HYDRAULIC MODEL STUDIES OF CHUTE OFFSETS, AIR SLOTS, AND DEFLECTORS FOR HIGH-VELOCITY JETS

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16. ABSTRACT
High-velocity jets discharging through slide gates into lined tunnels and chutes at outlet works installations have caused serious cavitation problems at several structures. To prevent cavitation erosion, air must be introduced along the underside and sides of a jet before the jet comes in contact with downstream concrete surfaces. Model studies of chute offsets, air slots, and deflectors were conducted to determine methods to aerate the jet and provide recommendations for altering two existing structures and designing new structures. A single test facility was used to model existing structures at Palisades and Navajo Dams and proposed structures at Pueblo, Crystal, and Teton Dams. Wall air vent slots combined with a floor deflector were developed for use immediately downstream from the gate frames in the two existing structures. Wall and floor air vent offsets away from the flow at the end of the frame were developed for new structures. These investigations, supplemented by general research, formed the basis for guidelines developed for design of future air-entraining devices to protect flow surfaces from cavitation erosion. (3 references)

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PURPOSE

To develop design criteria for methods of entraining air in the bottom and sides of jets from slide gates discharging into concrete-lined tunnels and chutes at outlet works installations for the purpose of preventing cavitation erosion.

APPLICATIONS

The results of these studies are to be used in designing aeration devices for protection against cavitation erosion. Application is general, except in cases where the situation is considerably different from those tested. In that event, separate hydraulic model studies should be made.

INTRODUCTION

Value Engineering Team No. 8 was formed within the Bureau of Reclamation's Engineering and Research Center to study cavitation problems that have occurred and might be expected to occur downstream from outlet works slide gates. As a result, model studies were conducted of several structures including: existing structures at Palisades and Navajo Dams, two proposed structures at Pueblo Dam, a proposed structure at Crystal Dam (designed as an earth dam when these tests were conducted, later redesigned as a concrete dam), and two proposed structures at Teton Dam. The model studies were conducted to determine ways to aerate a jet from slide gates before the jet comes in contact with downstream concrete flow surfaces.

The air was to be introduced through wall and floor air-vent slots in existing structures and through wall and floor offsets away from the flow in proposed structures. The concrete surfaces to be protected were the walls and floors of rectangular conduits and sloping chutes or circular conduits downstream from the gate frames.

The investigation was concerned first with providing recommendations for alterations of existing structures, second with providing recommendations for proposed new structures, and third in providing some general guidelines for use in the design of future structures without the benefit of individual project model testing.

THE LABORATORY TEST FACILITY

The laboratory test facility, Figure 1, consisted of a 4-foot (1.2 meter) long by 24-inch (61.0 cm) diameter manifold drum discharging into a 6-inch (15.2-cm) pipe to a slide gate control valve. The model gate, Figure 2, used in most of the studies was the one used in the Palisades regulating slide gate study.[1] The gate was 4.73 inches (12.0 cm) wide by 5.68 inches (14.4 cm) high. Except for the initial Palisades aeration study, the gate was modified by attaching solid plastic inserts to the roof of the gate frame upstream and downstream of the gate leaf to provide a square opening through the gate. The 18-inch (45.7-cm) long transition upstream of the gate was also modified by inserting a crown filler that provided a smooth curved transition surface from the 6-inch (15.2-cm) pipe to the 4.73-inch-square (12.0 cm) opening through the gate.

The features of each model downstream from the gate were adjusted to conform to each of the different prototype configurations tested. The model scale in each project study was determined by the ratio of the model and prototype gate widths.

PALISADES DAM OUTLET WORKS

Description

The outlet works tunnel and power tunnel at Palisades Dam, Figure 3, are designed to release flows up to 46,100 cfs (1,304.6 cms) through six 7-foot 6-inch (2.3-meter) by 9-foot (2.7-meter) regulating slide gates and two hollow jet valves under a maximum head of 235 feet (71.6 meters). The slide gates, operating alone or in pairs, are designed to discharge up to approximately 6,500 cfs (184.0 cms) each through a short rectangular covered passageway onto a trajectory chute to the stilling basin, Figures 3 and 4.

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[1] "Hydraulic Model Studies of the 7-foot, 6-inch (2.29-m) by 9-foot, 0-inch (2.74-m) Palisades Regulating Slide Gate, Palisades Project, Idaho," by W. P. Simmons Jr., U.S. Bureau of Reclamation, HYD-387, June 21, 1954.

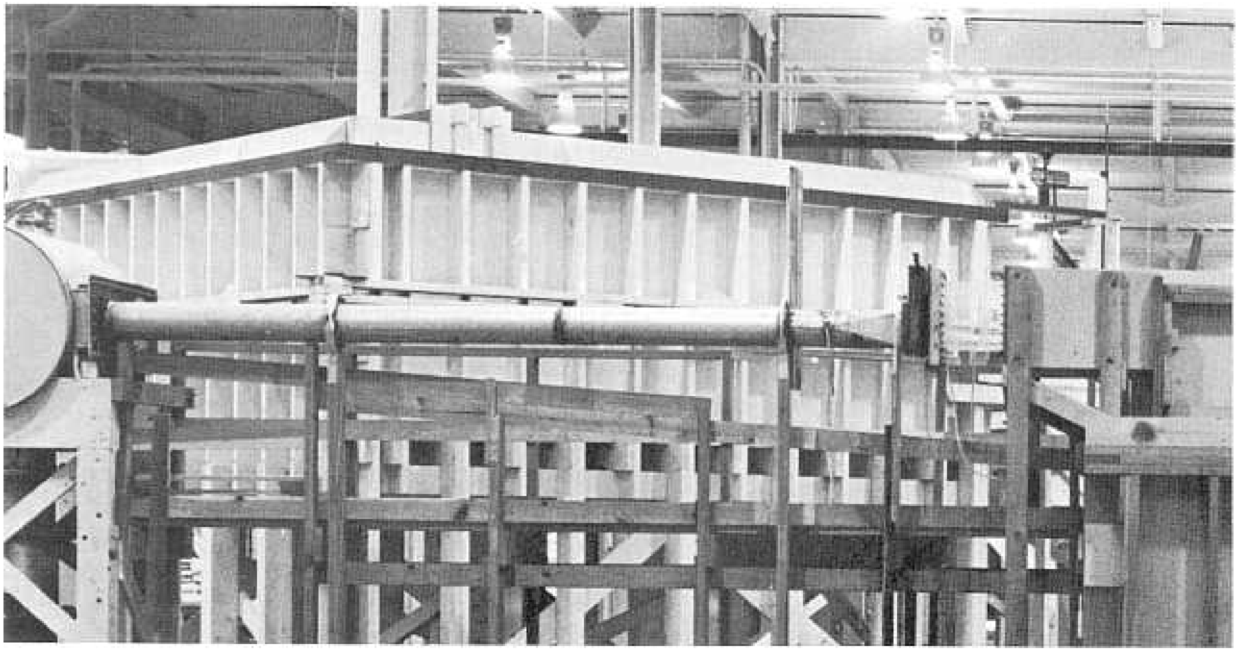


Figure 1. The laboratory test facility. General side view as constructed for the Palisades Outlet works model. Photo P801-D-73178

The outlet works operated at heads near 220 feet (67.1 meters) in 1964, 1966, 1967, and 1968 at gate openings ranging from approximately 8 to 45 percent of full open position. Minor cavitation erosion was noted in the concrete walls and floor downstream from the gate frame. Extensive cavitation erosion occurred in the floor of the trajectory chute downstream from Gates 1 and 2, Figure 5.

The Model

The value engineering test facility described above was used to provide a 1:19 scale model of one of the outlets, with a 7-foot 6-inch (2.3-meter) by 9-foot (2.7-meter) gate. The model included the covered passage downstream from the gate and a 17-foot (5.2-meter) wide section of the open chute and stilling basin.

The model pressure head in the transition section upstream of the gate was computed for various assumed operating conditions, including those that existed in the prototype just prior to the discovery of the cavitation erosion. The model was operated by regulating the gate opening to control the pressure head and by adjusting the supply valve to set the discharge.

For full open gate discharge at maximum reservoir elevation, the tailwater was set at elevation 5383 feet (1640.7 meters), 4.5 feet (1.4 meters) above the invert of the gate. This is approximately the tailwater elevation expected when both the outlet works and power tunnels are operating at full capacity. Using this tailwater gate setting, the tailwater was normally allowed to seek its own level for smaller discharges. However, the hydraulic behavior of the jet penetrating the stilling basin also was evaluated for both higher and lower tailwater elevations.

The Investigation

First modification.—A 12-inch (30.5-cm) wide by 12-inch (30.5-cm) deep slot was installed around the perimeter of the 9-foot (2.7-meter) high section immediately downstream of the steel gate frame, Figures 6 and 7a. Even though the slot was vented to the atmosphere at the ceiling, it filled with water along the bottom and up the sides at most operating conditions. Rounding and offsetting the downstream edges of the slot away from the flow did not prevent the slot from filling. Sloping the floor of the gate frame upward from the gate seat to a 1-inch (2.5-cm) rise at the upstream

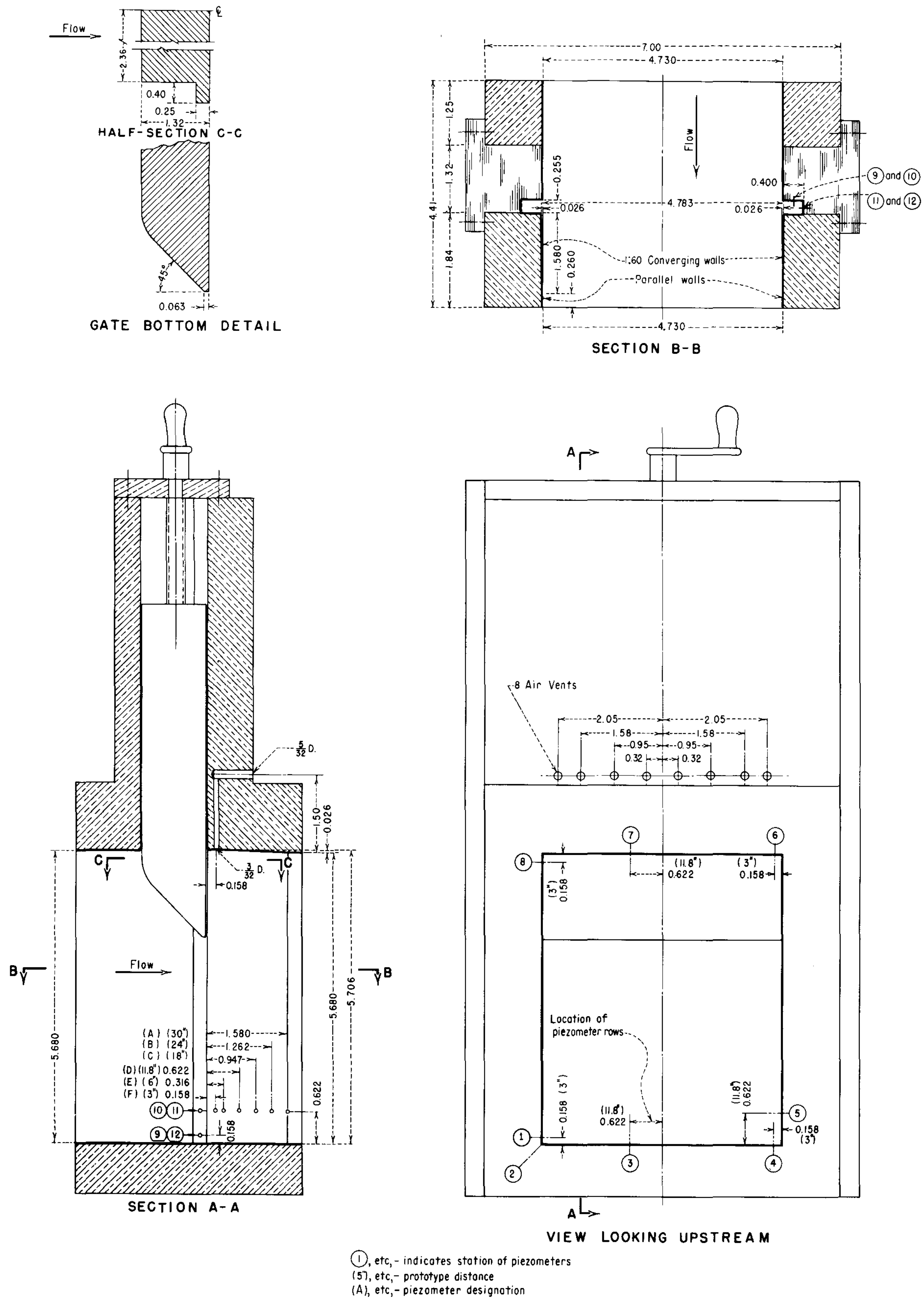
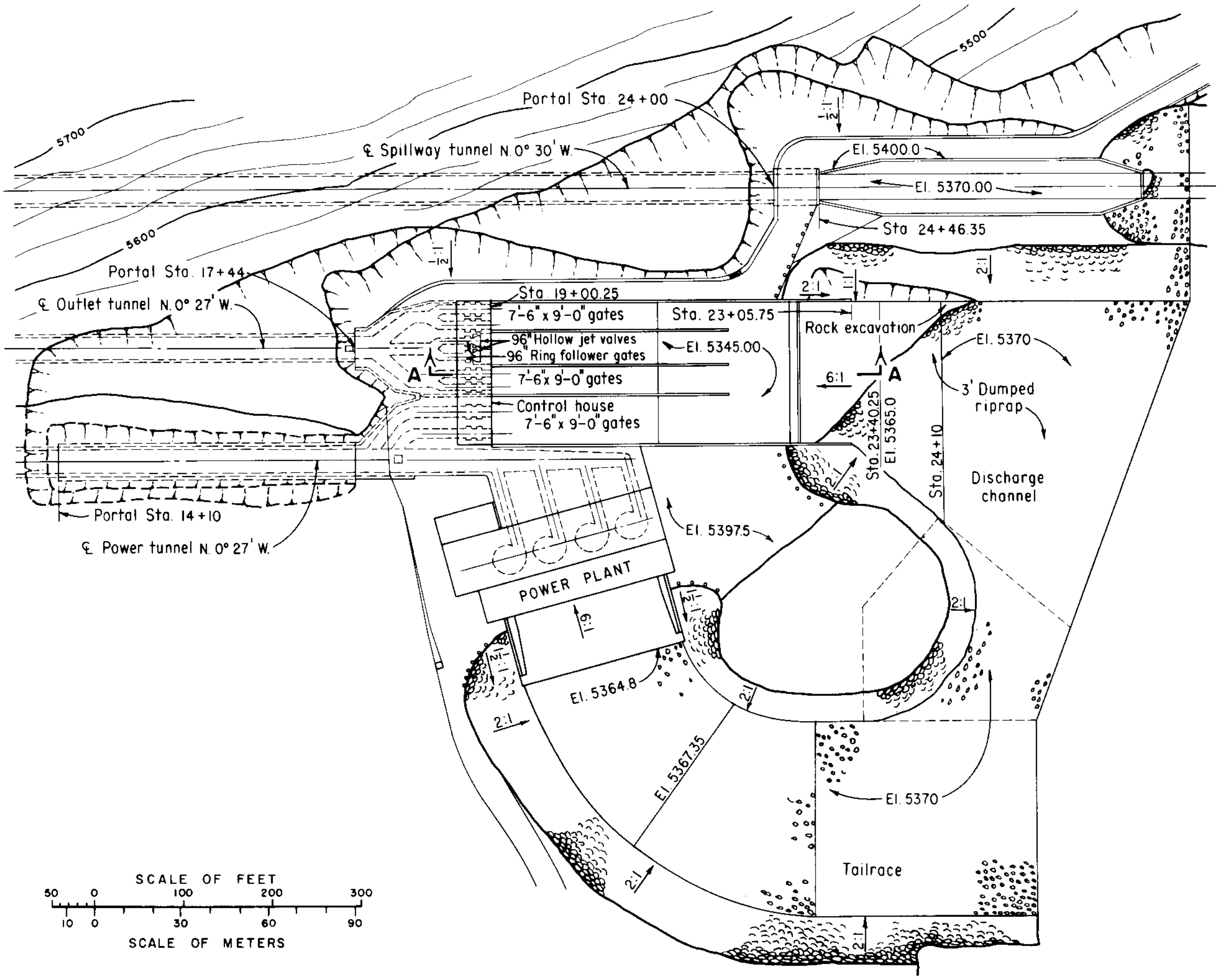
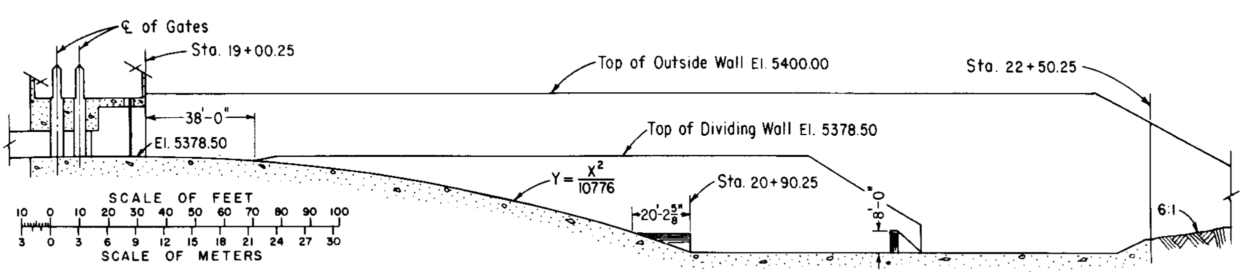


Figure 2. Palisades regulating slide gate model.



PLAN



SECTION A-A THROUGH OUTLET WORKS

Figure 3. Palisades Dam outlet works.

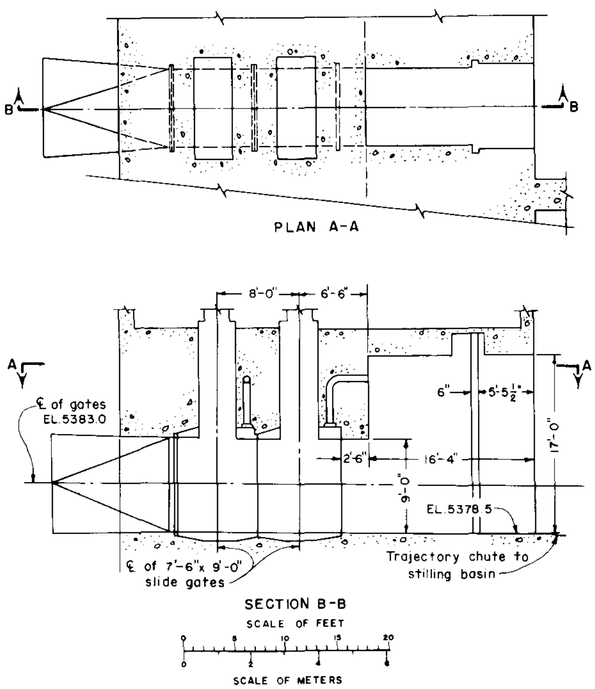


Figure 4. Palisades Dam existing outlet works gate and tunnel.

edge of the slot along the floor to deflect the flow upward was successful in providing an air space around the jet, even though the portion of the slot across the floor still filled with water. However, this formed a constriction in the gate frame and tended to reduce the discharge through the gate.

Second modification.—The 12- by 12-inch (30.5- by 30.5-cm) slot was relocated in the downstream end of the 30-inch (76.2-cm) long 9-foot (2.7-meter) high section, Figure 7b. This provided an 18-inch (45.7-cm) length of concrete wall and floor in which steel-lined converging surfaces could be installed to deflect the flow away from the concrete walls and floor to provide an air space around the flow. The first deflectors installed sloped upward from the gate to the air slot and inward on the walls at the rate of 1 on 9 to provide a 2-inch (5.1-cm) projection at the air slot. The jet sprang free of the walls and floor for all discharges, and air was drawn in through the wall slots to vent the circumference of the jet. However, the floor slot filled with water indicating that the floor slot was not needed.

Tests showed that the discharge coefficient was affected primarily by the wall deflectors rather than the floor deflector. The 2-inch (5.1-cm) high deflectors on the walls, sloping the full 18 inches (45.7 cm) from the gate frame, reduced the coefficient from about 0.94 to about 0.85 at full opening. The wall deflectors, with a 3-inch (7.6-cm) deflector on the floor, caused a large, high fin of water on the centerline of the jet that impinged on the ceiling at the portal when the gate openings were reduced to less than 43 percent at near maximum heads.

Third modification.—In the third modification, Figure 7c., the floor slot was abolished and the width of the side slots was reduced to 6 inches (15.2 cm), thereby lengthening the wall and floor deflectors to 24 inches (61.0 cm). This longer deflector reduced the slope of the 2-inch (5.1-cm) wall deflectors to 1 on 12, while the floor deflector was modified to provide a 1 on 8 slope to a 3-inch (7.6-cm) offset above the floor.

This arrangement did not provide adequate ventilation under the nappe at the floor deflector, since the jet fluttered at gate openings of less than 50 percent. The subatmospheric pressure beneath the jet was great enough to pull the trajectory of the jet down, reduce the volume of the air void beneath the jet, and demand more air which relieved the pressure in the void and allowed the jet to lift. This caused the flutter which in turn caused excessive surges in the stilling basin.

Recommended design modifications.—A 12- by 12-inch (30.5- by 30.5-cm) slot was placed in the walls of the 16-foot 4-inch (5.0-meter) covered passage immediately downstream of the 30-inch (76.2-cm) long, 9-foot (2.7-meter) high section. At this location, the top of the wall slots terminated in the walls of the 17-foot (5.2-meter) high section of the outlet, thus eliminating the need for vent pipes in the roof of the outlet. A floor slot was not used.

Initially, a 2-inch (5.1-cm) rise in the sidewall deflectors and a 4-1/8-inch (10.5-cm) rise in the floor deflector were tested and proved unsatisfactory. At gate openings of less than 25 percent with maximum reservoir elevation, this floor deflector caused the jet to spring free of the entire length of the chute trajectory to the stilling basin pool. The free jet in penetrating the pool created very unstable flow conditions in the basin. At full gate opening, the side deflectors deflected the flow away from the sidewalls, the full length of the covered section, but at gate openings less than 43 percent, high fins of water formed along the sidewalls reaching the ceiling of the covered passage at near maximum head.

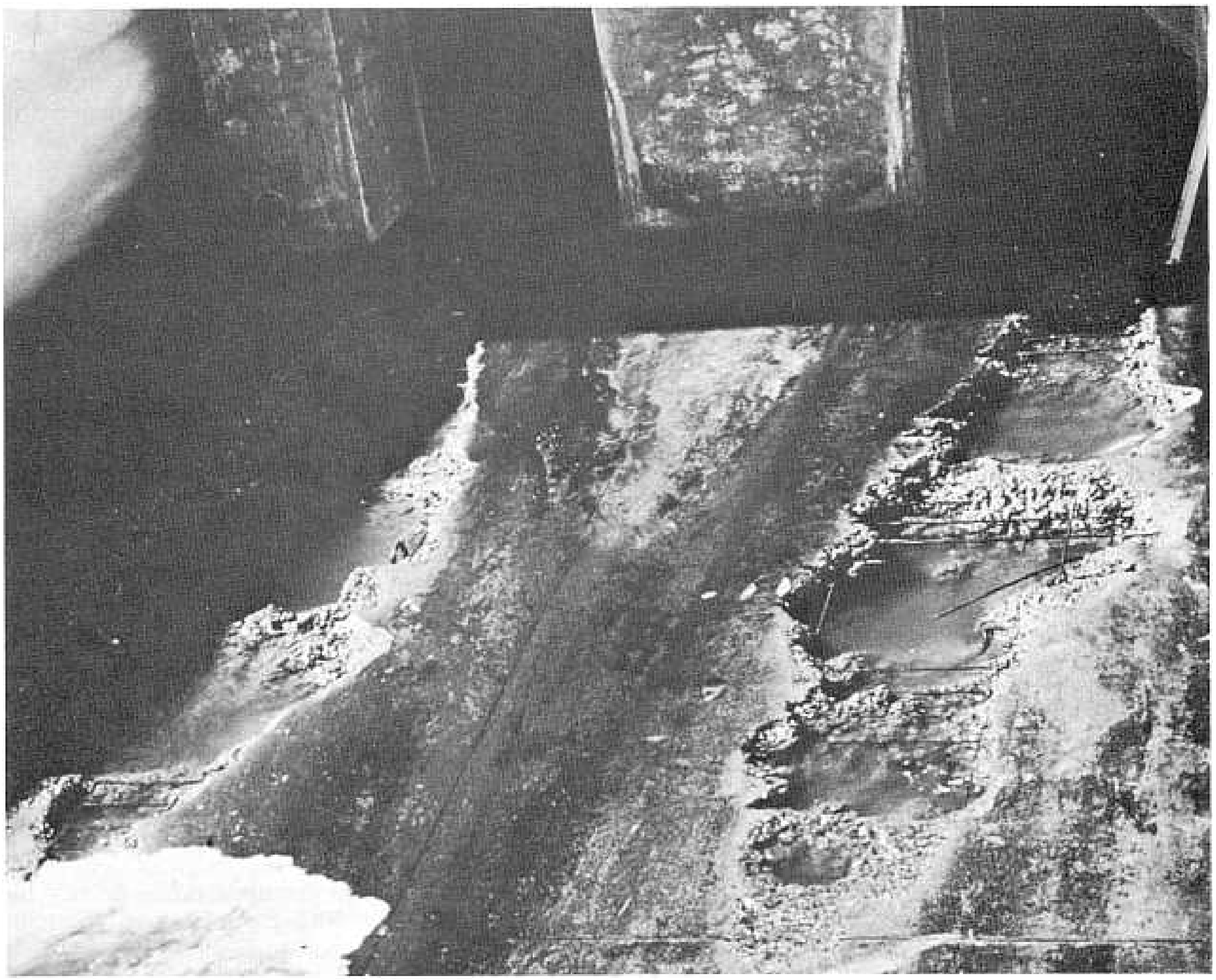


Figure 5. Cavitation erosion at Palisades Dam outlet works portal. Photo P546-D-45224NA

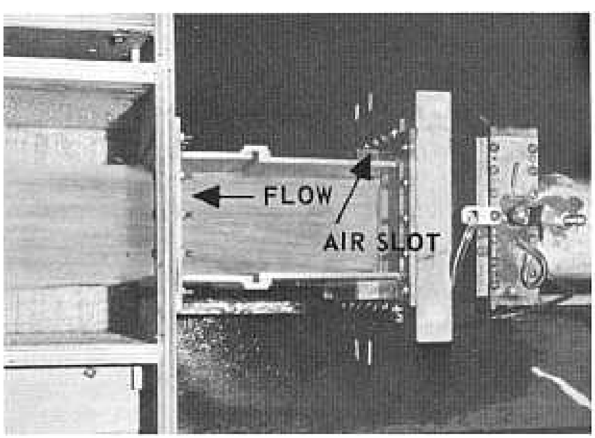


Figure 6. Palisades Dam outlet works 1:19 scale model. Top view with roof of covered section removed (see side view in Figure 1). Photo P801-D-73173

For the recommended modification, the height of the floor deflector was reduced to 2-1/2 inches (6.4 cm) and the inward projection of the wall deflectors was reduced to 1 inch (2.5 cm), Figure 7d. The wall and floor deflectors were each 30 inches (76.2 cm) long. The air slots in the walls extended to 11 feet (3.4 meters) above the floor. The downstream edge of the slot was offset outward approximately 1 inch (2.5 cm). The sidewalls converged at the rate of 1:20 to meet the existing wall surface.

This deflector arrangement lowered the discharge coefficient at full open gate from about 0.94 to approximately 0.90. This was an acceptable 4 percent reduction.

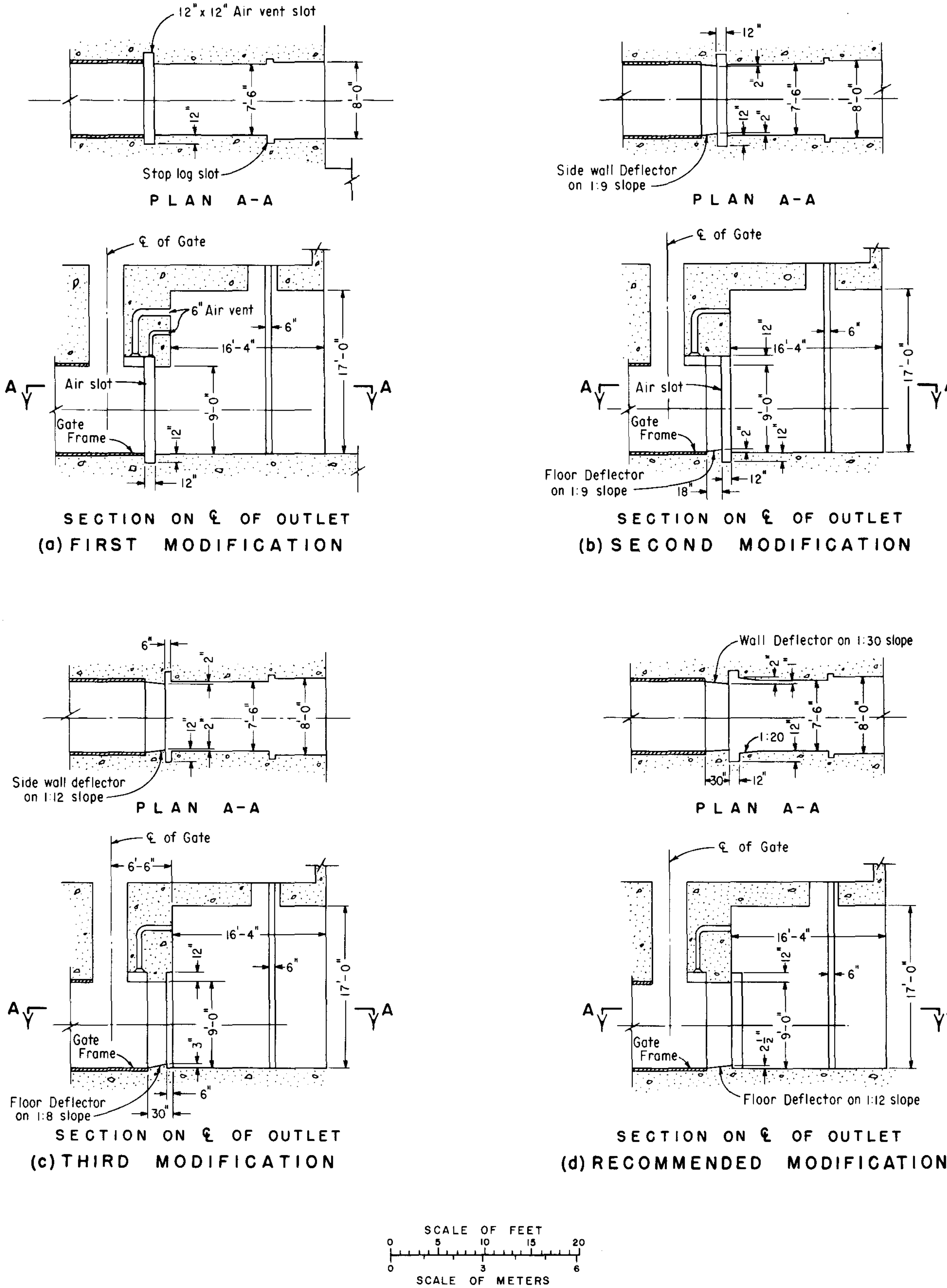


Figure 7. Palisades Dam outlet works modifications.

At full open gate and maximum head, the jet sprang free of the walls and floor to a point slightly beyond the portal of the covered section, Figure 8. As closure of the gate began, the point of impingement of the jet on the floor and walls moved upstream of the portal and was farthest upstream at near 75 percent gate opening, Figure 9a. At gate openings less than 75 percent, the point of impingement moved farther downstream beyond the portal. At 43 percent gate discharging at maximum head, a narrow layer of the top water surface of the jet impinged against the sidewalls to cause a thin fin of water to spread upward on the wall, Figure 9b. A fin of water occurred also on the centerline but neither of these reached the roof of the portal at this or any other gate opening.

The head was lowered to determine the discharge and velocity at which water began to accumulate in the bottom of the air slots. This is when the air void under the nappe completely filled with water to prevent any further aeration of the flow. The stoplog slots, normally, served to aerate the flow along the downstream wall surface. The point at which these slots began to fill with water was also noted in the tests. The results of these tests are shown in Table I.

Thus, for releases at heads exceeding those at which the air slots begin to fill shown in Table I, the jet will be aerated along the sides and across the bottom. For releases at lower heads, the flow velocity is considered too low to cause cavitation erosion.

Pressure taps installed in the air slots and the stoplog slots about 1 foot (0.3 meter) above the floor, Figure 10, showed the pressures to be slightly below atmospheric when the slots were vented. This assures movement of air into the slots and onto the flow surfaces.

Black and white photographs, color slides, and 16mm color movies of the outlet operation were obtained for a range of gate openings from 8 to 100 percent.

NAVAJO DAM AUXILIARY OUTLET WORKS

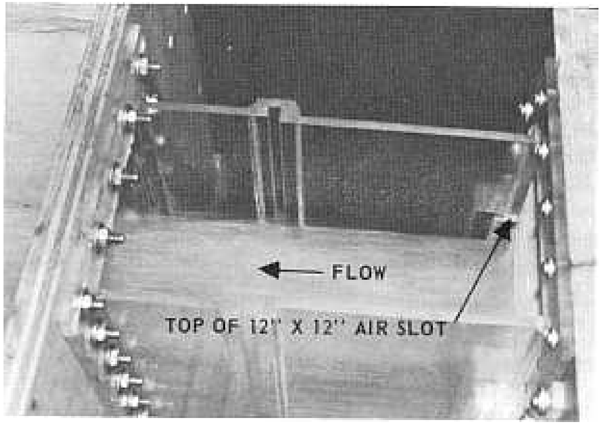
Description

The auxiliary outlet works at Navajo Dam, Figure 11, is an existing structure capable of releasing up to 1,790 cfs (50.7 cms) at maximum reservoir, 330 feet (100.6 meters) above the centerline of the gate. The release is from a 4- by 4-foot (1.2- by 1.2-meter) regulating gate into a 6-foot (1.8-meter) wide by 8-foot (2.4-meter) high flat bottom tunnel. The length of the tunnel is about 875 feet (266.7 meters) from the gate frame to the outlet portal in the spillway chute. The original operating instructions were to use the auxiliary outlet works only when the reservoir was at or below elevation 5920 feet (1804.4 meters) except under unusual circumstances. This limited the head to approximately 150 feet (45.7 meters) under normal operating conditions and, thus, minimized the possibility of cavitation erosion. However, it has become necessary to release flows up to 500 cfs (14.2 cms) at reservoir elevation 6085 feet (1854.7 meters) under a total head of approximately 314 feet (95.7 meters).

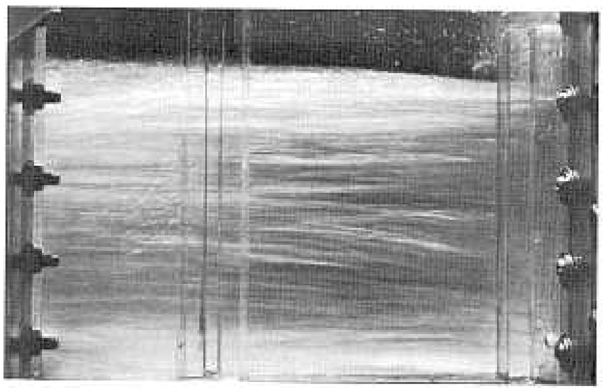
Table I

PALISADES OUTLET WORKS MODEL TEST DATA SUMMARY

Gate opening %	Head at gate ft (m)	Discharge cfs (cms)	Velocity at gate leaf ft/sec (m/sec)	Remarks
100	52 (16)	3,800 (107.5)	56 (17.1)	Nappe barely aerated; stoplog slots began to fill
100	36 (11)	3,200 (90.6)	47 (14.3)	Air slots began to fill (see Figure 10)
97	42 (13)	3,400 (96.2)	52 (15.9)	Stoplog slots began to fill
97	37 (11)	3,200 (90.6)	49 (14.9)	Air slots began to fill
75	28 (9)	1,800 (51.0)	35 (10.7)	Both air slots and stoplog slots began to fill
50	18 (5)	900 (25.5)	27 (8.2)	Stoplog slots began to fill
50	14 (4)	800 (22.7)	24 (7.3)	Air slots began to fill



Top view—Roof removed. Photo P801-D-73172

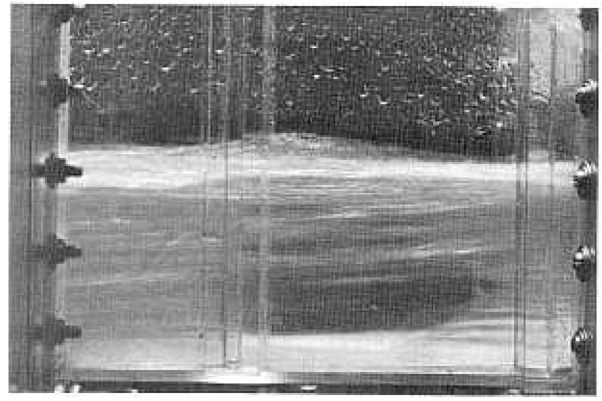


Side view of 16-foot 4-inch (5.0-meter) long passage. Photo P801-D-73176

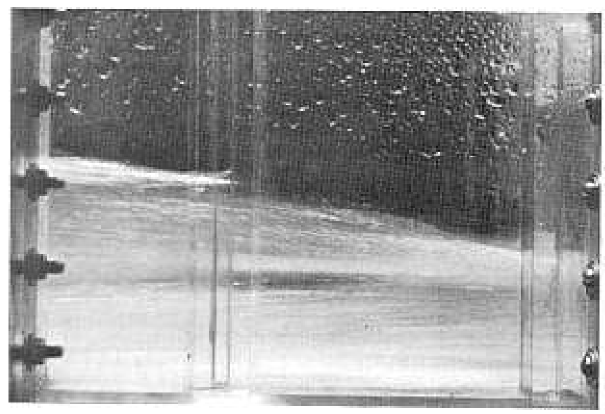
Figure 8. Palisades Dam outlet works—Recommended modification discharging at full open gate at maximum head.

The Model

The value engineering test facility was used to provide a 1:10.1 scale model of the 4- by 4-foot (1.2- by 1.2-meter) regulating slide gate and downstream tunnel, Figure 12. The model included the regulating gate, the gate frame, and the 30-foot 3-inch (9.2-meter) long tunnel transition plus 80 feet (24.4 meters) of the tunnel downstream from the transition. The model was operated at gate openings ranging from 12.5 to 100 percent with the reservoir ranging from elevation 5970 feet (1819.7 meters) to 6101.6 feet (1859.8 meters) which provided a total head of 199 feet (60.7 meters) and 330 feet (100.6 meters), respectively.



a. Seventy-five percent gate discharging at maximum head. (Note: The dark area in the flow designates impingement of the jet on the glass walls. The impingement ends at the stoplog slot. Impingement on the floor is at about the same distance downstream.) Photo P801-D-73175

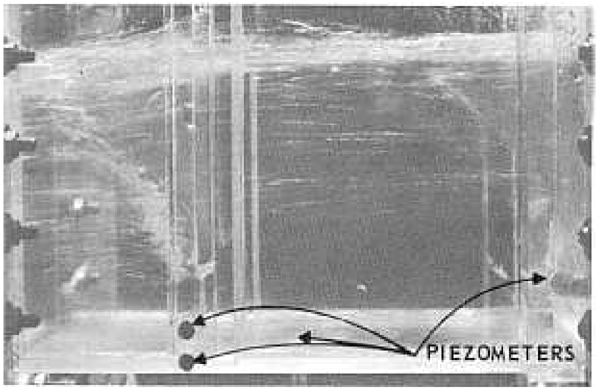


b. Forty-three percent gate discharging at maximum head. (Note: The narrow dark layer that ends at the stoplog slot is the impingement of the water surface on the glass walls from which a thin fin of water spreads upward. Impingement on the floor is downstream from portal.) Photo P801-D-73174

Figure 9. Palisades Dam outlet works—Recommended modification discharging at partial gate openings (flow is from right to left).

The Investigation

Recommended modification.—A 2-inch (5.1-cm) high by 18-inch (45.7-cm) long deflector was installed in the floor downstream from the gate frame, and 12- by 12-inch (30.5- by 30.5-cm) air slots were installed in the sidewalls, Figure 13.



Stop log slots are partially filled with water and the air slots are beginning to fill (flow is from right to left). Photo P801-D-73177

Figure 10. Palisades Dam outlet works—Recommended modification discharging 3,200 cfs (90.6 cms) at full open gate.

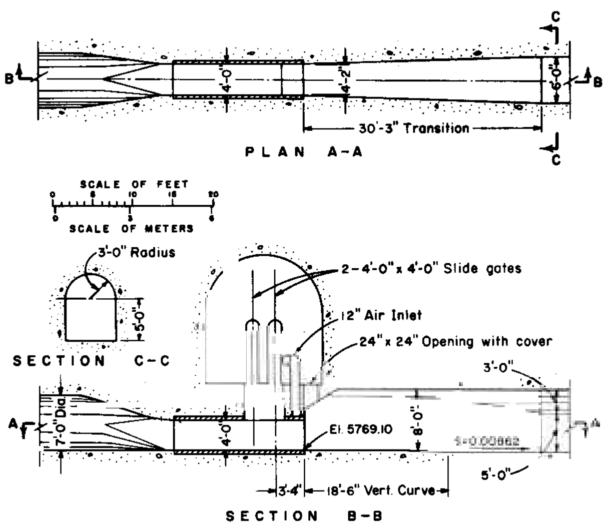


Figure 11 Navajo Dam auxiliary outlet works.

The air slots extended from the floor to the upward sloping ceiling in the tunnel. The sidewalls from the gate frame to the air slots were made parallel at the gate frame width of 4 feet 2 inches (1.3 meters). The downstream edges of the slots were rounded with 1-inch (2.5-cm) radii and offset 2 inches (5.1 cm) away from the flow with the walls remaining parallel downstream for a distance of 4 feet 6 inches (1.4 meters).

The deflector lifted the flow from the floor of the tunnel to aerate the underside of the jet. The parallel walls upstream of the air slots directed the flow away from the diverging walls downstream and provided an air space to aerate the sides of the jet.

It was difficult to see the air space under the jet at some flows, Figure 14, because of particles of water leaving the main flow to impinge on the walls and spread as a thin film of water on the invert. However, the slight subatmospheric pressures at the floor piezometers to the point of impingement gave proof of the aerated space.

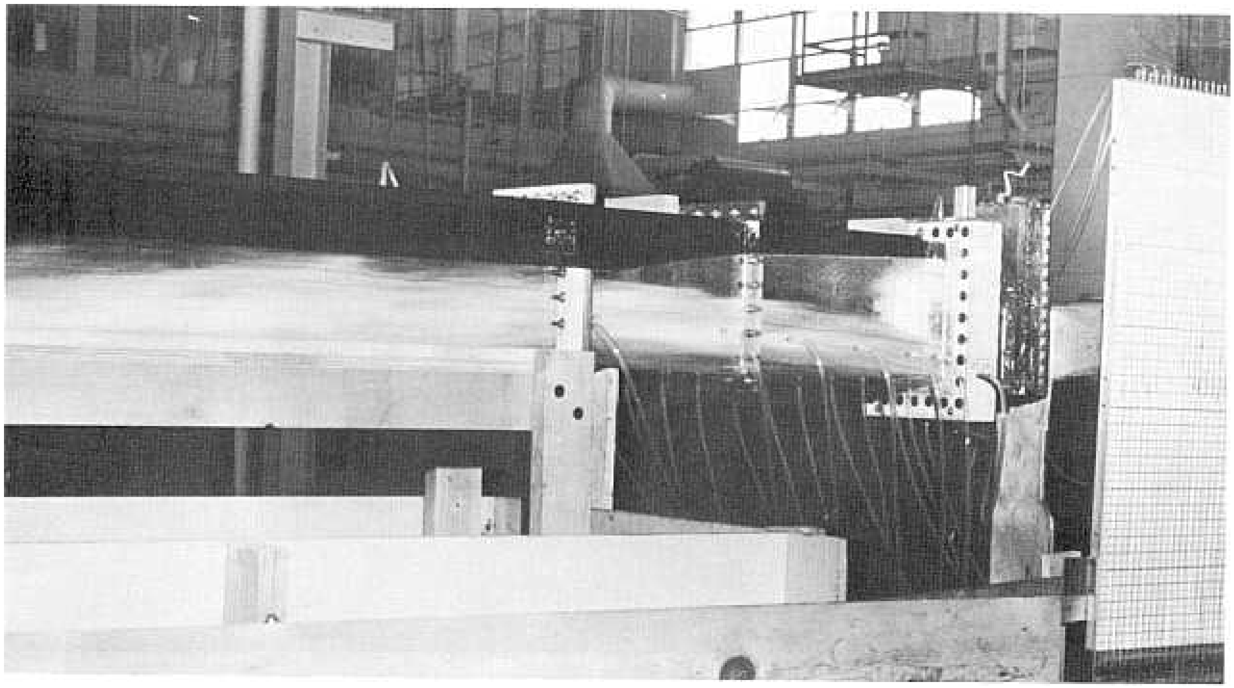
A small fin of water at the top of the air slot was deflected into the slot by the suction of air into the slots. Therefore, a thin layer of water about 1/2 inch (1.3 cm) deep (prototype) collected on the floor at the bottom of the slot and moved downstream with the airflow under the jet. Much of the deflected fin could have been prevented from entering the slot by reducing the width of the slot to 6 inches (15.2 cm), but the Palisades studies had shown that a narrower slot would not provide an adequate air supply to the sides and bottom of the jet. Although a 6-inch (15.2-cm) extension of the sidewalls into the slot, Figure 15, successfully prevented most of the water from entering the air slot, it was felt that this feature complicated the design beyond a practical limit. Therefore, the extension was not recommended for prototype use.

The subatmospheric pressures at the piezometers along the walls and floor of the transition, Figures 16 and 17, show the magnitude of the air demand in the air space under and around the jet. The pressures above atmospheric show the location at which the flow impinges upon the walls and floor of the tunnel.

All subatmospheric pressures recorded in the crown of the tunnel downstream of the transition, in the manhole cover near the gate frame vent, and in the air slot were nominal and of the magnitude needed to draw air into the tunnel and air slots.

The largest subatmospheric pressure was approximately 4 feet (1.2 meters) of water. This was observed in the air space below the lower nappe of the flow at Piezometer 3 on the floor of the tunnel a few feet downstream of the deflector. This occurred at full open gate and maximum head of 330 feet (100.6 meters).

At full gate opening, the gate frame flowed full and the existing air vent in the roof of the gate frame did not function. Lowering the gate leaf 2 to 3



Recommended design modification discharging from 50 percent open gate at 199 feet (60.7 meters) of head.

Figure 12. Navajo Dam auxiliary outlet works 1:10.10 scale model. Photo P801-D-73179

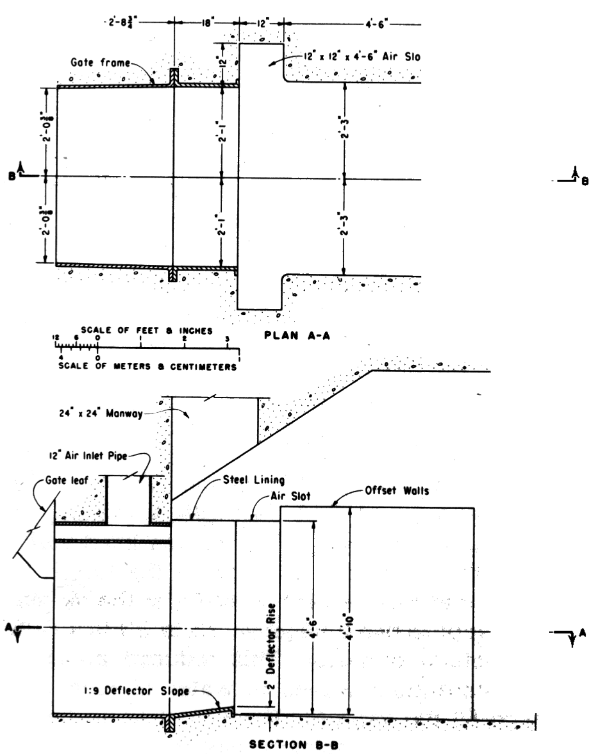


Figure 13. Navajo Dam auxiliary outlet works recommended modification.

inches (5.1 to 7.6 cm) into the flow caused the jet to spring free of the gate frame roof and the air vent functioned properly. However, whether the vent was functioning or not, most of the air came from the downstream portal along the crown of the tunnel. This was observed by the upstream movement of droplets of water along the crown of the clear plastic tunnel. Once the jet sprang free of the gate frame roof, the existing vent could be closed with no effect on the flow conditions; when the vent was open, it took in a considerable amount of air with no noticeable change in the piezometer pressures in the region of the air void. This suggested that the source of air was from the downstream portal when the vent was closed and from both the vent and the portal when it was open.

The water surface was below the springline of the tunnel at all operating conditions and did not interfere with the upstream flow of air from the portal. However, only 80 feet (24.4 meters) of the more than 800-foot (243.8-meter) long tunnel was modeled. To simulate the effects of a longer tunnel possibly hindering the flow of the return air, a board was placed over the downstream end of the model tunnel above the water surface, Figure 18. Thus, practically all of the space above the flow surface was blocked, but air still moved upstream.

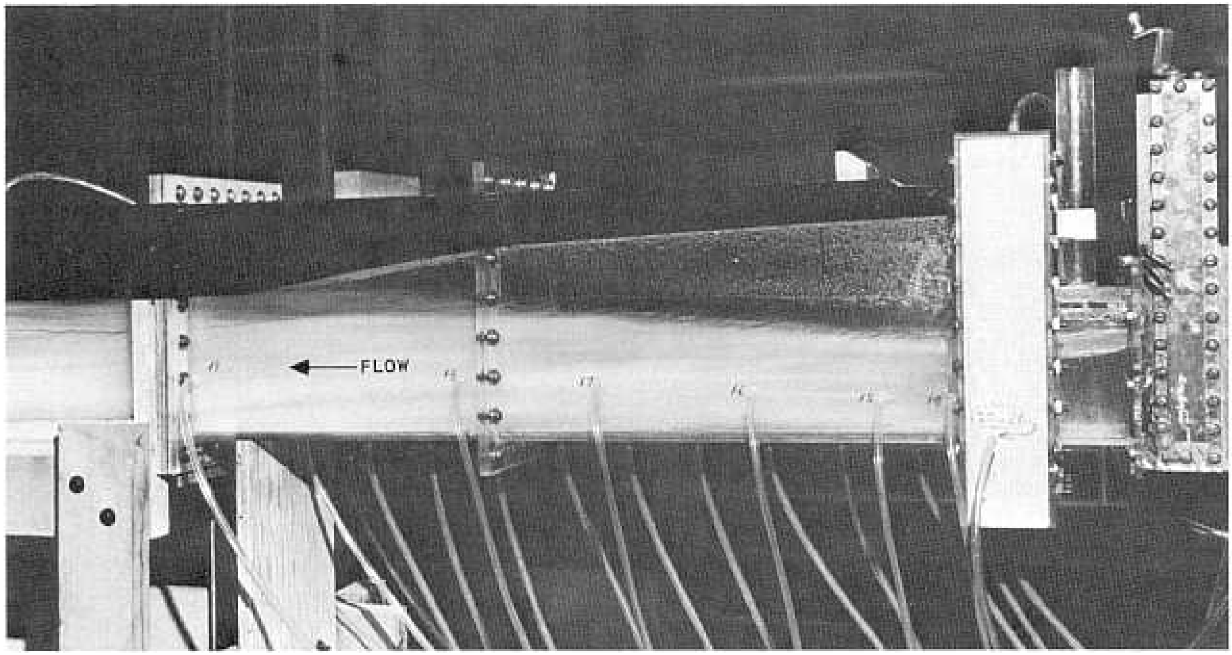
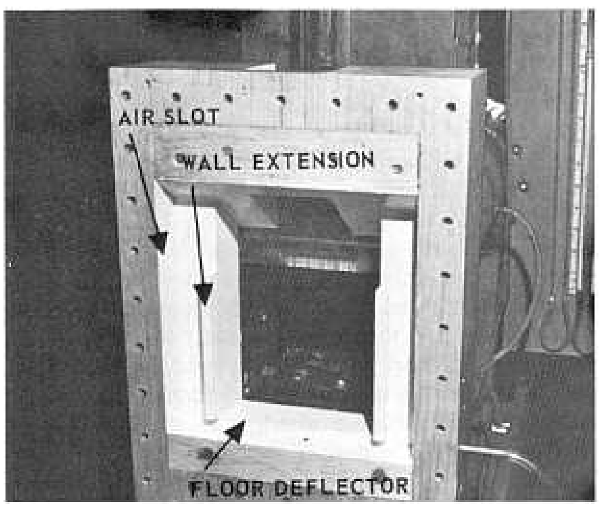


Figure 14. Recommended Navajo Dam auxiliary outlet works model discharging. Seventy-five percent open gate discharging at 314 feet (95.7 meters) of head. Photo P801-D-73181



Air slots are 12 by 12 inches (30.5 by 30.5 cm). Wall extension of 6 inches (15.2 cm). Floor deflector is a 2-inch (5.1-cm) rise in 18-inch (45.7-cm) length.

Figure 15. Navajo Dam auxiliary outlet works air slots, wall extension, and floor deflector. Photo P801-D-73180

The pressures under the nappe were not significantly affected until the board was actually lowered into the water surface approximately 1 foot (30.5 cm) below the springline. At this point the downstream end of the tunnel filled and the pressure above and below the jet suddenly approached a vacuum condition. This condition was relieved by uncovering the manhole in the tunnel ceiling to allow a large amount of air to be drawn into the tunnel.

As a result of this test, it is concluded that venting from the downstream portal will be adequate as long as a free surface exists in the tunnel. By closing the gate a few inches to spring the flow free of the gate frame ceiling, the existing vent in the roof of the gate frame will then supply some of the air demand.

Unsatisfactory modification.—A 3-inch (7.6-cm) floor deflector lifted the flow higher and farther downstream from the deflector and slightly increased the subatmospheric pressures under the flow at full gate opening, indicating some hindrance to the return airflow from the portal. With the gate 50 percent open at 313 feet (95.4 meters) of head, the upper surface of the jet was lifted sufficiently to block the return airflow in the tunnel to the extent that the ambient pressure at the air slot suddenly approached a negative 25 to 30 feet (7.6 to 9.1 meters) of water. This reduced pressure caused intermittent waves of water to rush upstream to fill the vacuum. The tunnel downstream from the transition completely filled with water, and severe vibration of the tunnel was experienced. With the space under the nappe filled with water,

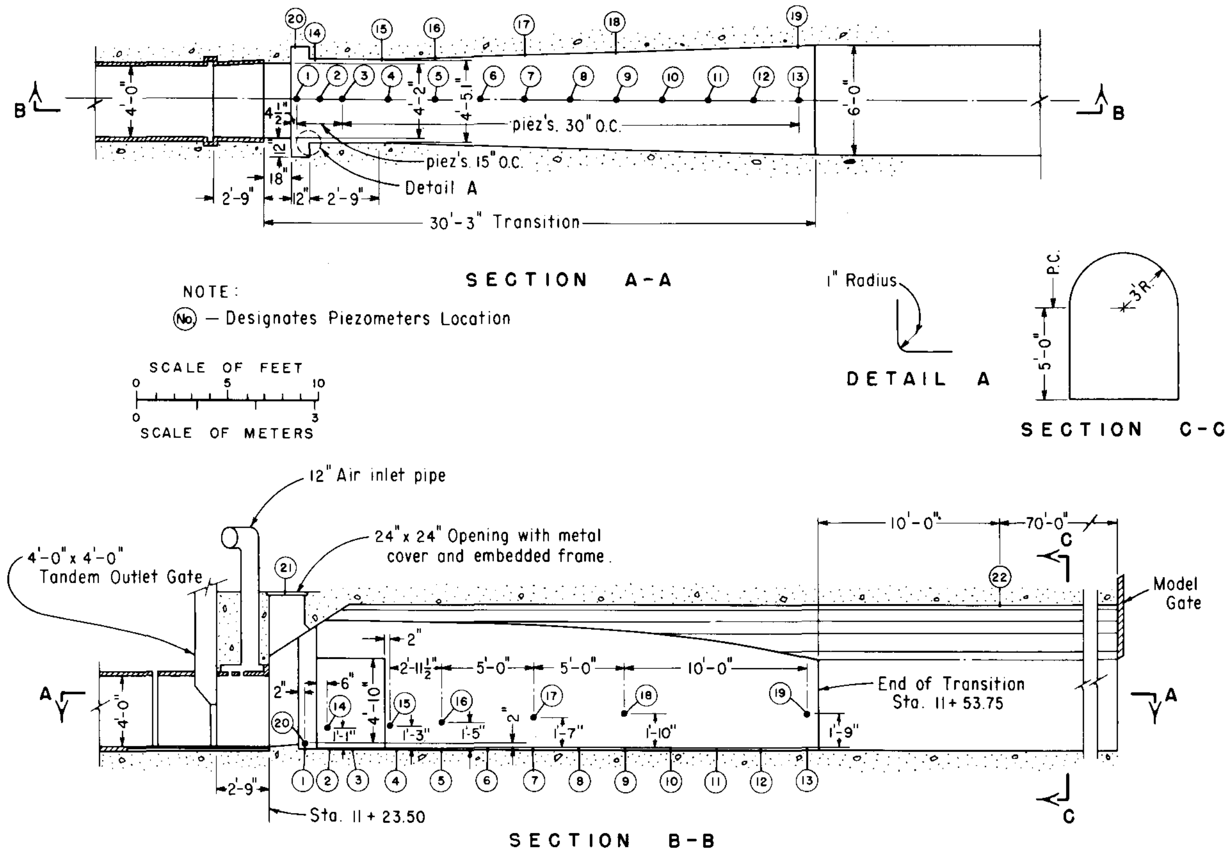


Figure 16. Piezometer locations in the recommended Navajo Dam auxiliary outlet works modification.

the jet was depressed and swept the water from under the jet and the process was repeated.

PUEBLO DAM OUTLET WORKS

Description

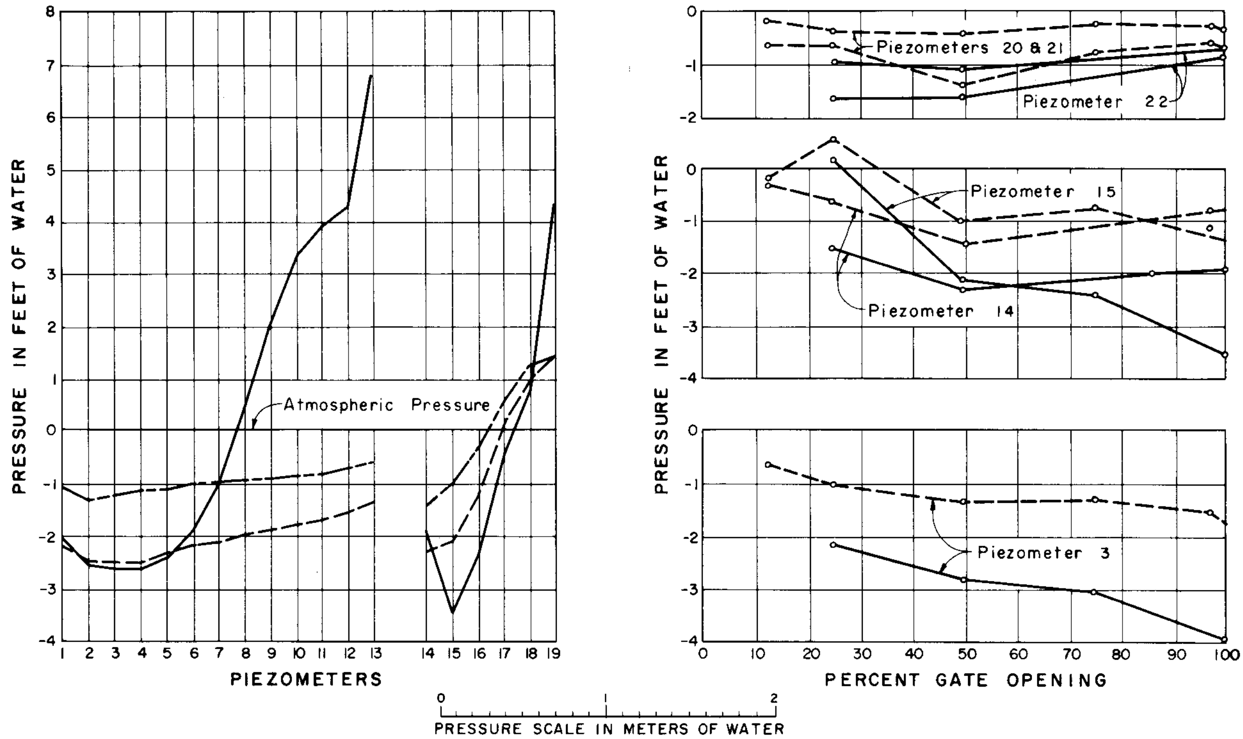
The outlet works at Pueblo Dam is a proposed facility consisting of three identical outlets through the concrete buttresses under the spillway (spillway outlet works) and an additional outlet in the buttress to the left of the spillway (river gorge outlet works). Sections through the outlets are shown in Figure 19.

The spillway outlet works will utilize 6-foot (1.8-meter) by 6-foot 6-inch (2.0-meter) high-pressure slide gates designed to release flows up to 3,080 cfs (87.2 cms) each at full gate opening with the reservoir at spillway crest elevation 4898.7 feet (1493.1 meters). This is a head of approximately 130 feet (39.6 meters) at the gate. Normally the releases will be controlled to a maximum of 1,500 cfs (42.5 cms) at heads as low as 28 feet (8.5 meters).

The river gorge outlet works will release 600 cfs (17.0 cms) from a 4- by 4-foot (1.2- by 1.2-meter) high-pressure slide gate at heads up to about 133 feet (40.5 meters). Fully open, the gate is capable of discharging 1,310 cfs (37.1 cms) at the maximum head of about 133 feet (40.5 meters) with the reservoir at the spillway crest elevation.

The Models

The value engineering test facility was used to provide a 1:15.19 scale model of one of the outlets under the spillway and a 1:10.10 scale model of the river gorge outlet. Each model included the regulating gate, the rectangular downstream conduit, and a portion of the tailwater area. The tailwater areas were not essential to this study but were included for the purpose of investigating the hydraulic characteristics of the jet penetration in the pool.



EXPLANATION

- – – 50 % Gate discharging at 199 feet (60.66 m) of head.
- —— 100 % Gate discharging at 259 feet (78.94 m) of head.
- – – – 50 % Gate discharging at 330 feet (100.58 m) of head.

EXPLANATION

- —— Total head at gate 330 feet (100.58 m)
- – – – Total head at gate 199 feet (60.66 m)

NOTES

Zero on the pressure scale is atmospheric pressure.
See Figure 16 for recommended design and piezometer locations
Ventilation from downstream end of tunnel was restricted and the manhole at upstream end was closed.

Figure 17. Pressures in the recommended modification Navajo Dam auxiliary outlet works.

Investigation of the Spillway Outlet Works

The preliminary design of the spillway outlet works was modified by offsetting the floor of the conduit 6 inches (15.2 cm) below the floor of the gate frame and offsetting the walls at that point 3 inches (7.6 cm) away from the flow. The gate frame extended 4 feet (1.2 meters) downstream from the gate, from which point the width of the conduit flared from 6-1/2 feet (2.0 meters) to 10 feet (3.0 meters) at the face of the buttress.

The offsets failed to aerate except when the gate was operated at near maximum head of 130.55 feet (39.8 meters). By installing at least two 3-3/4-inch (9.5-cm) diameter vents in the vertical face of the floor offset, the space around the jet leaving the gate frame aerated for a short distance downstream even when the head was reduced to only 30 feet (9.1 meters). The space under the jets aerated for even lower heads when the side offsets were eliminated. At all heads a shallow layer of water on the floor of the conduit backed up to the offset, so it was important to place the vents as far above the floor as possible.

A better method of aerating the under nappe was found by increasing the side offsets from 3 inches (7.6 cm) to 6 inches (15.2 cm) and the floor offset from 6 to 18 inches (45.7 cm). No vents were necessary in the vertical face of the offset. However, there was still a shallow layer of water on the horizontal floor downstream of the offset.

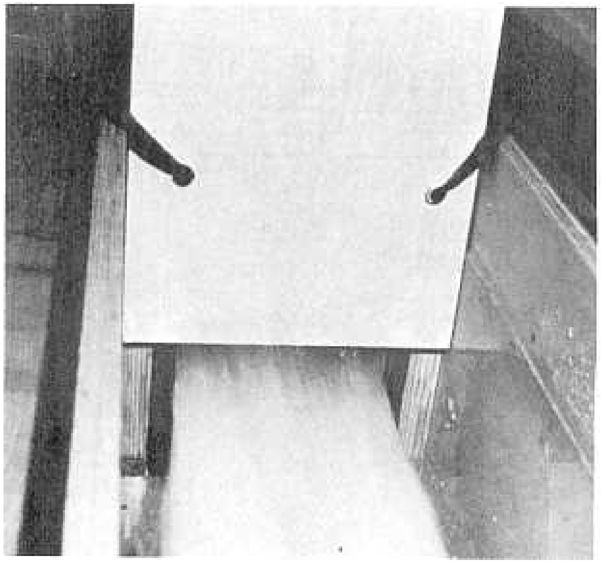


Figure 18. Return airflow obstruction at the portal of the Navajo Dam auxiliary outlet works model. Photo P801-D-73182

The final step in the development of the recommended design, Figure 20, was to slope the floor away from the offset at the rate of 1 on 8. To accomplish this the floor at the offset was raised to provide only a 12-inch (30.5-cm) offset at the gate frame, from which point the floor sloped for a distance of 44.56 feet (13.6 meters) to the point of curvature of the floor trajectory.

The hydraulic performance of this recommended design, Figure 21, was an improvement in that the jet from the gate frame was fully aerated and fins of water were almost nonexistent on the slightly diverging tunnel walls. Penetration of the jet into the pool was satisfactory. The jet was quite stable and the subatmospheric pressure below the nappe at the offset was nominal and steady for all flows. Satisfactory pressures were recorded on the trajectory of the conduit floor, Figure 22.

The distance from the offset to the point of impingement of the jet on the conduit floor is recorded in Table II. Of the flows recorded, only 1,500 cfs (42.5 cms) at the minimum head of 28.55 feet (8.7 meters) caused any flow to back up into the aerated space below the nappe, Figure 21. Even at this operating condition, the under nappe was still aerated; the backup water was only 1-inch (2.5-cm) deep at the 12-inch (30.5-cm) offset and could be reduced to zero by increasing the head to 33 feet (10.1 meters).

Table II

DISTANCE FROM OFFSET TO POINT OF IMPINGEMENT–PUEBLO DAM SPILLWAY OUTLET WORKS

Discharge cfs (cms)	Head ft (m)	Distance ft (m)
1,500 (42.5)	28.35 (8.6)	7.6 (2.3)
1,500 (42.5)	33.00 (10.1)	10.0 (3.1)
1,500 (42.5)	130.55 (39.8)	22.8 (7.0)
3,080 (87.2)	130.55 (39.8)	23.5 (7.2)

Investigation of the River Gorge Outlet Works

Recommended design.—The preliminary design of the river gorge outlet works, Figure 19, was modified to include aeration offsets. The recommended design, Figure 23, was patterned after the design developed for the spillway outlet works. The wall offsets were 1/12 the gate frame width and the floor offset 1/6, which provided offsets of 4 inches (10.2 cm) and 8 inches (20.3 cm), respectively, for the 4- by 4-foot (1.2- by 1.2-meter) gate. The slope of the rectangular conduit floor away from the offset was slightly less than the 0.1250 recommended for the three spillway outlets. It was set at 0.1203 to meet a minimum elevation requirement at the outlet end of the flow passage. The flare of the walls was slightly more, 0.0176 as compared to 0.0155, because of the wider buttress which permitted additional flare.

The hydraulic performance of the river gorge outlet, Figure 24, was satisfactory as designed except for some climbing of the walls by water fins 10 to 20 feet (3.0 to 6.1 meters) downstream from the offsets. However, because the tunnel conduit is high and rectangular this was not a problem.

Upon analyzing the performance of the two Pueblo outlet works, it can be concluded that the wall fins are more prominent for the river gorge outlet than for the spillway outlet. The wall offset at the river gorge outlet is only two-thirds that at the spillway outlet, yet the heads and wall divergences were nearly identical. Therefore, a minimum wall offset of 4 inches (10.2 cm) is recommended for any head to width ratio greater than that for the spillway outlet works (21.6:1).

Pressures were not recorded in the structure since there was no curvature in the chute floor. Flow conditions were stable and steady.

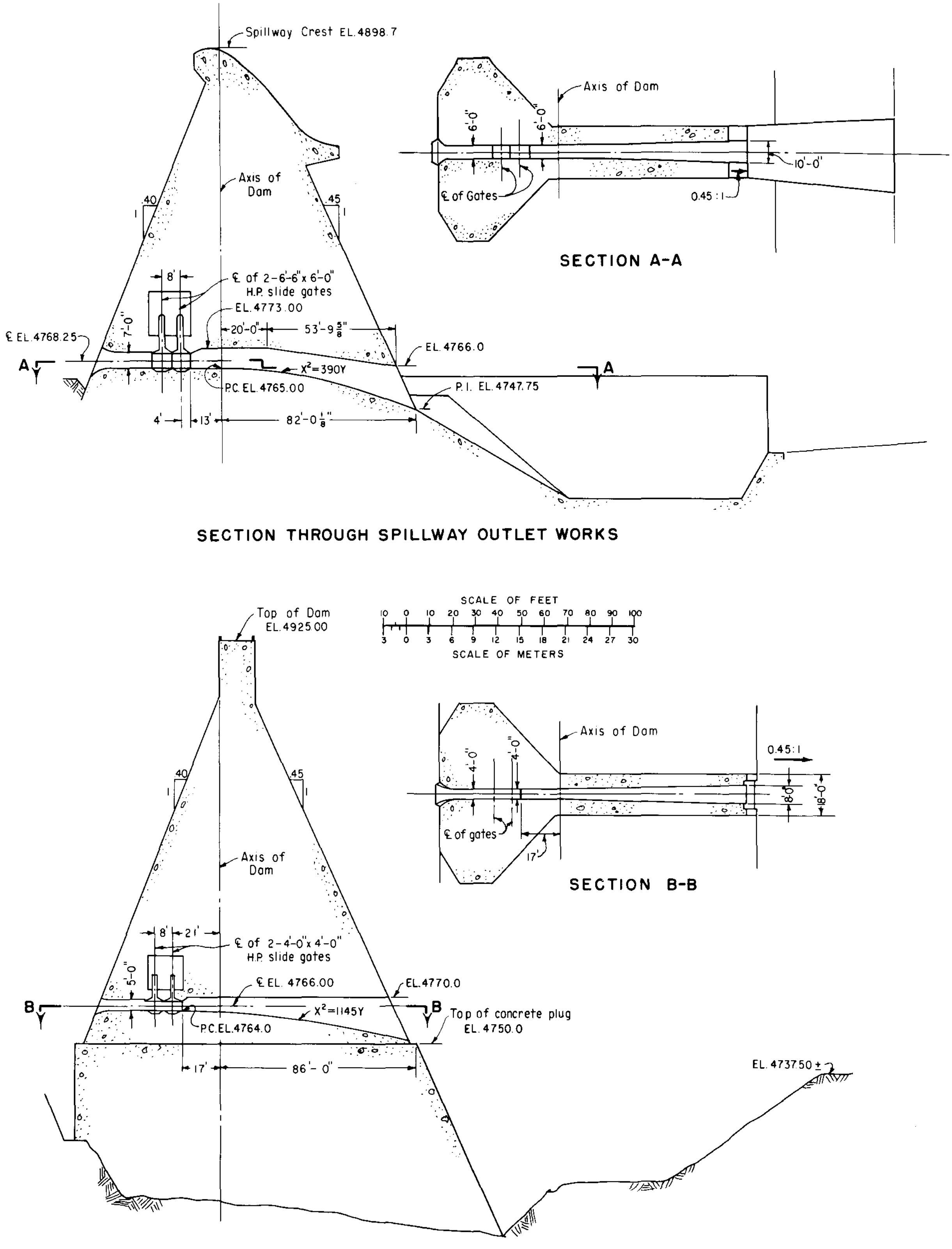


Figure 19. Pueblo Dam—Preliminary outlet works.

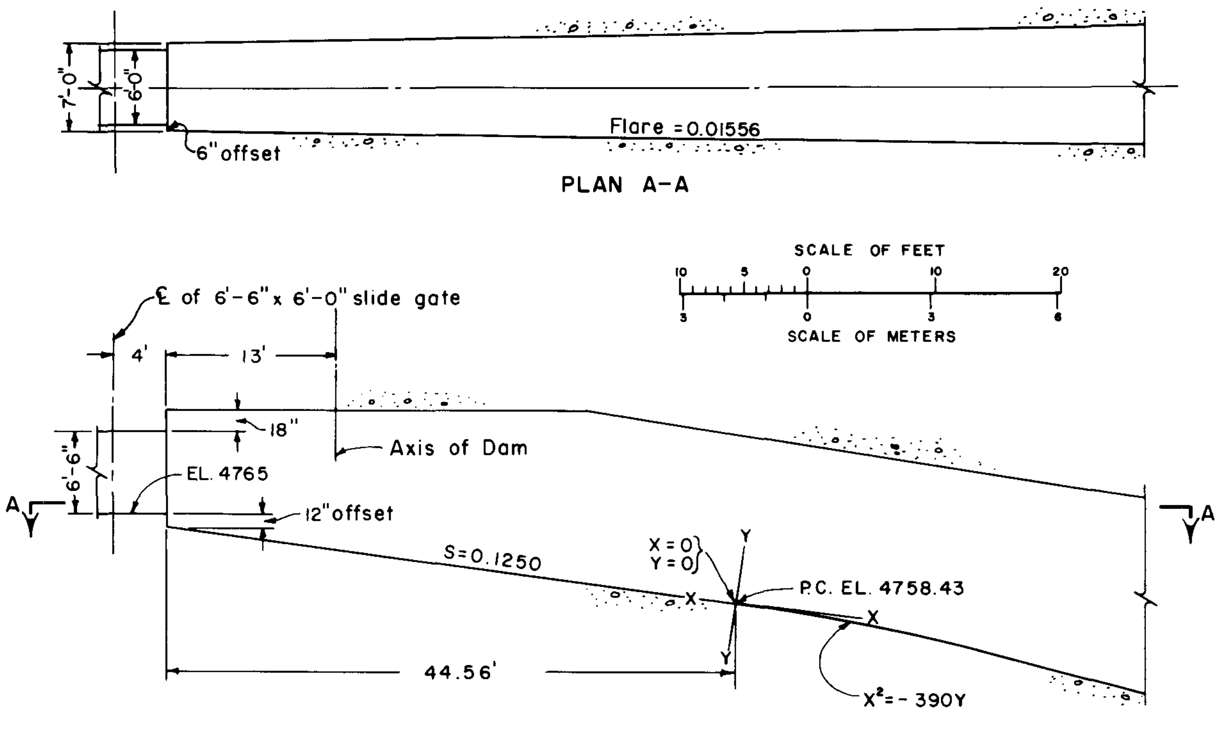


Figure 20. Pueblo Dam—Recommended spillway outlet works.

CRYSTAL (EARTH) DAM OUTLET WORKS

Description

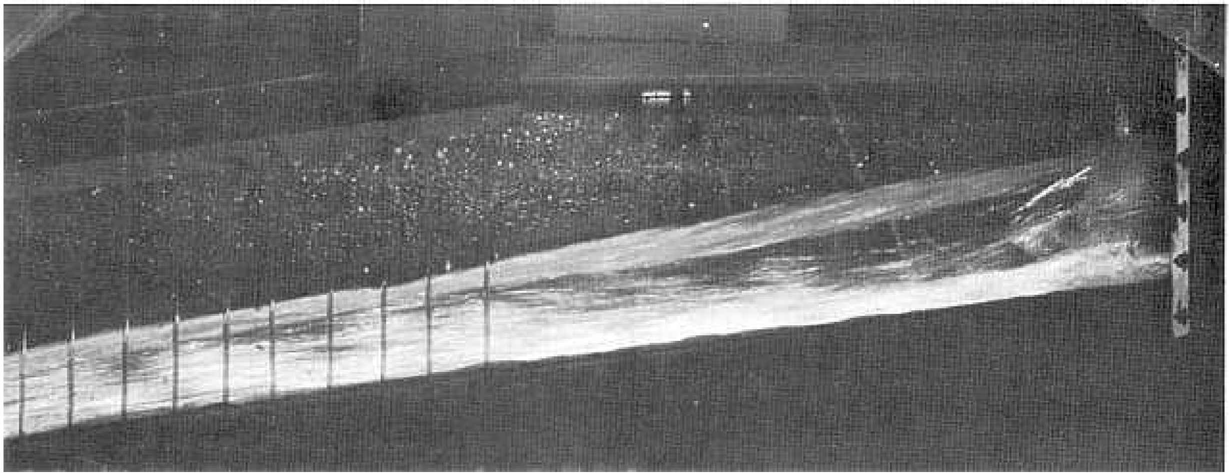
The outlet works at Crystal Dam (designed as an earth dam when these tests were conducted, later redesigned as a concrete dam), was a proposed facility consisting of two 3-foot 3-inch square (1.0-meter) high-pressure motor-operated slide gates installed side by side, Figure 25, each designed to release up to 980 cfs (27.7 cms) when operating together. When operating alone, one gate could release up to 1,060 cfs (30.0 cms) from maximum reservoir elevation 6750 feet (2057.4 meters) under a total head of 221.82 feet (67.6 meters). The gates were tilted downward 5° more than a 2:1 sloping chute, Figure 25, and discharged into a stilling basin with a center dividing wall. The 2:1 chute was lined with stainless steel in the upstream 10 feet (3.0 meters) of the chute. The walls of the gate frame and metal chute flared to a width of 3 feet 11-3/8 inches (1.2 meters), at which point there were 4-1/2-inch (11.4-cm) aeration offsets in the walls and a 9-inch (22.9-cm) offset in the floor. The offsets were recessed 9 inches (22.9 cm) into the concrete portion of the chute under and around the steel lining. The concrete chute walls flared at the rate of 0.0196 to the stilling basin. A curtain wall was hung from the basin roof just downstream from the offset for the purpose of preventing high tailwater from submerging the gates.

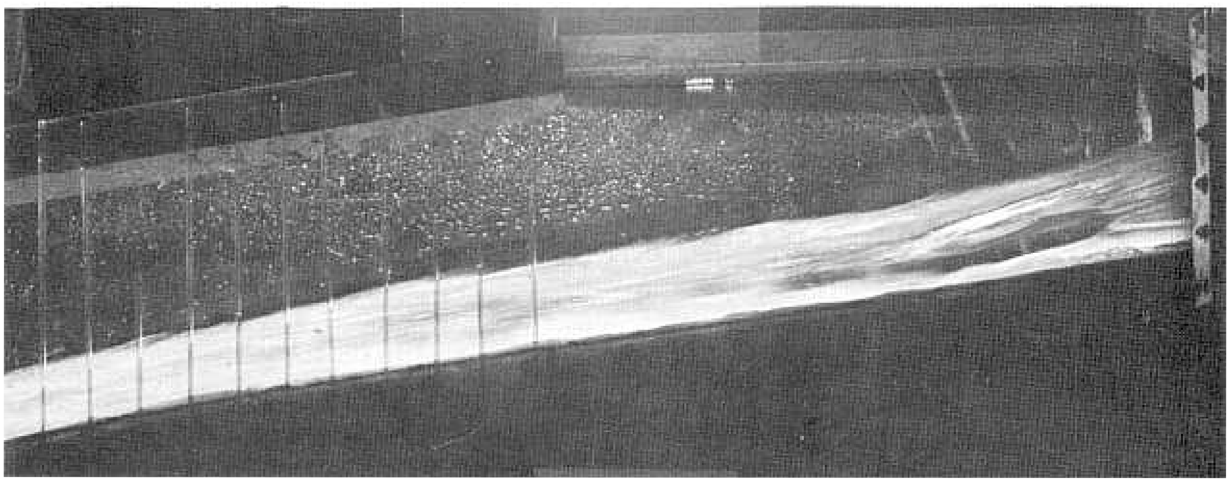
The Model

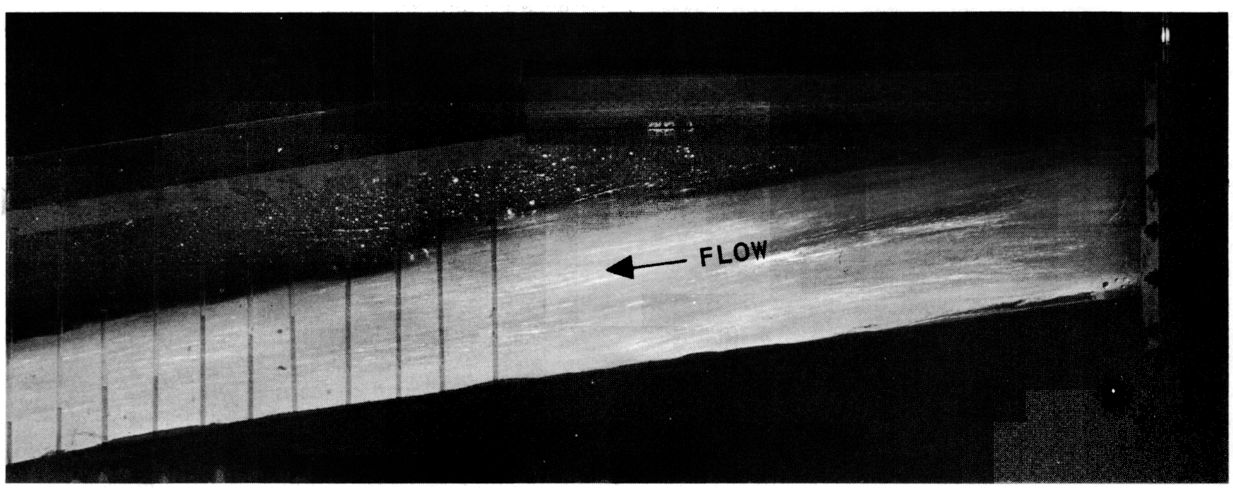
The value engineering test facility was used to provide a 1 to 8.21 scale model of the prototype. It included the gate, chute, and stilling basin. A tailwater regulating gate was installed at the downstream end of the horizontal basin floor.

The Investigation

The investigation was concerned with the range of discharges up to 950 cfs (26.9 cms) for one valve, as specified in Table III. The tailwater elevation varied depending upon whether or not the spillway was operating. Operation of the outlet works with spillway flows up to about 12,000 cfs (339.6 cms) before the hydraulic jump swept out of the spillway






FLOW

basin was of most interest because this produced the highest tailwater most apt to submerge the aeration offsets.

An earlier model study of the chute and stilling basin had shown that the water fins climbing the chute walls were reduced in magnitude by extending the walls from the gate frame 10 feet (3.0 meters) downstream before offsetting for air entrainment. This arrangement required the installation of cavitation resistant stainless steel walls from the gate to the offset.

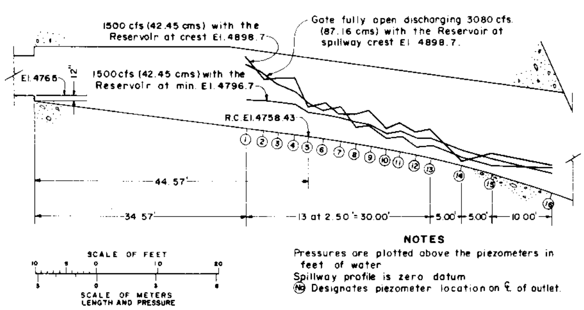


Figure 22. Pressures in the recommended Pueblo Dam spillway outlet works.

The studies described in this report indicate that offsets on the sides equal to 1/12 of the chute width and twice this amount on the bottom would be sufficient. This put the offset requirement at about 4 inches (10.2 cm) and 8 inches (20.3 cm) respectively, since the chute width at this point is 3 feet 11-3/8 inches (1.2 meters). However, since the space was available, minimum offset recommendations were exceed slightly. The offsets were made 4-1/2 and 9 inches (11.4 and 22.9 cm), respectively; and, in addition, were recessed 9 inches behind the steel lining, as described above.

The initial design of the chute and aeration offsets as tested was not modified and became the recommended design, Figure 25. Observation of the hydraulic performance, Figure 26, showed the jet to be fully aerated at the offset even at the highest

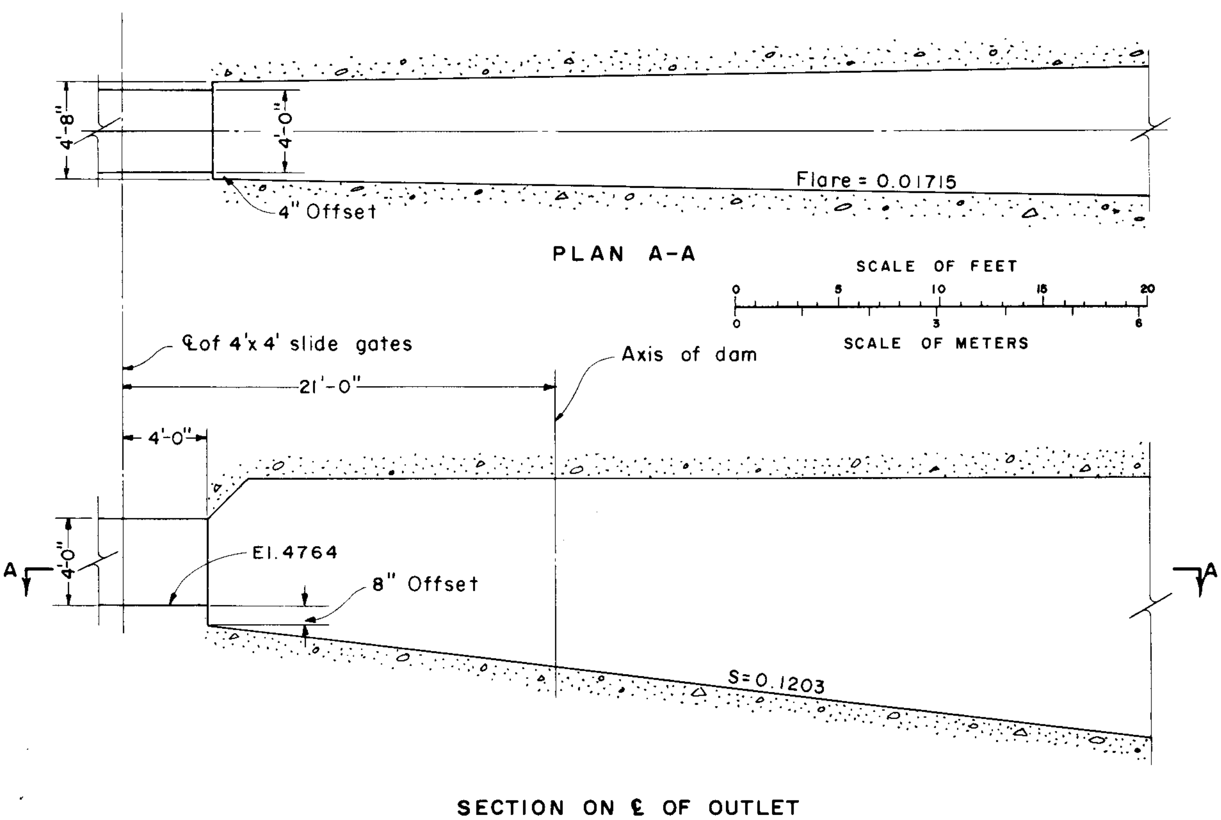
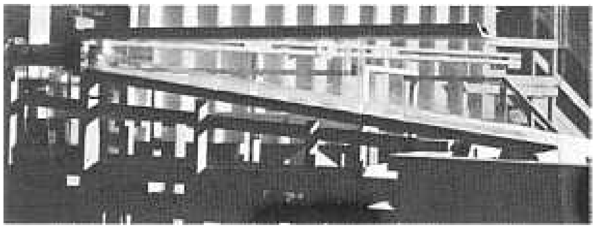
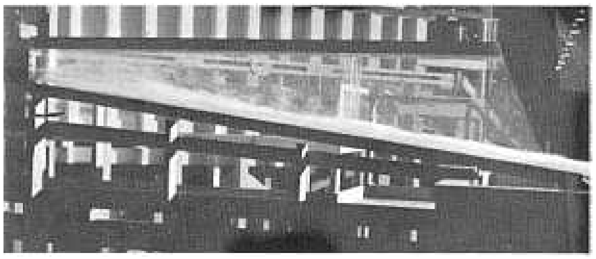


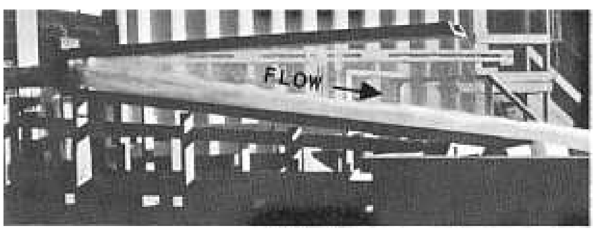
Figure 23. Pueblo Dam—Recommended river gorge outlet works.



One hundred percent gate opening—600 cfs (17.0 cms) at 28.7 feet (8.7 meters) head. Photo P801-D-73171



Fifty-two percent gate opening—600 cfs (17.0 cms) at 130.7 feet (39.8 meters) head. Photo P801-D-73169



One hundred percent gate opening—1,310 cfs (37.1 cms) at 130.7 feet (39.8 meters) head. Photo P801-D-73170

Figure 24. Pueblo Dam—Flow conditions in recommended river gorge outlet works.

tailwater conditions. The slight subatmospheric pressures recorded in Table IV were at those piezometers not in contact with the flow, which verified adequate air was present to provide good aeration of the flow. The test run at 28 percent gate opening and high tailwater, Figure 26, suggested that recirculation of the tailwater above the jet maintained pressures above atmospheric at all of the piezometers. Also, the jet entrained a large amount of air from the free surface between the gate and the offsets.

The location of the flow impingement on the chute floor is indicated by the positive pressure generally occurring at Piezometer 4. It is believed that cavitation erosion will not occur downstream from the impingements point because of air entrained in the bottom and side flow surfaces.

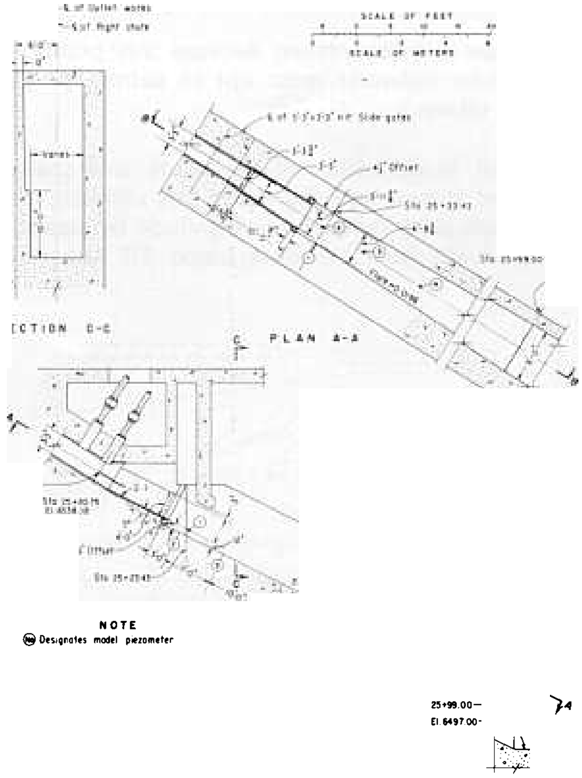


Figure 25. Crystal (earth) Dam outlet works—Recommended air vent offsets in chute.

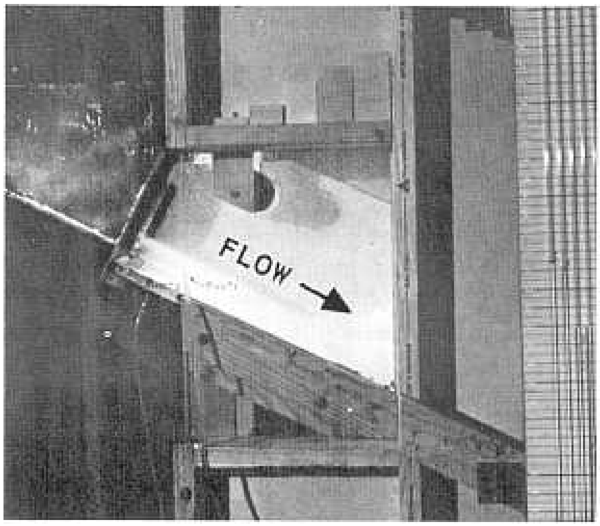
A test using the offsets without the 9-inch (22.9-cm) recesses showed the hydraulic performance to be equally satisfactory at the low tailwater condition but not quite as good with the high tailwater surges extending upstream to the offset.

Table III

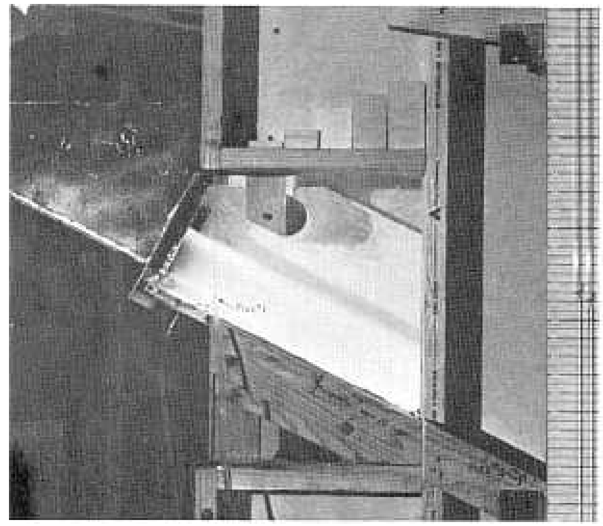
OPERATING DISCHARGES–CRYSTAL (EARTH) DAM OUTLET WORKS

Discharge* cfs (cms)	Percent gate opening	
	Reservoir at top of conservation storage El. 6750 feet (2057.4 m) Head 22 feet (6.71 m)	Reservoir at bottom of conservation storage El. 6700 feet (2042.2 m) Head 172 feet (52.4 m)
1,960 (55.5)	100	–
1,500 (42.5)	80	90
1,000 (28.4)	55	63
500 (14.2)	28	32
200 (5.7)	11	13
50 (1.4)	2.5	3

*The discharges are for two gates operating.

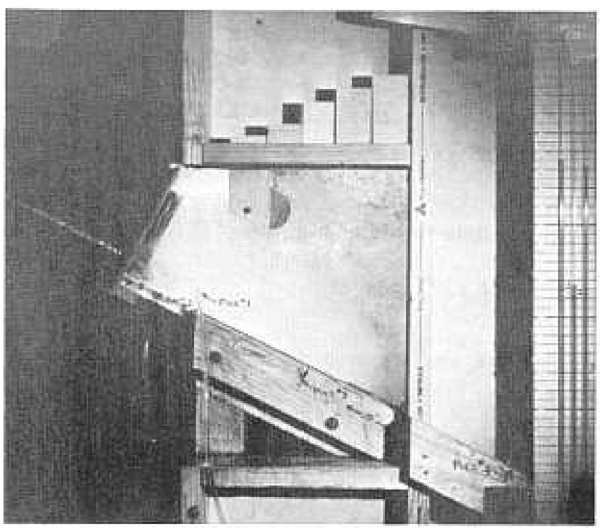


250 cfs (7.1 cms) at 32 percent gate opening. Photo P801-D-73185

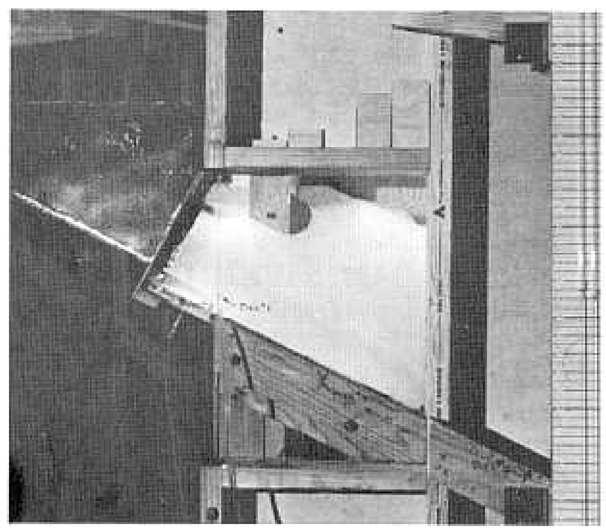


750 cfs (21.2 cms) at 90 percent gate opening. Photo P801-D-73184

Head 172 feet (52.4 meters)— Tailwater elevation 6525 feet (1988.8 meters)



250 cfs (7.1 cms) at 28 percent gate opening. Photo P801-D-73186



950 cfs (26.9 cms) at 100 percent gate opening. Photo P801-D-73183

Head 22 feet (6.7 meters)— Tailwater elevation 6536 feet (1992.2 meters)

Figure 26. Crystal (earth) Dam—Recommended outlet works.

Table IV

CRYSTAL (EARTH) DAM OUTLET WORKS
PRESSURES AT THE CHUTE OFFSET

Piezometer No.*	Percent gate open	Discharge per gate cfs (cms)	Tailwater elevation feet (m)	Pressure head feet (m)**
1	32	250 (7.1)	6525 (1988.8)	–4.16 (1.3)
2	32	250	6525	–4.16
3	32	250	6525	–4.16
4	32	250	6525	5.25 (1.6)
1	28	250	6536 (1992.2)	5.74 (1.8)
2	28	250	6536	0.57 (0.2)
3	28	250	6536	9.11 (2.8)
4	28	250	6536	13.96 (4.3)
1	90	750 (21.2)	6526 (1988.8)	–0.25 (0.1)
2	90	750	6526	–0.25
3	90	750	6526	–0.25
4	90	750	6526	–0.25
1	100	950 (26.9)	6536 (1992.2)	–0.26
2	100	950	6536	–0.16 (0.5)
3	100	950	6536	0.57 (0.2)
4	100	950	6536	2.79 (0.9)

*See Figure 25 for piezometer locations.
**Negative values represent pressures below atmospheric.

Fins of water climbing the walls occurred only near the downstream end of the chute and were minor in nature. At the higher tailwaters the fins were completely submerged by the hydraulic jump and produced no hydraulic problems.

TETON DAM RIVER OUTLET WORKS

Description

The river outlet works at Teton Dam, Figure 27, is a proposed facility having two 4-foot (1.2-meter) square slide gates installed side by side, each discharging down a chute into a stilling basin. The flows from the two valves are separated by a center wall similar to the arrangement at Crystal Dam outlet works. The gates are designed to release up to 1,850 cfs (52.4 cms) each under a maximum head of about 300 feet (91.4 meters). Each valve is tilted downward at a 2:1 slope and parallels the slope of the chute.

The gate frame extends 3 feet, 8 inches (1.1 meters) downstream from the centerline of the gate, at which point the chute floor is offset 9 inches (22.9 cm) and the sidewalls 4-1/2 inches (11.4 cm). The gate frame width at the offset is 4 feet 2 inches (1.3 meters). The chute walls flare from the gate frame at the rate of 0.0968.

The Model

The value engineering test facility was used to provide a 1:10.1 scale model of the prototype. It included the gate, the chute, and the stilling basin. A tailwater control gate was installed at the downstream end of the horizontal basin floor. The maximum tailwater was of special interest to the study to be sure that the aeration offsets were not submerged for any flow release.

The Investigation

Recommended design.—Observation of the hydraulic performance, Figures 28, 29, and 30,

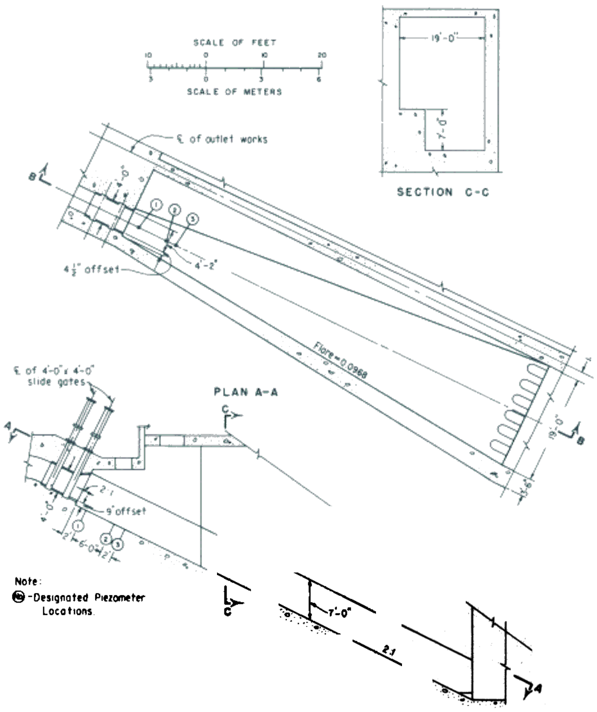
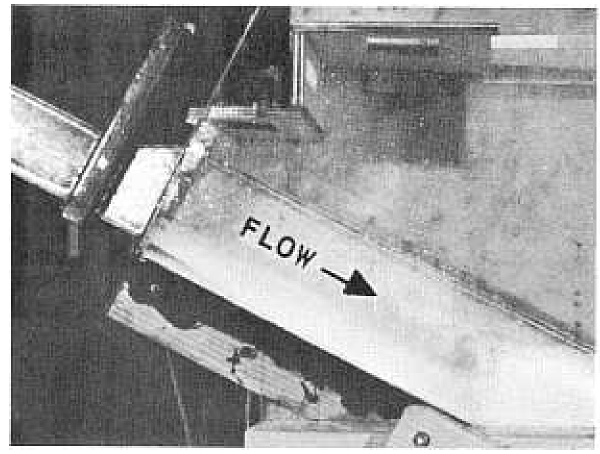


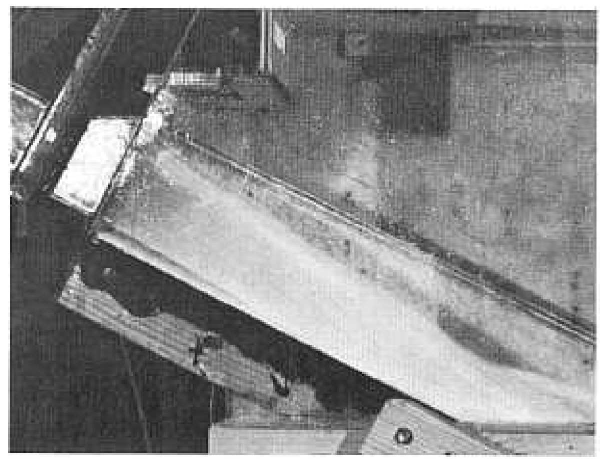
Figure 27. Teton Dam—Recommended river outlet works.

showed the jet to be fully aerated at all operating heads from the minimum of about 120 feet (36.6 meters) to the maximum of about 300 feet (91.4 meters). At the high tailwater condition for the maximum flow discharging at maximum head, the basin water surface surged to the chute offsets, Figure 30, but the jet remained fully aerated.

Pressures recorded at the three piezometers on the floor of the chute are shown in Table V. Piezometers 1 and 2 nearest the offset were quite steady and only slightly subatmospheric, indicating a normal demand for air. Piezometer 3 was usually above atmospheric pressure, indicating that impingement of the jet on the floor of the chute had occurred.



275 cfs (7.8 cms) at 25 percent gate opening. Tailwater elevation 5014 feet (1528.3 meters). Photo P801-D-73209



1,150 cfs (32.5 cms) at 100 percent gate opening. Tailwater elevation 5015.5 feet (1528.7 meters). Photo P801-D-73208

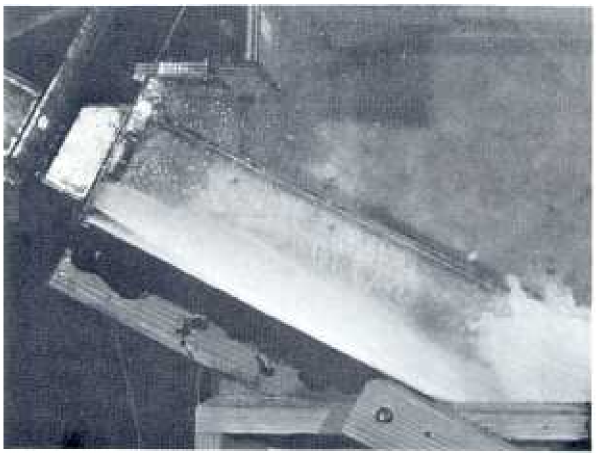
Figure 28. Teton Dam river outlet works discharging at 120 feet (36.6 meters) of head.

TETON DAM AUXILIARY OUTLET WORKS

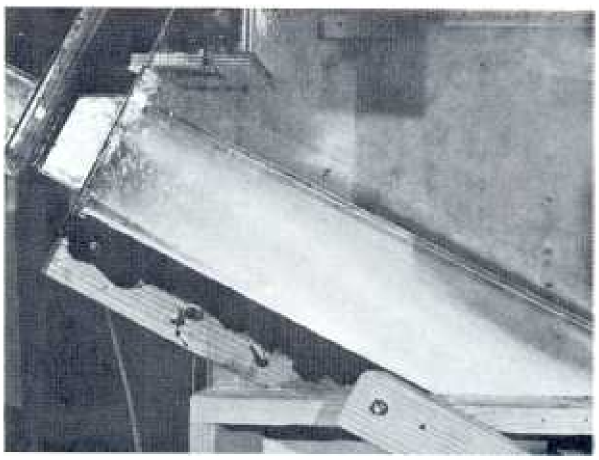
Description

The auxiliary outlet works at Teton Dam, Figure 31, is a proposed facility designed to release up to 850 cfs (24.1 cms) from one 4-foot (1.2-meter) square slide gate into a 7-foot 3-inch (2.2-meter) diameter tunnel, 625 feet (190.5 meters) long. The design flow can be released under heads ranging from 100 feet (30.5 meters) at full gate opening to 279 feet (85.0 meters) at maximum reservoir elevation. Flows as low as 150 cfs (4.2 cms) may be released to any head up to 279 feet (85.0 meters).

In the recommended design, the downstream gate frame is 4 feet 3/4 inch (1.2 meters) wide by 6 feet (1.8 meters) high and extends 3 feet 8 inches (1.1 meters) from the gate leaf. The floor of the frame is 1.42 feet (0.4 meter) above the invert of

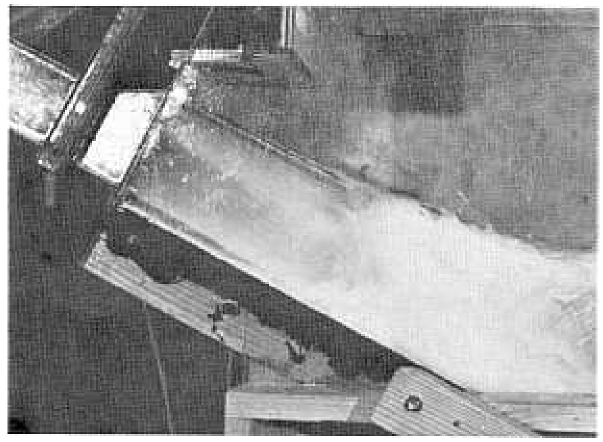


425 cfs (12.0 cms) at 25 percent gate opening. Tailwater elevation 5015 feet (1528.6 meters). Photo P801-D-73190

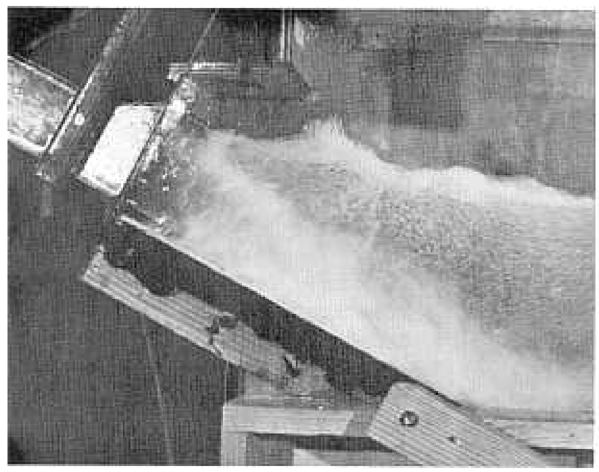


1,700 cfs (48.1 cms) at 100 percent gate opening. Tailwater elevation 5019 feet (1529.8 meters). Photo P801-D-73189

Figure 29. Teton Dam river outlet works discharging at 300 feet (91.4 meters) of head.



Tailwater elevation 5028.6 feet (1532.7 meters) (without surge). Photo P801-D-73188



Tailwater elevation 5028.6 feet (1532.7 meters) (with surge). Photo P801-D-73187

Approximately 1,700 cfs (48.1 cms) at 300 feet (91.4 meters) head at 100 percent gate opening.

Figure 30. Teton Dam river outlet works discharging at high tailwater.

the tunnel. The downstream tunnel has a slope of 0.0124.

The Model

The value engineering test facility was used to provide a 1:10.1 scale model of the prototype. It included the gate and approximately 115 feet (35.1 meters) of the tunnel.

The Investigation

The preliminary design.—The preliminary design included a 3-inch (7.6-cm) offset in the walls of the gate frame, 2-1/2 inches (6.4 cm) from the gate leaf, Figure 32, for the purpose of aerating the sides of the jet through the gate frame section. This increased the gate frame width to 4 feet 6-3/4 inches (1.4 meters).

Table V

TETON DAM RIVER OUTLET WORKS
PRESSURES AT THE CHUTE OFFSET

Piezometer No.*	Percent gate open	Head feet (m)	Discharge per gate cfs (cms)	Tailwater elevation feet (m)	Pressure head feet (m)***
1	25	120 (36.6)	275 (7.8)	5014 (1528.3)	–0.50 (0.2)
2	25	120	275	5014	–0.80 (0.2)
3	25	120	275	5014	0.50 (0.2)
1	100	120	1,150 (32.6)	5015.5 (1528.7)	–0.20 (0.1)
2	100	120	1,150	5015.5	–0.40 (0.1)
3	100	120	1,150	5015.5	0.70 (0.2)
1	25	300 (91.4)	425 (12.0)	5015 (1528.6)	–0.40 (0.1)
2	25	300	425	5015	–1.40 (0.4)
3	25	300	425	5015	1.50 (0.5)
1	100	300	1,890 (53.5)	5019 (1529.8)	–0.10 (0.03)
2	100	300	1,890	5019	–0.50 (0.2)
3	100	300	1,890	5019	0.20 (0.1)
1	100	300	1,700 (48.1)	5028.6 (1532.7)	–0.10 (0.03)
2	100	300	1,700	5028.6	–0.40 (0.1)
3	100	300	1,700	5028.6	0.30 (0.1)
1	100	300	1,700	5028.6	**–0.10 (0.03)
2	100	300	1,700	5028.6	**0.0 (0.0)
3	100	300	1,700	5028.6	**1.4 (0.4)

*See Figure 27 for piezometer locations.
**Tailwater surge at the offset occurs with these pressures.
***Negative pressure heads are pressures below atmospheric.

At full open gate discharging the design flow of 850 cfs (24.1 cms) at a head of 100 feet (30.5 meters) the sides of the jet through the gate frame were aerated as intended with impingement of the jet on the walls of the frame at the lower downstream corner. However, with slight closure of the gate this impingement point moved upstream. At 96 percent open ventilation to the floor of the frame ceased. At 90 percent open the offset was completely filled with water when the gate was discharging at 100 feet (30.5 meters) head.

Extremely high pressures were recorded at Piezometers 1, 4, 16, and 17 on the wall of the gate frame, Figure 32, at these controlled flows at high head. These data indicated possible cavitation erosion in the walls of the offset due to the formation of vortex trails into the region.

At smaller gate openings, generally in the vicinity of 30 percent or less depending on head, the offset upstream of the impingement point did not fill with water even though a sheet of water spread on the walls radially from the impingement point, Figure 33.

Since the sheets of water appeared to fill the tunnel with spray, hampering ventilation from the downstream portal, and since at the larger gate openings there was no ventilation of the jet at the gate frame offset, it was decided to abandon the idea of an offset in the gate frame near the gate leaf.

The preliminary design also included a horseshoe transition section from the rectangular gate frame to the round tunnel, over a distance of 7.58 feet (2.3

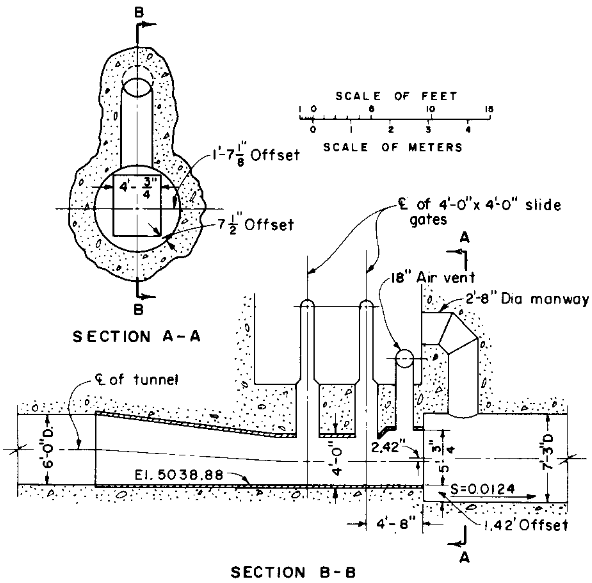


Figure 31. Teton Dam—Recommended auxiliary outlet works.

meters). The floor offset at the gate frame was 9 inches (22.9 cm) and the wall offset was 1 foot 7-1/8 inches (48.6 cm) on each side. At maximum head of 277 feet (84.4 meters), the flow of 860 cfs (24.3 cms) impinged on the sides and bottom surfaces of the transition at about three-fourths of the transition length. It appeared that cavitation erosion might occur downstream from the end of the transition at about 45° up from the invert of the tunnel because of the abrupt change in continuity of the flow surface. Except near the invert, there appeared to be no entrainment of air downstream from the impingement point, as observed by the lack of air bubbles in the flow.

The recommended design.—In the recommended design the offset in the walls of the gate frame (other than 3/8 of an inch (1.0 cm) across the gate slot) and the transition section downstream from the gate frame were eliminated, Figure 32. In eliminating the transition it was necessary to lower the tunnel invert in relation to the gate frame to provide an offset at the junction of the gate frame and circular tunnel. Therefore, the slope of the tunnel upstream and downstream of the gate section was reduced enough to provide an offset of approximately 7-1/2 inches (19.1 cm) at the corners of the gate frame.

The jet from the gate frame was fully aerated in the recommended design when discharging the design flow of 850 cfs (24.1 cms) at approximately 100 feet (30.5 meters) of head from full gate opening, Figure 34a. Fins of water spun over the crown of the tunnel as the result of the flow impinging upon the walls of the tunnel approximately 15 feet (4.6 meters) downstream from the offset. These fins were approximately 30 feet (9.1 meters) long followed by a fin on the water surface at the centerline of the tunnel that intermittently reached the crown of the tunnel another 30 feet (9.1 meters) farther downstream. The tunnel appeared to be large enough that these fins did not hinder the upstream flow of air along the crown of the tunnel. The air vent in the ceiling of the gate frame provided some of the air needed in and around the jet but could be closed completely without any noticeable difference in the flow characteristics. Most of the air demand appeared to be satisfied from the downstream portal.

Leaving the gate fully open, the head was gradually lowered to reduce the flow to 150 cfs (4.2 cms), the minimum fish flow requirement, to represent evacuation of the reservoir. At 300 cfs (8.5 cms), the maximum fish flow requirement, Figure 34(b), the jet fluctuated slightly, apparently due to the very low head and lack of an adequate air demand between the underside of the jet and the pool of water on the invert of the tunnel; however, this was not considered objectionable.

At maximum reservoir elevation 5320 feet (1621.5 meters) the total head on the valve will be 279 feet (85.0 meters), at which the maximum flow of 850 cfs (24.1 cms) will be discharged at about 56 percent gate opening. At this operating condition, Figure 34c., the pool of water under the jet was completely swept out and the sidewall fins were greatly reduced. Although the air demand increased, the outlet portal supplied adequate air without the use of the air vent. Flow along the invert and sides of the tunnel appeared well aerated for the 100-foot (30.5-meter) representative length of model tunnel.

Other controlled flows performed similarly to that described for the maximum flow of 850 cfs (24.1 cms). The maximum fish flow requirement of 300 cfs (8.5 cms) at two heads and gate openings is shown in Figures 34d. and e. The jet is fully aerated even at the low head condition with a pool of water standing in the tunnel below the jet.

Pressures on the gate frame and the circular tunnel, recorded in Table VI, show the high-pressure areas expected on the gate frame walls and the slightly

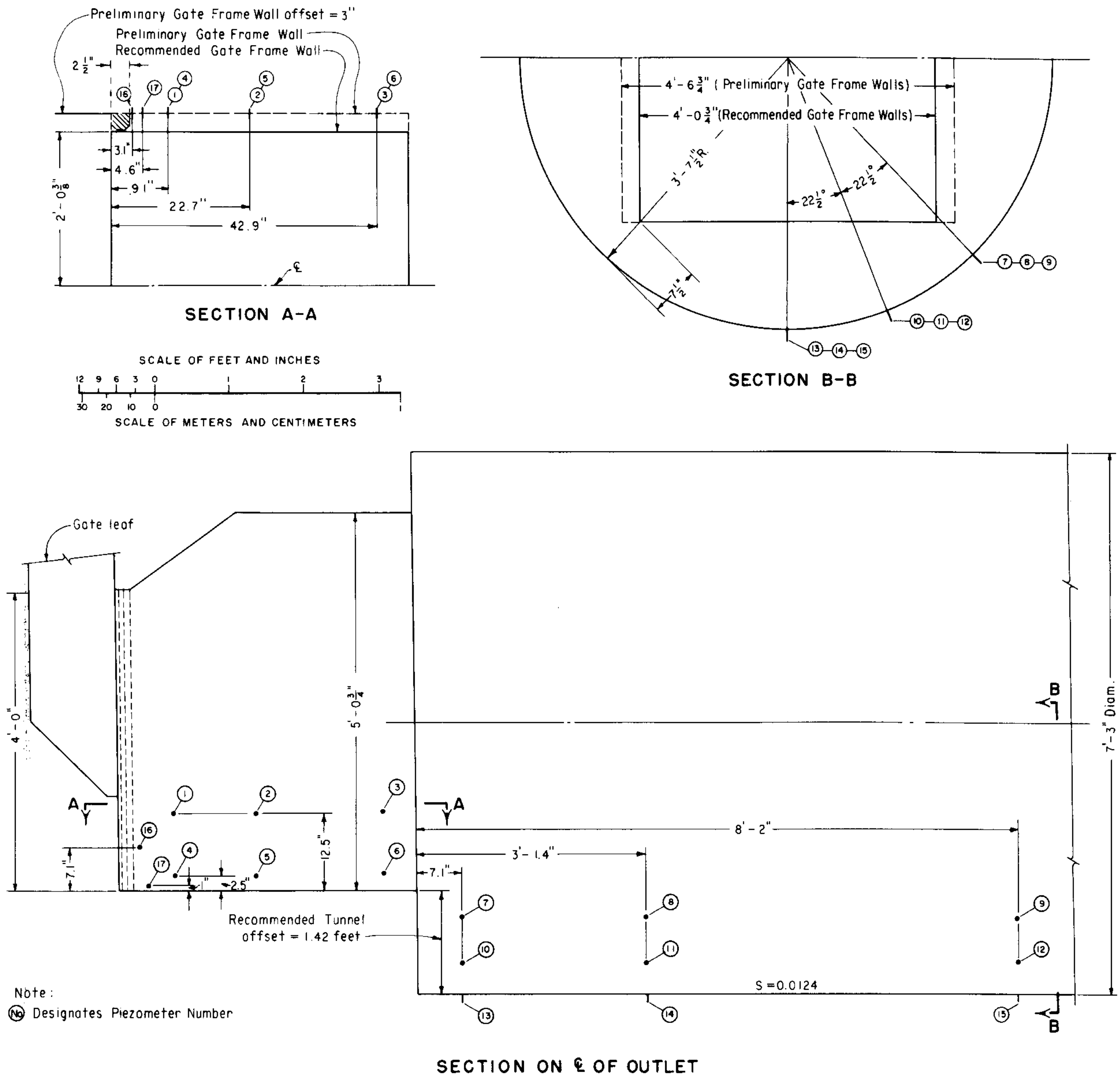


Figure 32. Teton Dam auxiliary outlet works—Piezometer locations in preliminary gate frame offset and in recommended tunnel offset.

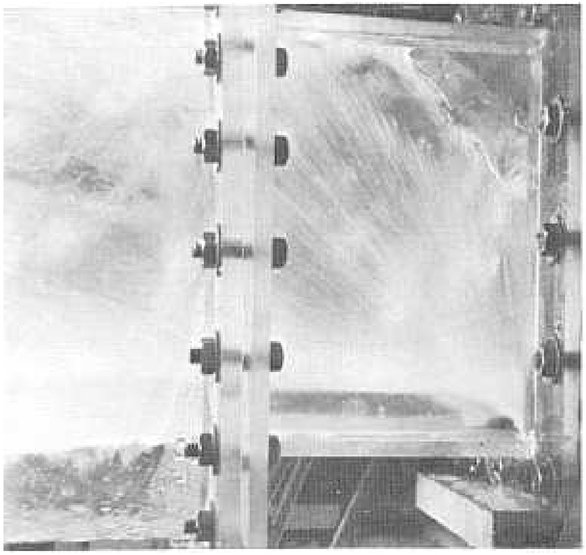
subatmospheric pressures caused by the air demand in the circular tunnel.

SUMMATION OF PROJECT STUDIES

The operating conditions in the preceding project studies and the recommended test results of each are summarized in Tables VII and VIII for existing and proposed structures, respectively.

Existing Structures

Air vent slots.—In existing structures, Table VII, a 12-inch (30.5-cm) square air slot is sufficient for flows from outlet works gates in conduits ranging from 4 to 7-1/2 feet (1.2 to 2.3 meters) wide discharging at heads up to 330 feet (100.6 meters). The size of this slot in relation to the width of conduit and head can be compared with the 36- by 36-inch (0.9- by 0.9-meter) air slot developed



Twenty percent gate opening discharging 300 cfs (8.5 cms) at 270 feet (82.3 meters) head. Photo P801-D-73191

Figure 33. Teton Dam auxiliary outlet works with preliminary gate frame offset.

for the 32-foot (9.8-meter) diameter spillway tunnel at Yellowtail Dam[2] which operates at heads up to about 360 feet (109.7 meters).

Floor deflectors.—The floor deflector at Palisades Dam gained a height of 2-1/2 inches (6.4 cm) in a length of 30 inches (76.2 cm). At Navajo, the deflector was 2 inches (5.1 cm) high in a length of 18 inches (45.7 cm). Floor deflectors, 3 inches (7.6 cm) and 4 inches (10.2 cm) high, were tested in the Palisades model, but a fin of water formed on the centerline of the jet top surface, due partly to the use of sidewall deflectors. This fin rose to the roof of the flow passage at the portal (16 feet 4 inches (5.0 meters) downstream) for gate openings less than 50 percent at high heads. Also, the close proximity of the deflectors to the gate leaf substantially reduced the discharge coefficient and, therefore, the higher deflectors are not recommended. As a general rule, the upward slope of the floor deflectors should begin at the end of the gate frame, which is usually 4 feet (1.2 meters) or more downstream from the gate leaf. The deflector should have a rise of at least 2 inches (5.1 cm), and a slope of not more than 1 on 9. The deflector developed for the air slot in the Yellowtail Dam spillway tunnel[3] sloped upward 1 on 9 to a height of 3 inches (7.6 cm) at the invert, reducing to zero deflection at the spring line.

Wall deflectors.—Wall deflectors converging inward 1 inch (2.5 cm) were used at Palisades. The deflectors were 30 inches (76.2 cm) long beginning at the gate frame, extending to the air vent slot, the same length and station as the floor deflector. Larger deflectors were not tested because of reduction in the discharge coefficient of the gate and because of the center fin that formed, as described above. At Navajo, wall deflectors were not necessary because the walls diverged downstream from the gate frame. Therefore, the 18-inch (45.7-cm) long walls from the gate frame to the air vent were made parallel, which in effect directed the flow away from the diverging walls downstream. As a general rule, the walls upstream of the air slot should be parallel if the downstream walls diverge and a deflector slope of 1:30 should be used in the walls upstream of the air slot if the downstream walls are parallel.

Downstream from the air slot the walls were offset outward 1 inch (2.5 cm) at Palisades and then angled back to the original wall surface at the rate of 1 on 20. At Navajo, the downstream edge of the air slot was offset 2 inches (5.1 cm) and the walls were parallel until they intersected the original divergent walls. As a general rule, the walls downstream of the slot should be offset at least 1 inch (2.5 cm) when a wall deflector is used upstream of the slot, and 2 inches (5.1 cm) when the upstream walls are parallel. The intersecting angle of the wall downstream of the air slot and the existing wall must be within the limits previously set forth by the Bureau of Reclamation in report HYD-448.[4]

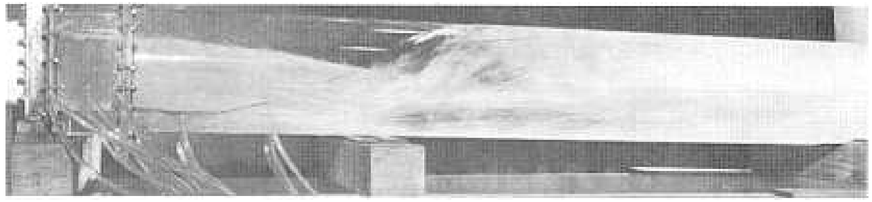
Proposed Structures

In the design of the proposed structures, Table VIII, wall and floor offsets away from the flow were used instead of wall air slots and floor deflectors for venting the flow surfaces. An offset generally provides more exposure of air to the jet. The floor

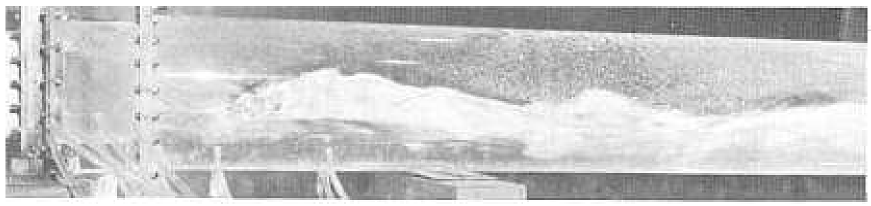
[2] "Hydraulic Model Studies of Aeration Devices for Yellowtail Dam Spillway Tunnel," by D. C. Colgate, U.S. Bureau of Reclamation, REC-ERC-71-47, December 1971.

[3] Ibid.

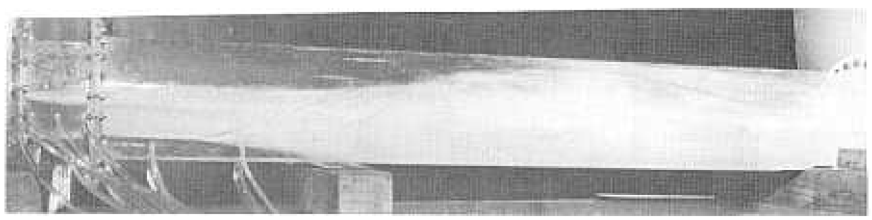
[4] "Importance of Smooth Surfaces on Flow Boundaries Downstream from Outlet Works Control Gates," by J. W. Ball, U.S. Bureau of Reclamation, HYD-448, July 15, 1958.



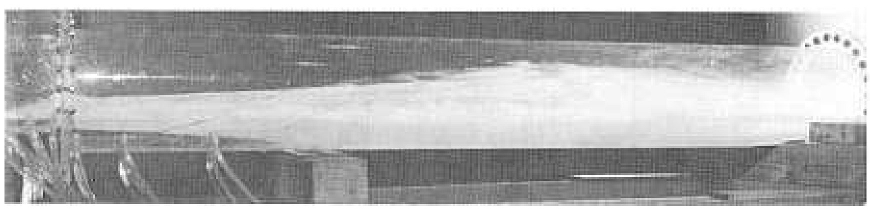
One hundred percent open gate discharging 850 cfs (24.1 cms) at 100 feet (30.5 meters) of head. Photo P801 D-73193



One hundred percent open gate discharging 300 cfs (8.5 cms) at very low head. Photo P801-D-73192



Fifty-six percent open gate discharging 850 cfs (24.1 cms) at near maximum head. Photo P801-D-73194



d. Twenty percent open gate discharging 300 cfs (8.5 cms) at maximum head of 279 feet (85.0 meters). Photo P801-D-73196

e. Fifty percent open gate discharging 300 cfs (8.5 cms) at 40 feet (12.2 meters) of head. Photo P801-D-73195

Figure 34. Teton Dam recommended auxiliary outlet works.

Table VI

TETON DAM AUXILIARY OUTLET WORKS
PRESSURES AT THE CHUTE OFFSET

Piezometer No.*	Percent gate opening	Head feet (m)	Discharge per gate cfs (cms)	Pressure head feet (m)**
1	100	100 (30.5)	850 (24.1)	3.8 (1.2)
2	100	100	850	1.9 (0.6)
3	100	100	850	0.3 (0.1)
4	100	100	850	4.6 (1.4)
5	100	100	850	2.7 (0.8)
6	100	100	850	0.7 (0.2)
7	100	100	850	–0.4 (0.1)
8	100	100	850	–0.4 (0.1)
9	100	100	850	–0.4 (0.1)
10	100	100	850	0.3 (0.1)
11	100	100	850	0.1 (0.03)
12	100	100	850	0.0 (0.0)
13	100	100	850	1.7 (0.5)
14	100	100	850	0.4 (0.1)
15	100	100	850	0.5 (0.2)
16	100	100	850	3.7 (1.1)
17	100	100	850	5.2 (1.6)
1	52	279 (85.0)	850	51.5 (15.7)
2	52	279	850	13.0 (4.0)
3	52	279	850	3.0 (0.9)
4	52	279	850	62.0 (18.9)
5	52	279	850	24.0 (7.3)
6	52	279	850	6.5 (2.0)
7	52	279	850	–0.9 (0.3)
8	52	279	850	–0.9 (0.3)
9	52	279	850	–0.9 (0.3)
10	52	279	850	–0.5 (0.2)
11	52	279	850	–0.6 (0.2)
12	52	279	850	–0.7 (0.2)
13	52	279	850	1.6 (0.5)
14	52	279	850	–0.6 (0.2)
15	52	279	850	–0.5 (0.2)
16	52	279	850	65.0± (19.8)
17	52	279	850	66.0± (20.1)

Table VI—Continued

Piezometer No.*	Percent gate opening	Head feet (m)	Discharge per gate cfs (cms)	Pressure head feet (m)**
1	100	279 (85.0)	300 (8.5)	−1.0 (0.3)
2	100	279	300	−1.0 (0.3)
3	100	279	300	19.0 (5.8)
4	100	279	300	−0.5 (0.2)
5	100	279	300	2.7 (0.8)
6	100	279	300	−0.8 (0.2)
7	100	279	300	−0.5 (0.2)
8	100	279	300	−0.7 (0.2)
9	100	279	300	−0.7 (0.2)
10	100	279	300	−0.6 (0.2)
11	100	279	300	−0.6 (0.2)
12	100	279	300	−0.6 (0.2)
13	100	279	300	−0.5 (0.2)
14	100	279	300	−0.4 (0.1)
15	100	279	300	−0.3 (0.1)
16	100	279	300	−0.5 (0.2)
17	100	279	300	60.0 (18.3)

*See Figure 32 for piezometer locations.
**Negative pressures are below atmospheric.

Table VII

AERATION DESIGN RECOMMENDATIONS FOR EXISTING STRUCTURES

Project	Kind of structure	Gate size feet (m)	Full open gate discharge cfs (cms)	Total head feet (m)	Floor deflector height inches (cm)	Floor deflector slope	Divergent or parallel walls	Wall deflector projection inches	Wall deflector convergence	Wall air slot size inches (cm)
Palisades outlet works	Short horizontal tunnel and chute	7.5x9 (2.3 x 2.7)	6,740 (190.9)	235 (71.6)	2.5 (6.4)	1:12	parallel	1	1:30	12x13 (30.5 x 33.0)
Navajo auxiliary outlet works	Long horizontal tunnel	4x4 (1.2 x 1.2)	1,790 (50.7)	330 (100.6)	2 (5.1)	1:9	divergent	0	0	12x12 (30.5 x 30.5)

Table VIII

AERATION DESIGN RECOMMENDATIONS FOR PROPOSED STRUCTURES

Project	Operating Requirements											
	Kind of structure	Gate size feet (m)	Gate percent open	Discharge cfs (cms)	Total head feet (m)	Gate frame width feet (m)	Head to width ratio	Floor offset inches (cm)	Floor offset to width ratio	Flared or parallel walls	Wall offset inches (cm)	Wall offset to width ratio
Pueblo spill-way outlet works	Trajec-tory tunnel	6x6 (1.8 x 1.8)	100 50+	3,080 (87.2) 1,500 (42.5)	130 (39.62) 130 (39.62)	6 (1.8)	21.65	12 (30.5)	1/6	Flared 0.01556	6 (15.2)	1/12
Pueblo river gorge outlet works	Trajec-tory tunnel	4x4 (1.2 x 1.2)	100 52	1,310 (37.1) 600 (17.0)	130 (39.62) 130 (39.62)	4 (1.2)	32.50	8 (20.3)	1/6	Flared 0.01715	4 (10.2)	1/12
Crystal outlet works	2:1 slope chute	3.25 x 3.25 (1.0 x 1.0)	100 11	1,060 (30.0) 200 (5.7)	222 (67.7) 222 (67.7)	3.95 (1.2)	56.20	9 (22.9)	1/6.25	Flared 0.01968	4.5 (11.4)	1/12.5
Teton outlet works	2:1 slope chute	4x4 (1.2 x 1.2)	100 25	1,850 (52.4) 275 (7.8)	300 (91.44) 120 (36.58)	4.17 (1.27)	71.94	9 (22.9)	1/5.5	Flared 0.0968	4.5 (11.4)	1/11.1
Teton auxil-iary outlet*	Circular tunnel	4x4 (1.2 x 1.2)	100 56	850 (24.1) 850 (24.1)	100 (30.5) 279 (85.0)	4.06 (1.24)	68.72	17.04 (43.3)	1/2.9	—	19.12 (48.6)	1/2.55

*Floor offset is measured to invert. Wall offset is measured to tunnel width at centerline elevation. Normal offset radius at rectangular gate frame corner is 7-1/2 inches (19.1 cm) = offset to width ratio of 1/6.5.

offset most commonly recommended for use at each of the structures tested was 1/6 of the gate frame width; the sidewall offset was 1/12 of the width. These offsets were ample in all cases; therefore, as a general rule, offsets of these magnitudes may be used at other structures.

An exception to this rule may be in the case of a large head-to-gate width ratio. In the two Pueblo outlet works' studies, it was determined that the ratio of the head to the gate width was a factor. Each of the two Pueblo outlets discharged at approximately the same head but one discharged from a 6-foot (1.8-meter) wide gate frame while the other discharged from a 4-foot (1.2-meter) wide gate frame. The wall offsets were 6 inches (15.2 cm) and 4 inches (10.2 cm), respectively, 1/12 of the gate frame width. Since the head was nearly the same in both cases, the spreading jet from the gates impinged on the 4-inch wall offset sooner than on the 6-inch offset and caused more extensive spreading of the jet and larger fins of water on the walls. Therefore, as a general rule, the wall offset should never be less than 4 inches, unless the head-to-width ratio is less than about 20:1 as at Pueblo spillway outlet.

The same rules apply to the offsets whether the gate is vertical and discharges into a horizontal rectangular bottom tunnel or tilted downward to discharge into a rectangular sloping chute. However, sloping chutes would help prevent water from submerging the jet at lower heads.

If the discharge from a rectangular slide gate is into a circular tunnel, a general guideline would be that the offset normal to the tunnel wall from the rectangular corner be about one-sixth of the gate width, which is similar to that used for Teton Dam auxiliary outlet works, Table VIII. However, a hydraulic model study should be made to verify the design.

GENERAL STUDIES

Using the Navajo outlet works model and the design requirements for Navajo in a general design study, a design was developed using parallel walls offset 1/12 of the gate frame width, rather than the diverging walls with air slots. With these parallel walls, it was found that either a floor offset of one-sixth the gate frame width or a 2-inch (5.1-cm) by 18-inch (45.7-cm) long deflector on the floor beginning at the gate frame could be used. Offsets provide advantages over air slots, in that offsets are less critical to construct and they move the wall farther from the flow surface for a greater distance downstream.

The Navajo model also showed that the use of deflectors is limited by the depth and velocity of flow over the deflector and the height of tunnel downstream. To assure ventilation from the downstream portal, it is important that the jet does not rise to the crown of the tunnel. If the nappe comes too close, pressures in the air void under the nappe will begin to fluctuate from lack of adequate ventilation. Model data in Figure 35 show the limiting conditions for which a 1:9 sloping floor deflector can be used in a tunnel beginning at the downstream end of the gate frame.

Ventilation from the downstream portal also can be a problem when using a floor offset if the crown of the tunnel is too close to the water surface. The limiting condition for use of the offset is shown in Figure 35.

With the walls offset 1/12 of the gate frame width and the floor offset 1/6 of the width at the gate frame, without deflectors, the Navajo model was used to determine the distance downstream from

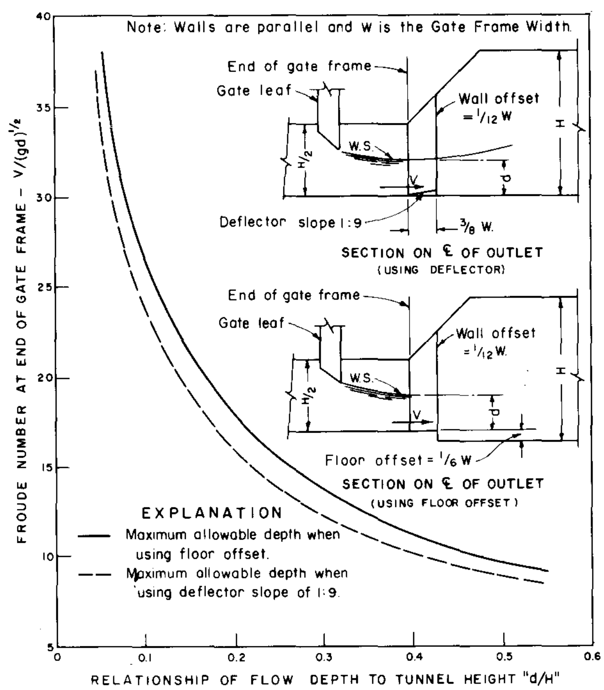


Figure 35. Design limitation for ventilation from the downstream portal.

the offset at which an air void under the nappe might be expected to exist. The first floor piezometer, Figure 16, that registered a pressure greater than atmospheric indicated the distance downstream from the offset at which the jet impinged on the floor. The location of the piezometers and, thus, the distance that the air void extended downstream from the offset is shown in dimensionless terms in Figure 36.

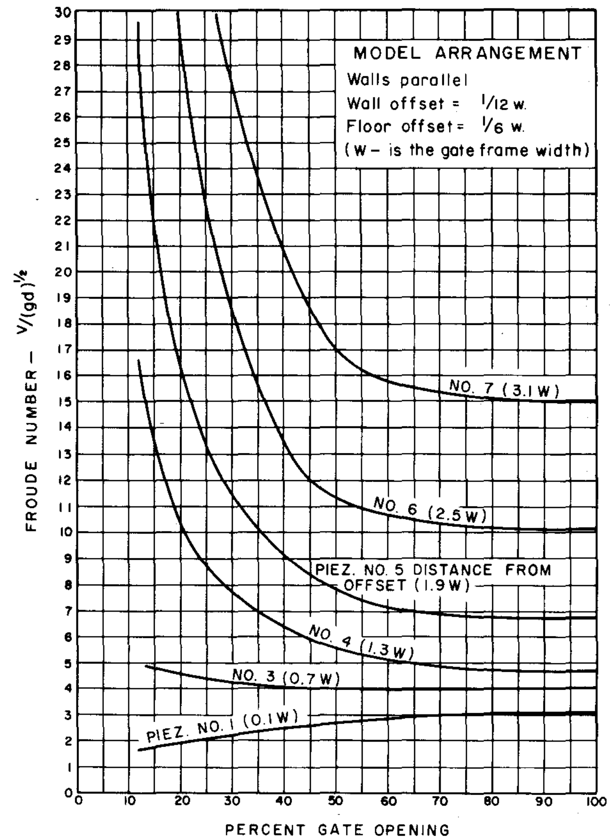
DESIGN CONCLUSIONS AND RECOMMENDATIONS

1. The feasibility of using wall and floor offsets versus air slots and deflectors must be determined, based on structural and economic considerations. In new construction, wall and floor offsets would usually take preference over air slots and deflectors since the former are less critical to construct, provide more water surface for aeration, and separate the flow surfaces from the jet for longer distances. For modification of existing structures, air slots and deflectors will usually be the only reasonable alternative.

2. When air slots are used, the cross-sectional dimensions of each slot should be a minimum of 1-foot (30.5-cm) square. Larger slots should maintain a square nor nearly square configuration. No data are available for sizing larger slots.

3. The downstream edge of the slot should be offset 1 to 2 inches (2.5 to 5.1 cm) away from the flow. Any transition between the downstream edge of the slot and the narrower downstream tunnel should be accomplished with a slope not greater than 1:20 for velocities exceeding 40 ft/sec (12.2 m/sec), 1:50 for velocities exceeding 90 ft/sec (27.4 m/sec), and 1:100 for velocities exceeding 120 ft/sec (36.6 m/sec).[5]

4. If the walls downstream from the air slots are parallel, a wall deflector is required upstream from each air slot to ensure that the jet will clear the slot. A deflector with a maximum projection of 1 inch (2.5 cm) and a slope of 1:30 is recommended to ensure that the deflected jet will not cause fins and excessive spray in the tunnel, and not reduce the discharge capacity by forming a restriction in the tunnel.



The curves show the first floor piezometer from offset at which impingement of the jet occurs. (See Figure 16 for piezometer location.) Froude number is computed for velocity and depth of flow at end of gate frame. Example: For 50 percent gate opening at a Froude number of 10, first impingement occurs between Piezometers 5 and 6 (1.9 to 2.5 W).

Figure 36. Jet impingement location on chute floor.

5. If a floor deflector is used, its rise should be determined from the jet velocity. In the cases tested, the rise was 2.5 and 2 inches (6.4 and 5.1 cm), with respective slopes of 1:12 and 1:9. Jet velocities were approximately 100 and 112 ft/sec (30.5 and 34.1 m/sec), respectively, at the gate.

6. If offsets are used, they should normally be located at the downstream end of the gate frame. Wall offsets should be 1/12 of the gate frame width at that location, with a minimum offset of 4 inches (10.2 cm). Floor offsets should be twice the wall offsets, or one-sixth of the gate frame width.

[5] Ibid.

7. If the gate is to discharge down a sloping chute to a stilling basin, the same rules as to size and location of the slots and offsets apply as for discharging into a tunnel. However, the tailwater should not be allowed to submerge the slots or offsets.

8. If a square or rectangular gate discharges into a circular tunnel, offsets or aeration slots may be used. However, the size, shape, and location of the offsets or slots will depend on the slope and size of the downstream tunnel and the geometry of the transition. In such cases, the design should be determined by hydraulic model studies.

9. These guidelines are based on model studies of specific structures. If a given future application is considerably different than these structures, separate hydraulic model studies should be made.

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
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*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
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*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
Short tons (2,000 lb)	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
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	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
Pounds per cubic foot	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
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	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
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	$*0.965873 \times 10^{-6}$	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles 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
Pounds	*4.4482	Newtons
Pounds	$*4.4482 \times 10^5$	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	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 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*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

GPO 835-188

ABSTRACT

High-velocity jets discharging through slide gates into lined tunnels and chutes at outlet works installations have caused serious cavitation problems at several structures. To prevent cavitation erosion, air must be introduced along the underside and sides of a jet before the jet comes in contact with downstream concrete surfaces. Model studies of chute offsets, air slots, and deflectors were conducted to determine methods to aerate the jet and provide recommendations for altering two existing structures and designing new structures. A single test facility was used to model existing structures at Palisades and Navajo Dams and proposed structures at Pueblo, Crystal, and Teton Dams. Wall air vent slots combined with a floor deflector were developed for use immediately downstream from the gate frames in the two existing structures. Wall and floor air vent offsets away from the flow at the end of the frame were developed for new structures. These investigations, supplemented by general research, formed the basis for guidelines developed for design of future air-entraining devices to protect flow surfaces from cavitation erosion. (3 references)

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REC-ERC-73-5
Beichley, G L
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Bur Reclam Rep REC-ERC-73-5, Div Gen Res, Mar 1973. Bureau of Reclamation, Denver, p, 36 fig, 8 tab, 3 ref

DESCRIPTORS—/ *outlet works/ *cavitation/ discharge (water)/ hydraulic models/ tunnels/ stilling basins/ *jets/ model tests/ gates/ *vents/ dams/ slide gates/ hydraulic structures/ chutes/ *air demand/ nappe/ steel linings/ slots/ *deflectors/ *aeration/ laboratory tests/ design criteria/ *cavitation control/ air admission/ offsets
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