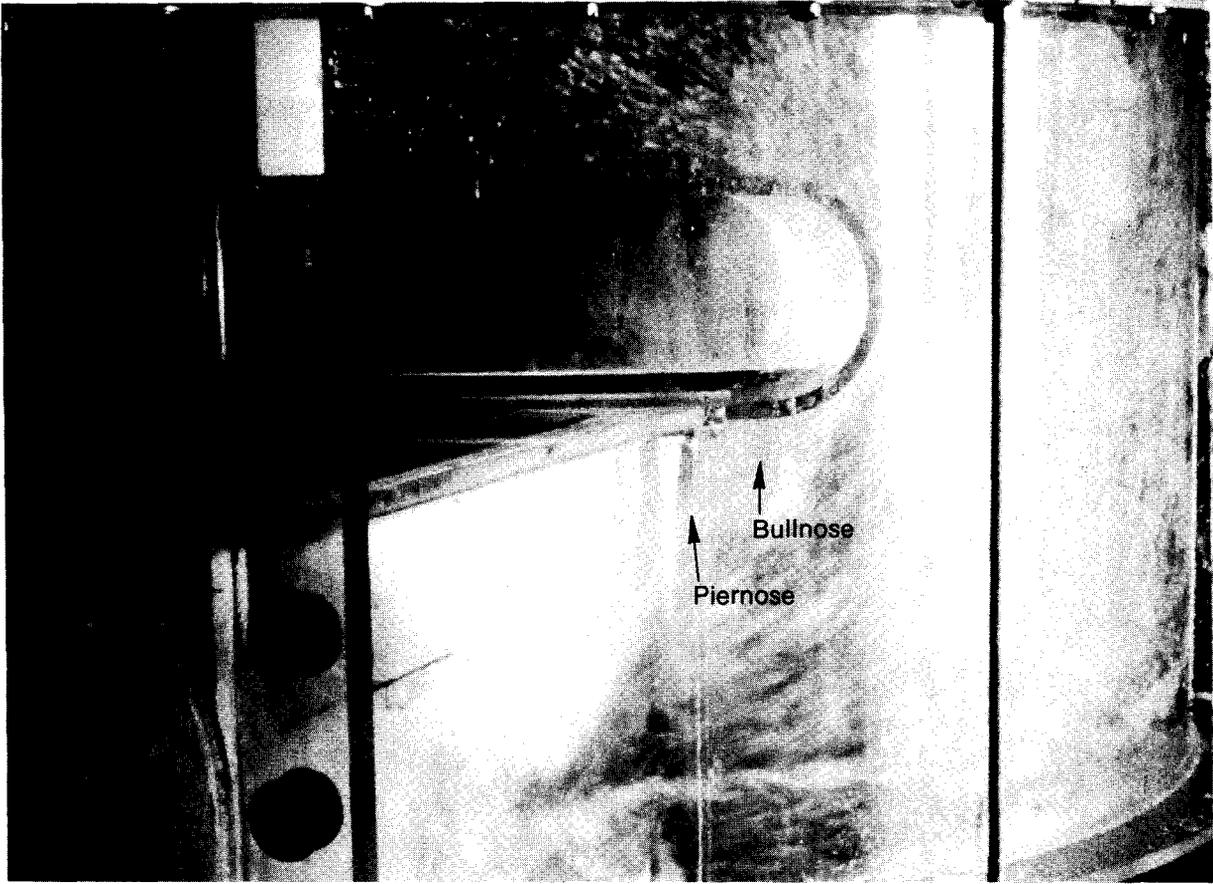
Figure 11. – Roller vortex at junction of tower wall and floor, for the unmodified structure (reservoir EL = 1460.3, Q = 107.5 m³/s, 100 percent gate opening). Photo 80306
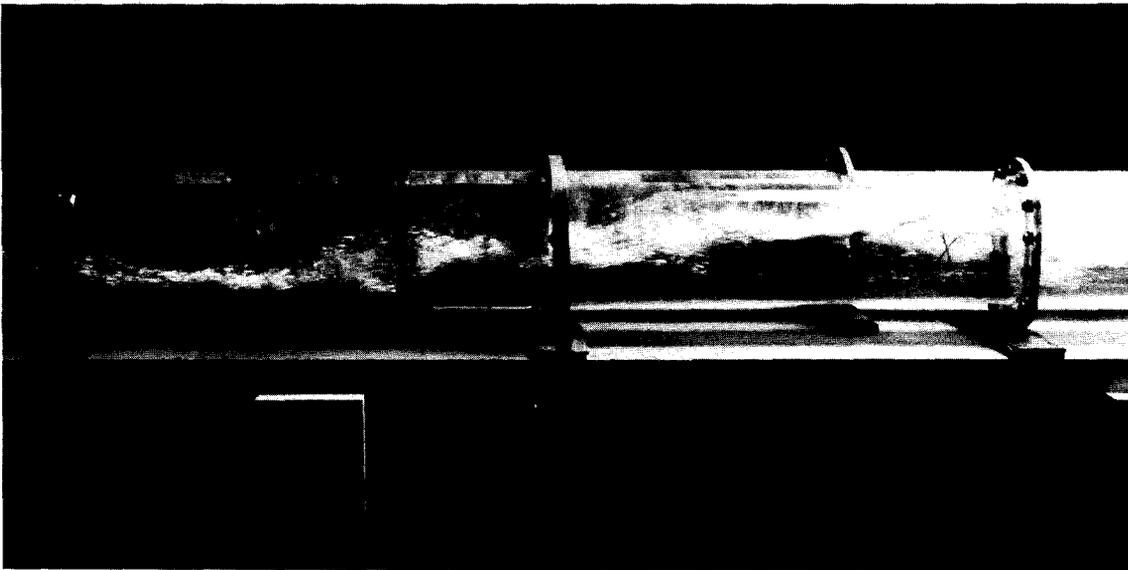
Figure 12.—Tunnel swirl occurring in the unmodified structure during spillway flow (Q = 100 m³/s, flow from left to right). Photo 80307

Figure 13.—A 2.43-m-radius fillet placed between upstream tower wall and tower floor (one fillet on each side of tower), reservoir EL = 1460.2, Q = 107.5 m³/s. Photo 80308
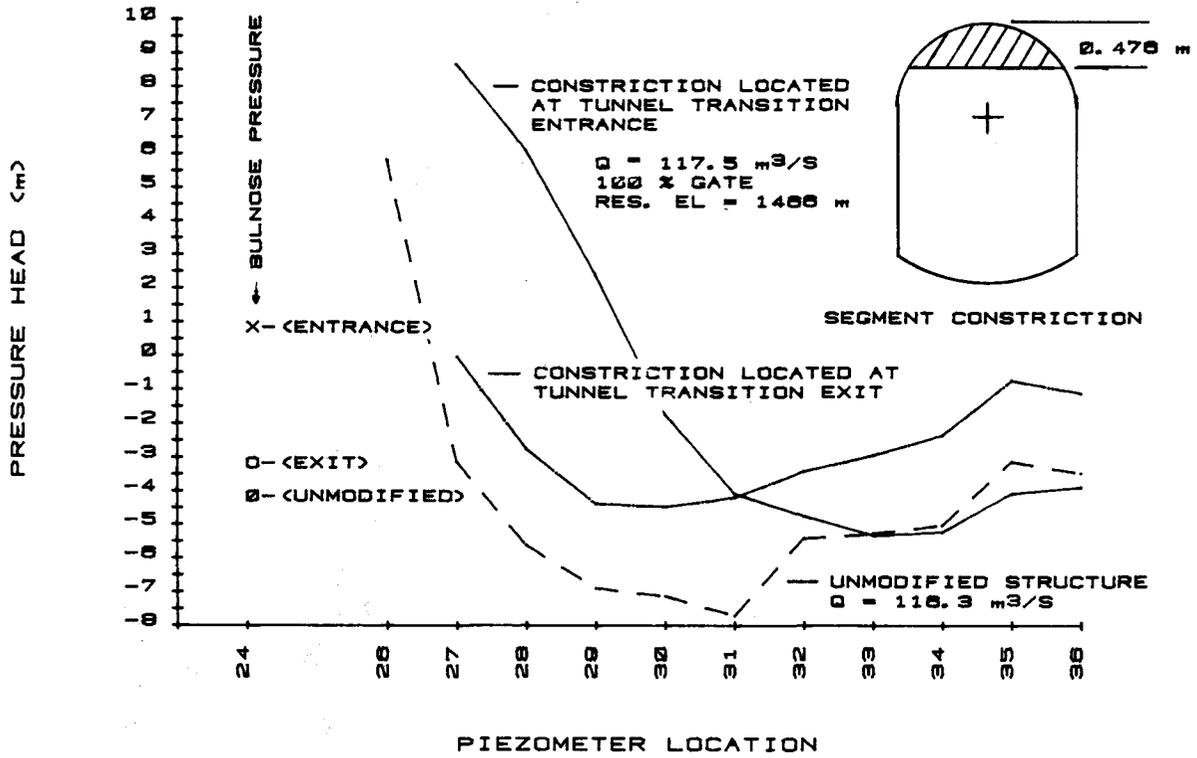
Figure 14.—Bullnose and tunnel entrance wall pressures using segment constrictions.

STA 5.07

0.232
0.125m
A 0.55 m

CONSTRICTION PLAN

0.25m | FLOW

SECTION A-A

43
42   44   D/S PIEZOMETERS
            Right Tunnel

0.77m

41   45
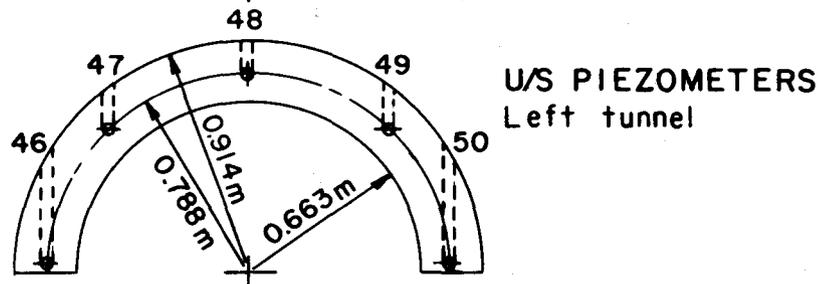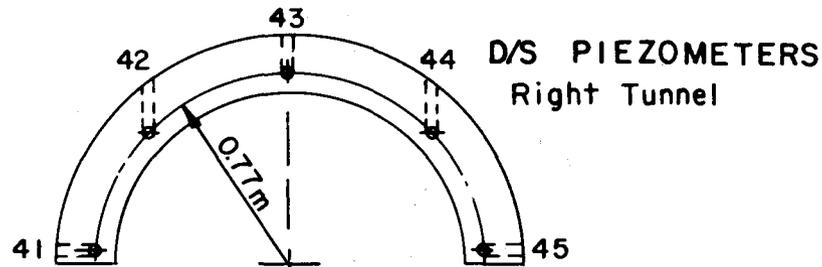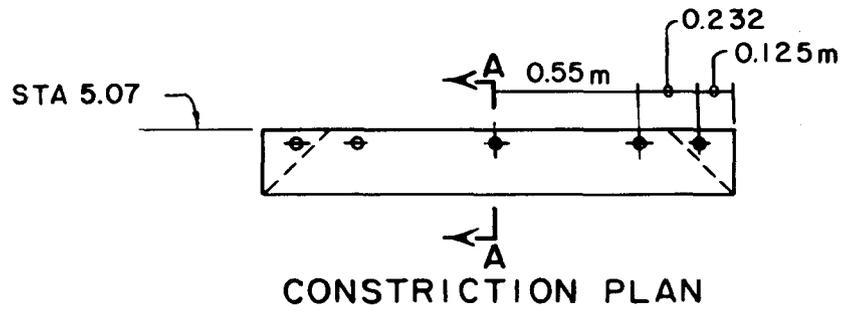
PIEZ	Elevation (m)
41	1440.45
42	1440.79
43	1440.98
44	1440.78
45	1440.45
46	1440.46
47	1440.81
48	1440.99
49	1440.81
50	1440.46

48
47   49   U/S PIEZOMETERS
            Left tunnel
46   50

0.914m
0.788m
0.663m

CONSTRICTION ELEVATION

Figure 15.—Arch constriction, location of piezometers 41 through 50.

24
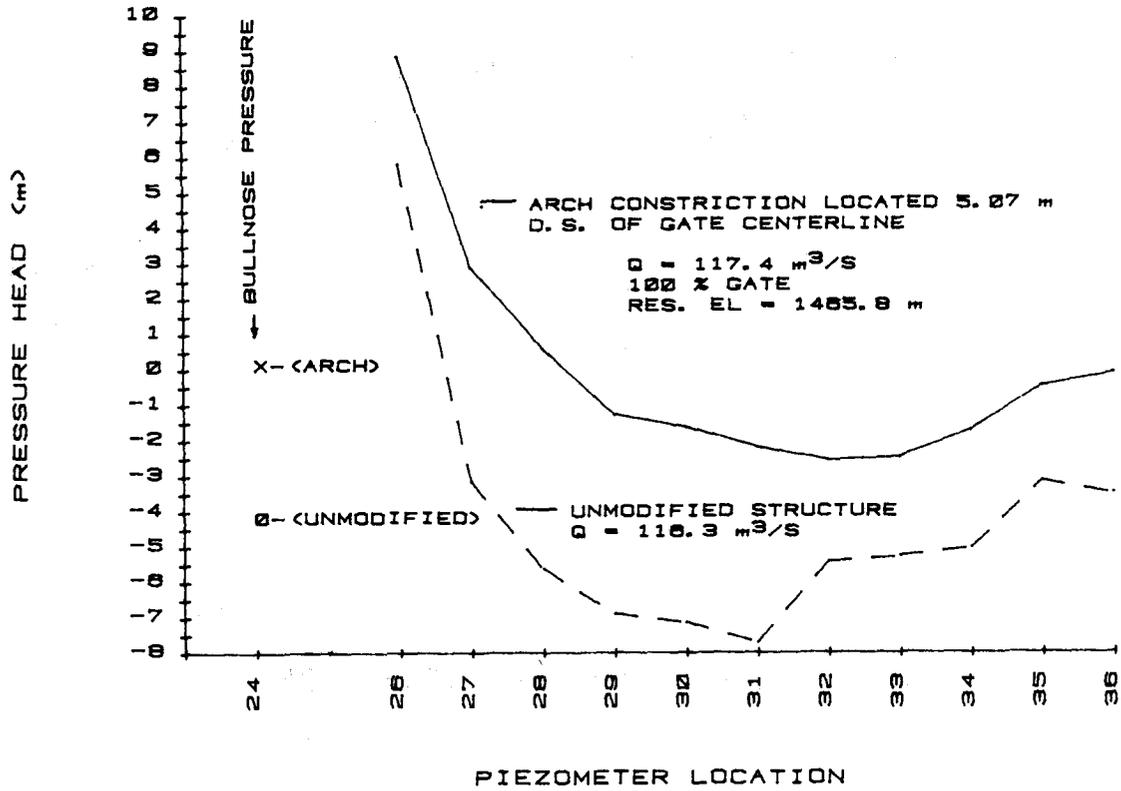
Figure 16.—Bullnose and tunnel entrance pressures using arch constrictions.
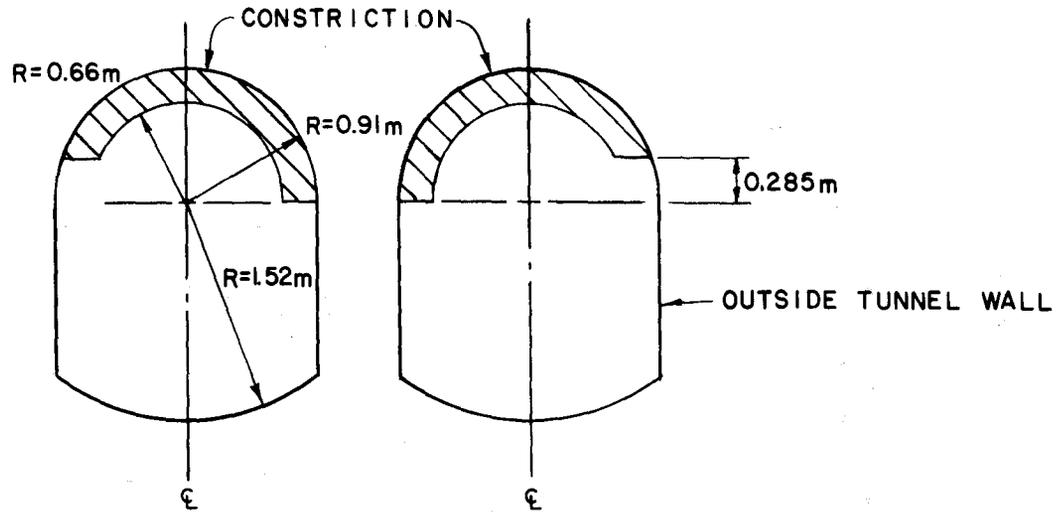
Note: Constricted tunnel transition area = 3.42 m²/tunnel

ARCH TUNNEL CONSTRICTION ELEVATION

Figure 17. — Nonsymmetric arch constrictions in tunnel.

Figure 18.—Bullnose and tunnel entrance pressures using nonsymmetric arch constrictions with air venting to the downstream side of the constrictions (Q_{air} per tunnel).
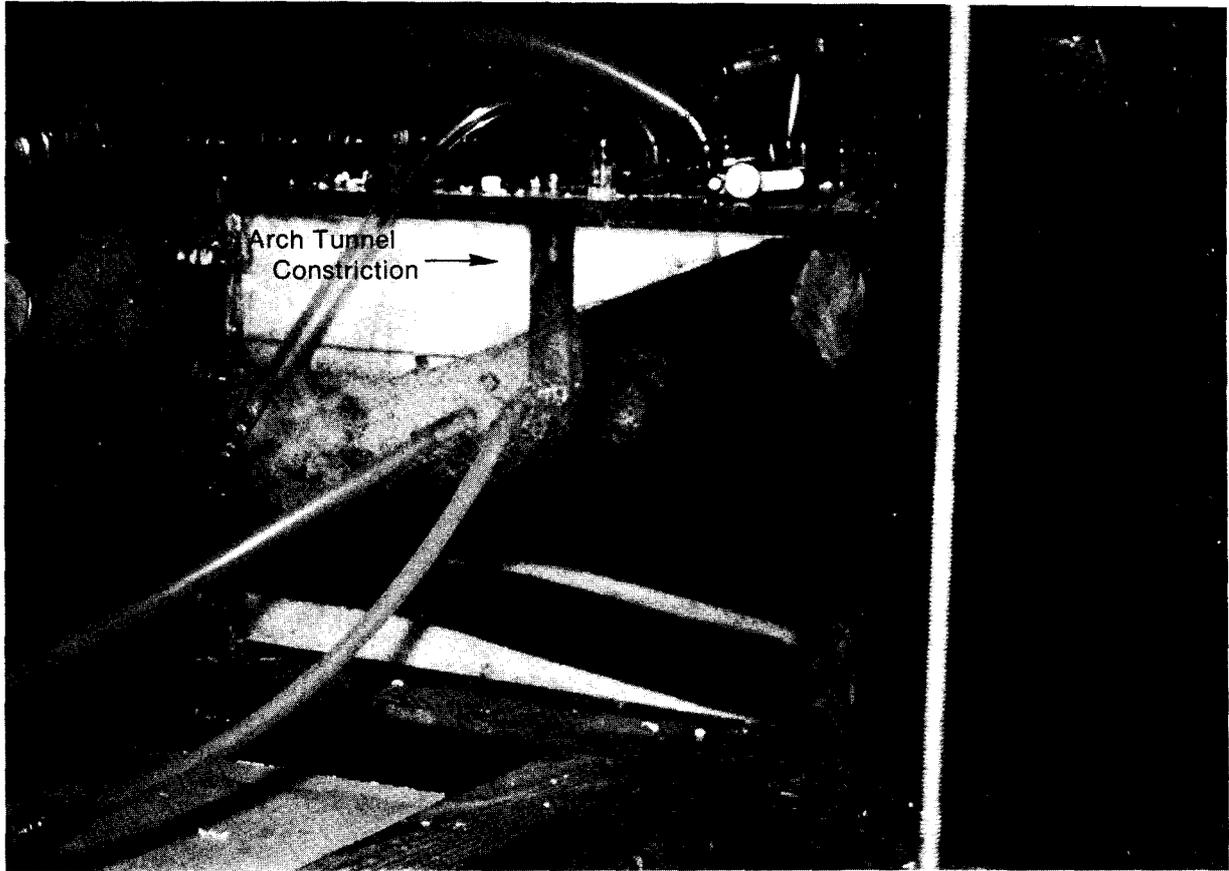
Figure 19.—Elevation view of air venting downstream of the nonsymmetric arch constrictions, reservoir EL = 1465.8, 100 percent gate opening, Q = 114.7 m³/s. Photo 80309
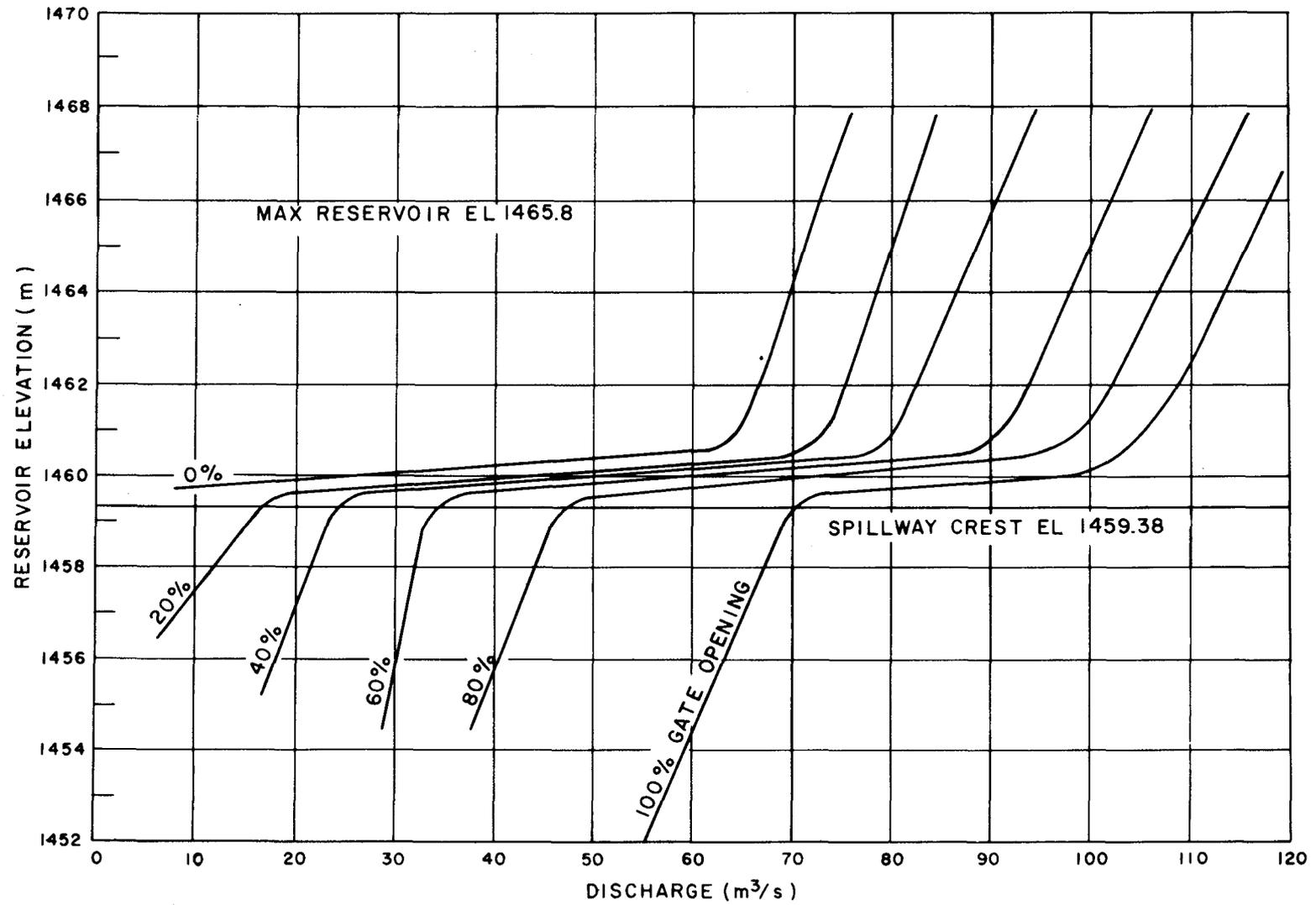
SHERBURNE DISCHARGE RATINGS

Figure 20.—Discharge rating using nonsymmetric arch constrictions with air vents downstream of constrictions (SI metric units).

SHERBURNE DISCHARGE RATINGS
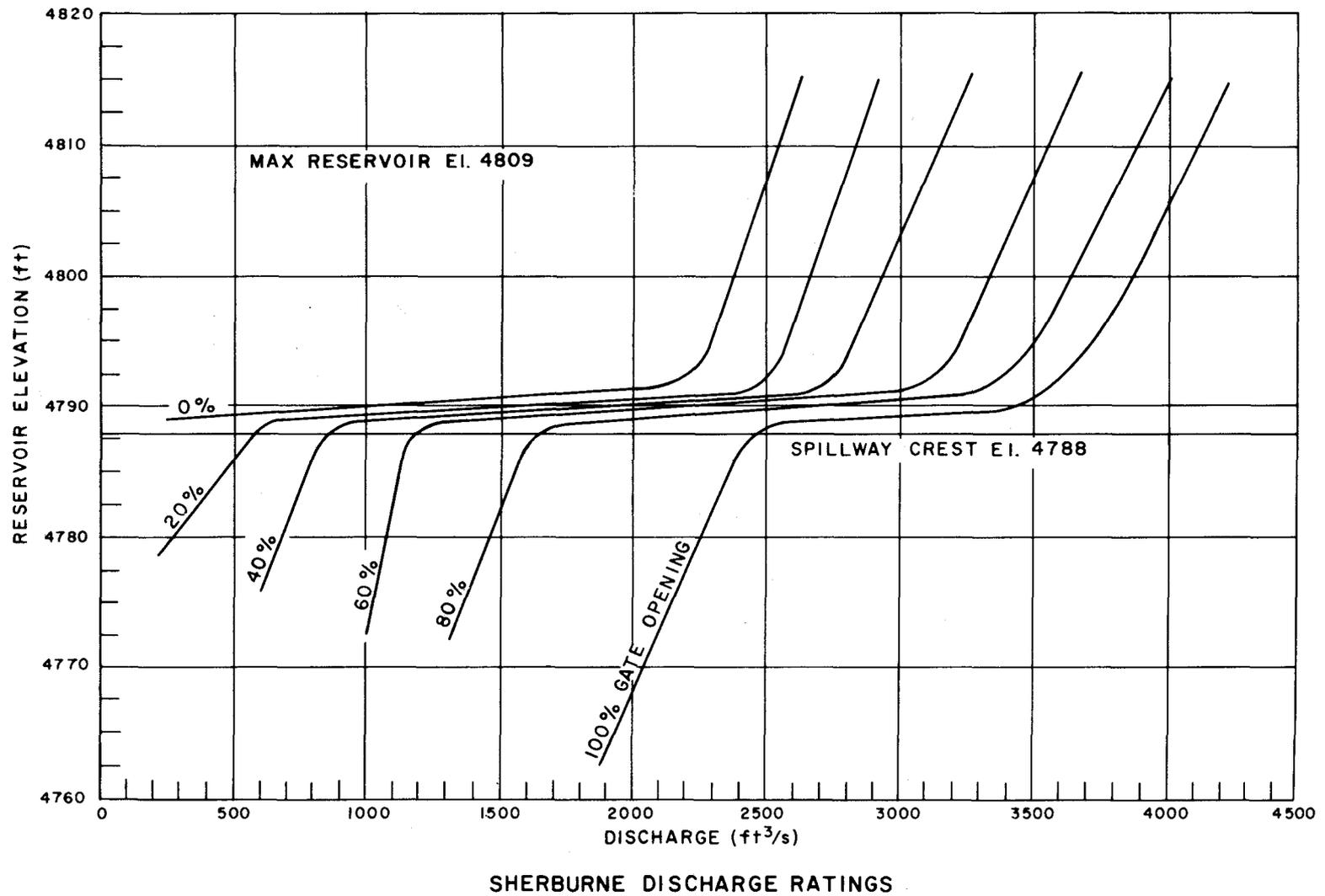
Figure 21.—Discharge rating using nonsymmetric arch constrictions with air vents downstream of the constrictions (inch-pound units).
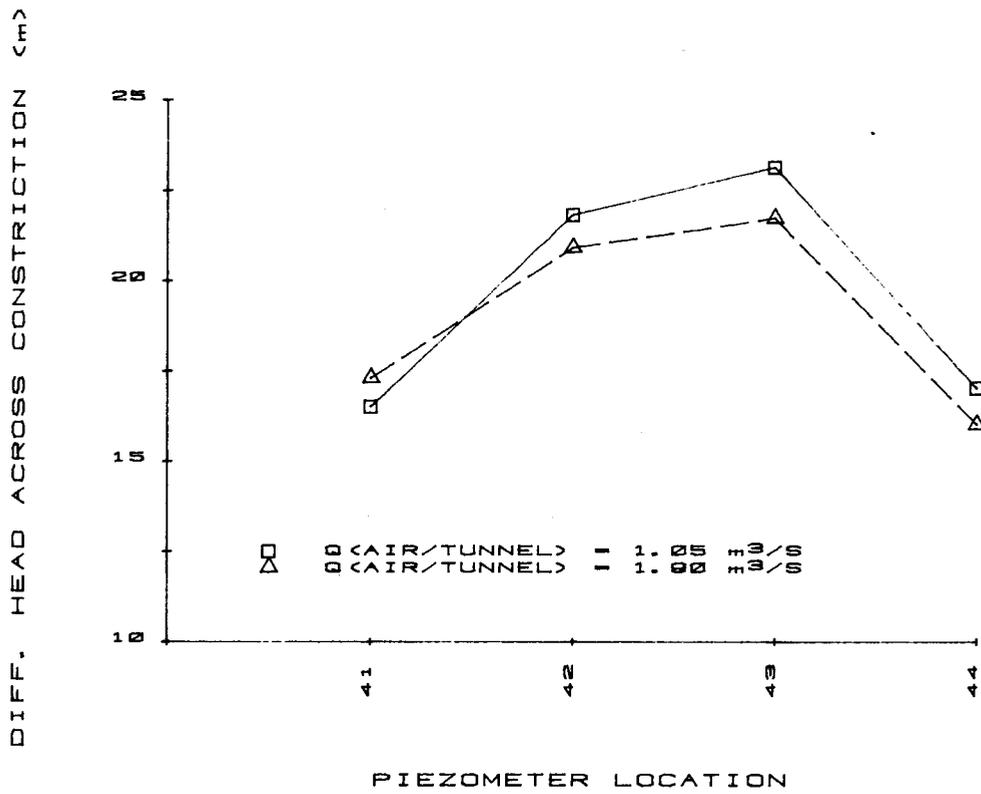
Figure 22.—Effect of air vent supply on the pressure differential across the nonsymmetric arch constrictions.
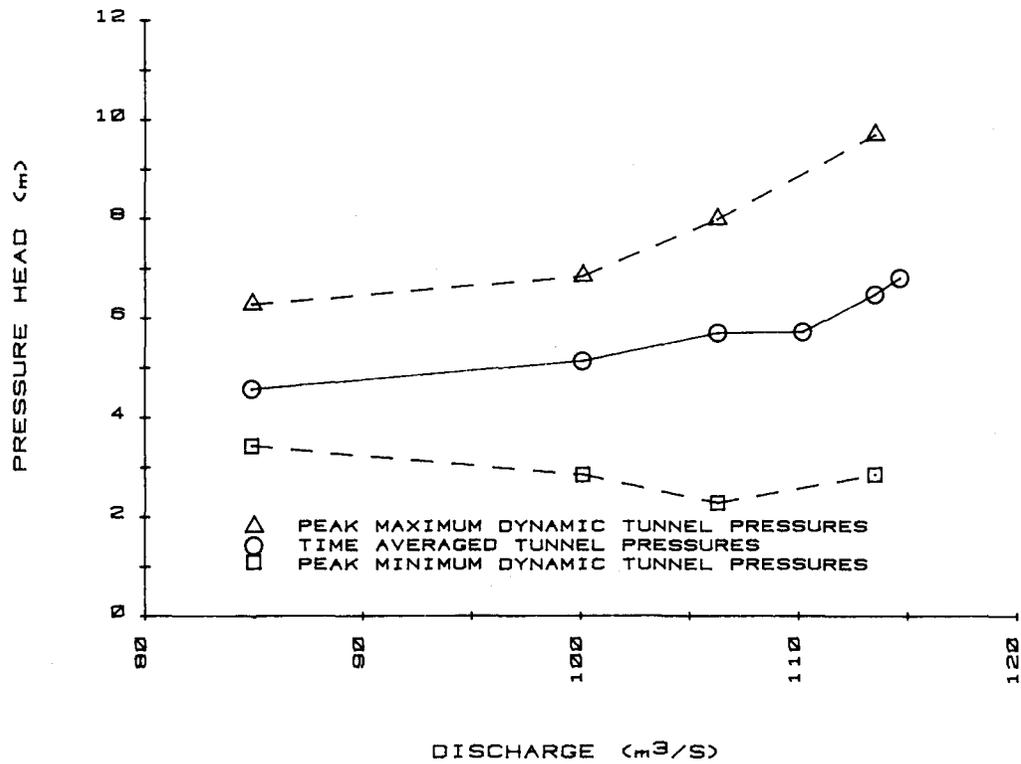
Figure 23.—Tunnel pressures 10.55 m downstream of gate centerline, reservoir EL = 1465.8, $Q = 114.7$ m³/s.

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.