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Cavitation Control By Aeration of High-Velocity Jets

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Introduction

High-velocity jets discharging through slide gates into lined tunnels and chutes at outlet works installations have caused serious cavitation problems at several structures. Model studies were conducted of a few specific structures to develop means to prevent cavitation erosion. These studies included 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 and later redesigned as a concrete dam), and two proposed structures at Teton Dam. Air was to be introduced into the jet 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 the sloping chutes or circular conduits downstream from the gate frames.

Palisades Dam Outlet Works

The outlet works tunnel and power tunnel at Palisades Dam are designed to release flows through six 7-1/2-ft (2.3-m) by 9-ft (2.7-m) regulating slide gates and two hollow jet valves under a maximum head of 235 ft (71.6 m). The slide gates, operating alone or in pairs, are designed to discharge up to approx 6,500 cfs (184 m^3/s) each through a short rectangular covered passageway onto a trajectory chute to the stilling basin (Fig. 1).

The outlet works operated during 4 yr at heads near 220 ft (67 m) at gate openings ranging from approx 8%-45% of full open. Minor cavitation erosion was noted each year in the concrete walls and floor downstream from the gate frame. Extensive cavitation erosion occurred in the floor of the trajectory

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chute downstream from Gates 1 and 2 (Fig. 2). In contrast, no damage occurred downstream from the hollow jet valves, which were fully aerated.

The test facility was used to provide a 1:19 scale model of one of the slide gate controlled outlets. The model included the gate, the covered passage downstream from the gate, and a section of the open chute and stilling basin.

Recommended Design Modifications.—Following several unsuccessful trials, a 12-in. by 12-in. (300-mm by 300-mm) slot was placed in the walls of the

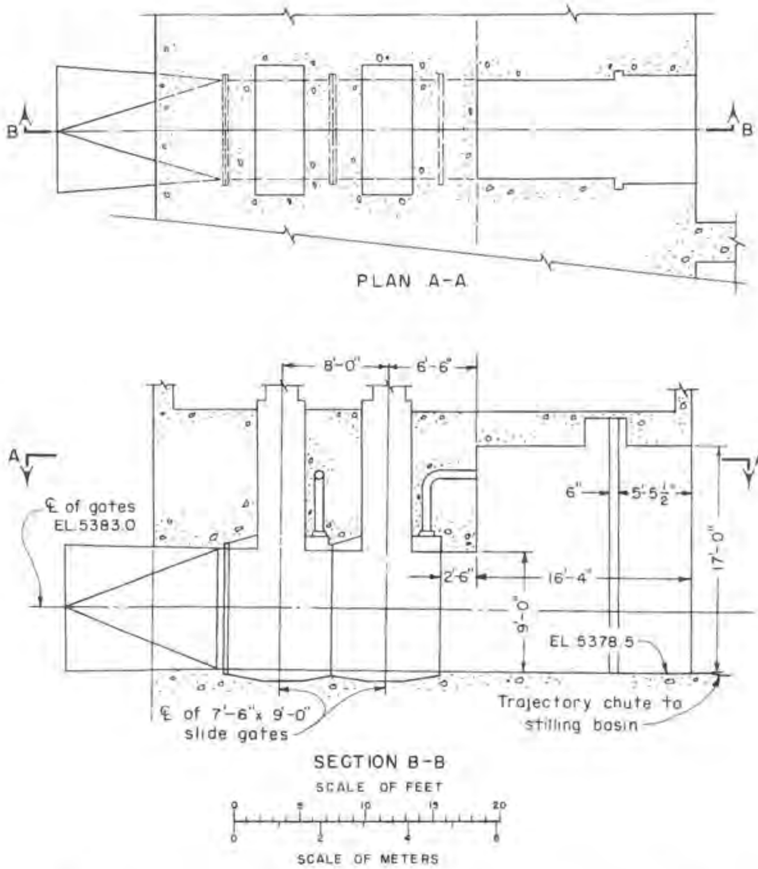

FIG. 1.—Palisades Dam Existing Outlet Works Gate and Tunnel

covered passage immediately downstream of the 9-ft (2.7-m) high section (Fig. 3). At this location, the top of the wall slots terminated in the walls of the 17-ft (5.2-m) high section of the outlet, 10 ft (3 m) above the floor, thus eliminating the need for vent pipes in the roof of the outlet.

For the recommended modification, the height of the floor deflector was set at 2-1/2 in. (64 mm) and the inward projection of the wall deflectors was set at 1 in. (25 mm) (Fig. 3). The wall and floor deflectors were each 30 in. (760 mm) long. The downstream edge of each wall slot was offset outward

FIG. 2.—Cavitation Erosion at Palisades Dam Outlet Works Portal

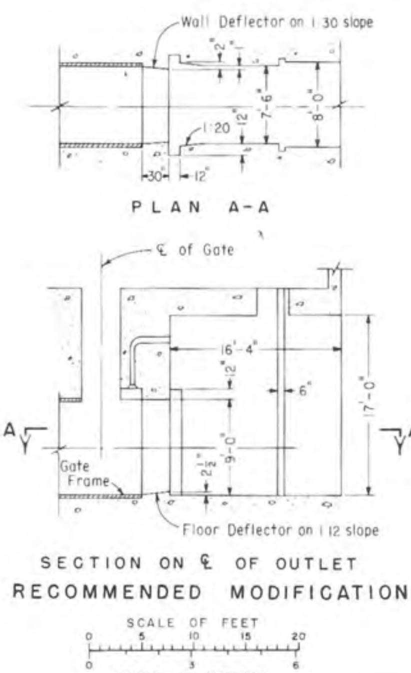

FIG. 3.—Palisades Dam Outlet Works Modifications

approx 1 in. (25 mm). 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 approx 0.90, which was an acceptable reduction. A previous trial with wall deflectors projecting 2 in. (51 mm) into the flow reduced the discharge coefficient to 0.85. Pressure taps installed in the air slots about 1 ft (0.3 m) above the floor showed the pressures to be slightly below atmospheric when the slots were vented. This assured movement of air into the slots and onto the flow surfaces.

Prototype Tests.—One of the slide gate controlled outlets at Palisades Dam was equipped with aeration slots and deflectors. Inspection of the modified

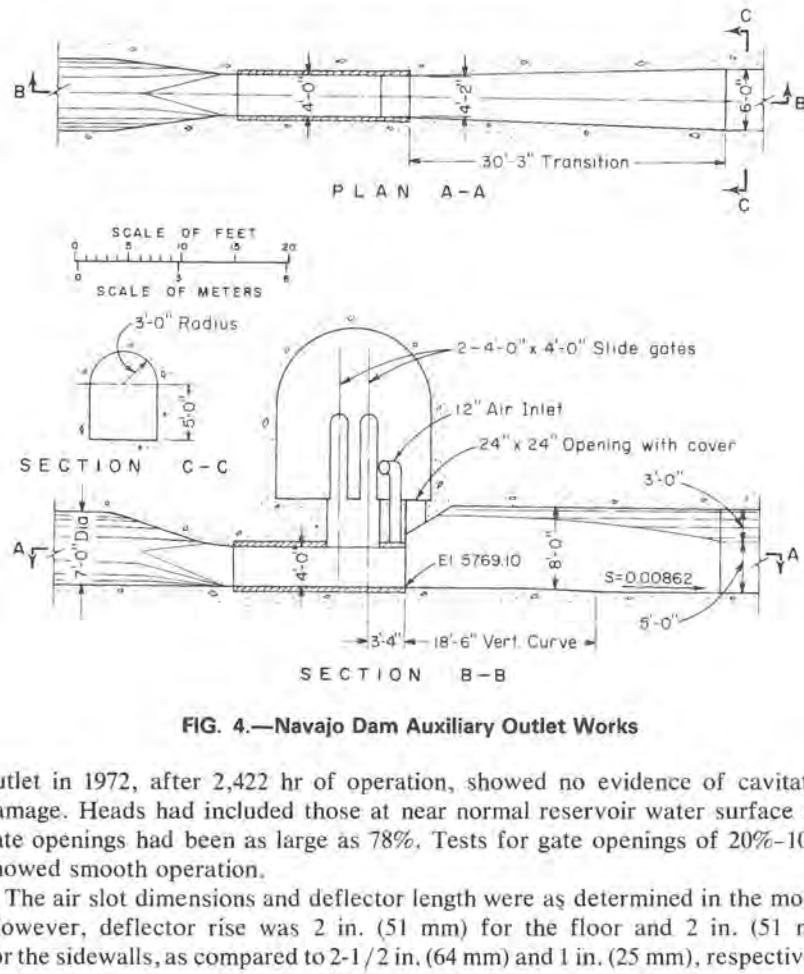

FIG. 4.—Navajo Dam Auxiliary Outlet Works

outlet in 1972, after 2,422 hr of operation, showed no evidence of cavitation damage. Heads had included those at near normal reservoir water surface and gate openings had been as large as 78%. Tests for gate openings of 20%-100% showed smooth operation.

The air slot dimensions and deflector length were as determined in the model. However, deflector rise was 2 in. (51 mm) for the floor and 2 in. (51 mm) for the sidewalls, as compared to 2-1/2 in. (64 mm) and 1 in. (25 mm), respectively, in the model. Also, the 1-in. (25-mm) recess at the downstream edge of the air slot was not included in the prototype. Observation of the prototype operation suggested that 1-in. (25-mm) side deflectors and the 1-in. (25-mm) recess would have provided adequate aeration. The 2-in. (51-mm) side deflector in the prototype caused a back pressure on the gate and a 9% reduction in flow at full open gate, which conformed with the model findings. The 2-in. (51-mm) floor deflector was determined to be adequate, as compared to the 2-1/2-in. (64-mm) rise recommended from the model study.

Navajo Dam Auxiliary Outlet Works

The auxiliary outlet works at Navajo Dam (Fig. 4) is an existing structure capable of releasing up to 1,790 cfs (50.7 m^3/s) at maximum reservoir, 330 ft (101 m) above the center line of the gate. The release is from a 4-ft by 4-ft (1.2-m by 1.2-m) regulating gate into a 6-ft (1.8-m) wide flat bottom horseshoe tunnel. The length of the tunnel is about 875 ft (267 m) from the gate frame to the outlet portal in the spillway chute. The original operating instructions, in effect, limited the head on the auxiliary outlet works to approx 150 ft (45.7 m) under normal operating conditions to minimize the possibility of cavitation. However, it had become necessary to release flows up to 500 cfs (14 m^3/s) at a total head of approx 314 ft (95.7 m).

The test facility was used to provide a 1:10.1 scale model of the regulating slide gate and downstream tunnel. The model included the regulating gate, the gate frame, and the tunnel transition plus 80 ft (24 m) of the tunnel downstream from the transition. The model was operated at gate openings ranging from 12.5%-100% with heads of 199 ft (60.7 m) and 330 ft (101 m).

Recommended Modification.—A 2-in. (51-mm) high by 18-in. (460-mm) long deflector was installed in the floor downstream from the gate frame, and 12-in. by 12-in. (300-mm by 300-mm) air slots were installed in the sidewalls (Fig. 5). The air slots extended from the floor to the upward sloping ceiling in the tunnel and the sidewalls from the gate frame to the air slots were made parallel at the maximum gate frame width. The downstream edges of the slots were rounded with 1-in. (25-mm) radii and offset 2 in. (51 mm) away from the flow with the walls remaining parallel downstream for a distance of 4-1/2 ft (1.4 m).

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

Subatmospheric pressures along the walls and floor of the transition demonstrated demand for air in the air space under and around the jet. The largest subatmospheric pressure was approx 4 ft (1.2 m) of water, observed in the air space below the lower nappe of the flow on the floor of the tunnel a few feet downstream of the deflector at full open gate and maximum head. All subatmospheric pressures recorded in the crown of the tunnel downstream of the transition, in the manway opening 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.

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 in.-3 in. (51 mm-76 mm) 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 determined from 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; however, as subsequently described, this was not confirmed in prototype tests.

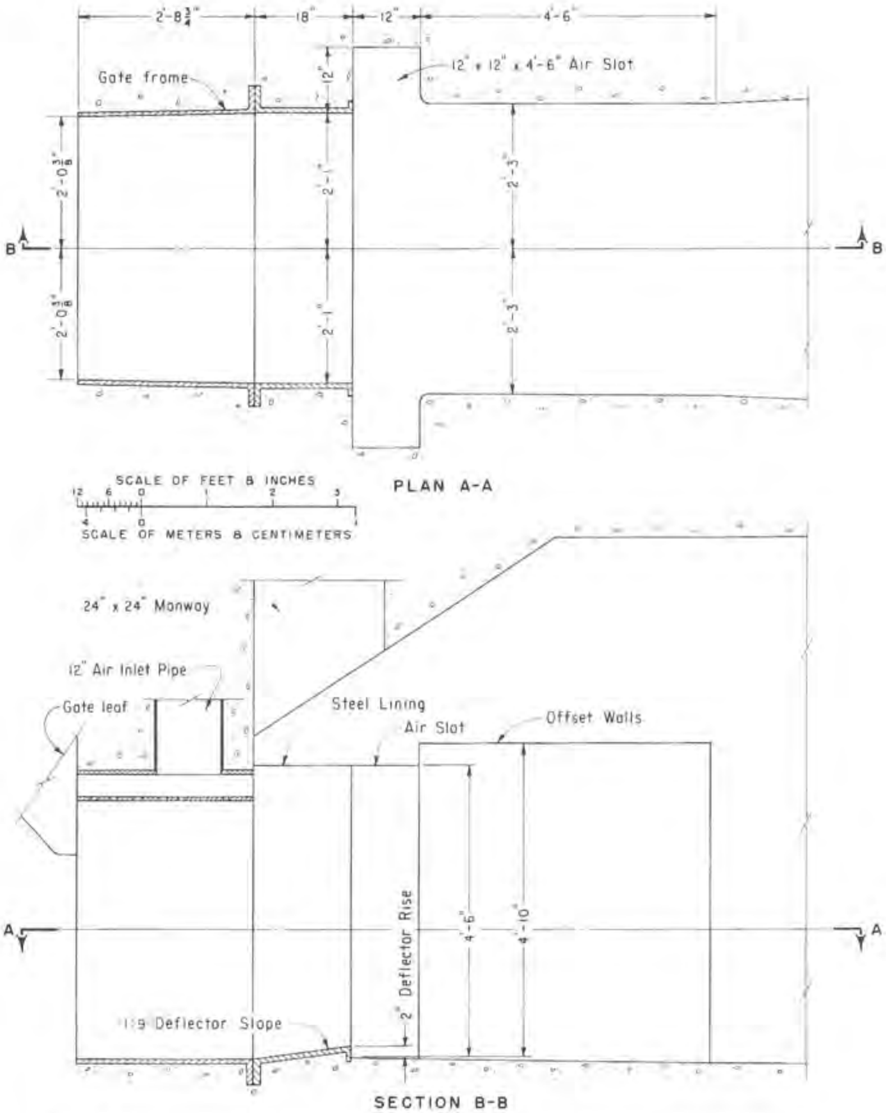

FIG. 5.—Navajo Dam Auxiliary Outlet Works Recommended Modification

The water surface was below the spring line of the tunnel at all operating conditions and did not interfere with the upstream flow of air from the portal. [An earlier trial with a 3-in. (76-mm) floor deflector caused surging flow in the tunnel.] However, only 80 ft (24 m) of the more than 800-ft (240-m) long tunnel was modeled and bulking due to air entrainment was not represented. To simulate the effects of a longer tunnel or bulking, or both, possibly hindering the flow of the return air, a solid baffle was placed over the downstream end of the model tunnel above the water surface. The pressures under the nappe were not significantly affected until the baffle was actually lowered into the water surface approx 1 ft (0.3 m) below the spring line. 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 was concluded that venting from the downstream portal would be adequate as long as a free surface existed in the tunnel. However, some remaining uncertainty pointed to the necessity for the vent in the gate frame. By closing the gate a few inches to spring the flow free of the gate frame ceiling, the existing vent would supply the air demand.

Prototype Tests.—The slots and deflectors developed by the model study were installed in the prototype and tested in 1972. Tests conducted with the 2-ft (0.6-m) square manway opening closed and the air vent open showed that the jet was adequately aerated at gate openings up to and including 47-3/4 in. (1,200 mm) [full gate opening is 48-1/2 in. (1,230 mm)]. Pressure below the jet at the downstream end of the floor deflector was −8.6 ft (−2.6 m) of water at a gate opening of 47-3/4 in. (1,210 mm), −13.8 ft (−4.21 m) at 48 in. (1,200 mm), and −24.5 ft (−7.47 m) at full gate opening. Apparently, the jet impinged on the air vent and closed off the air supply.

Uncovering the access opening resulted in air velocities of 39 fps (12 m/s) in the gate chamber entryway at a gate opening of only 25%. Air velocity was 245 fps (74.7 m/s) at the access opening. It was recommended, instead of this method, that the access opening remain closed and that the gate opening be restricted to a maximum of 47-1/2 in. (1,200 mm).

Pueblo Dam Outlet Works

The outlet works at Pueblo Dam will consist 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 Fig. 6. The spillway outlet works [Fig. 6(*a*)] will utilize 6-ft by 6-1/2-ft (1.8 m by 2.0 m) high-pressure slide gates designed to release flows up to 3,080 cfs (87.2 m^3/s) each at full gate opening with the reservoir at spillway crest El. 4,898.7 ft (1,493.1 m). This is a head of approx 130 ft (40 m) at the gate. Normally the releases will be controlled to a maximum of 1,500 cfs (43 m^3/s) at heads as low as 28 ft (8.5 m). The river gorge outlet works [Fig. 6(*b*)] will release 600 cfs (17 m^3/s) from a 4-ft by 4-ft (1.2-m by 1.2-m) high-pressure slide gate at heads up to about 133 ft (40.5 m). Fully open, the gate is capable of discharging 1,310 cfs (37.1 m^3/s) at the maximum head with the reservoir at the spillway crest elevation.

The 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.

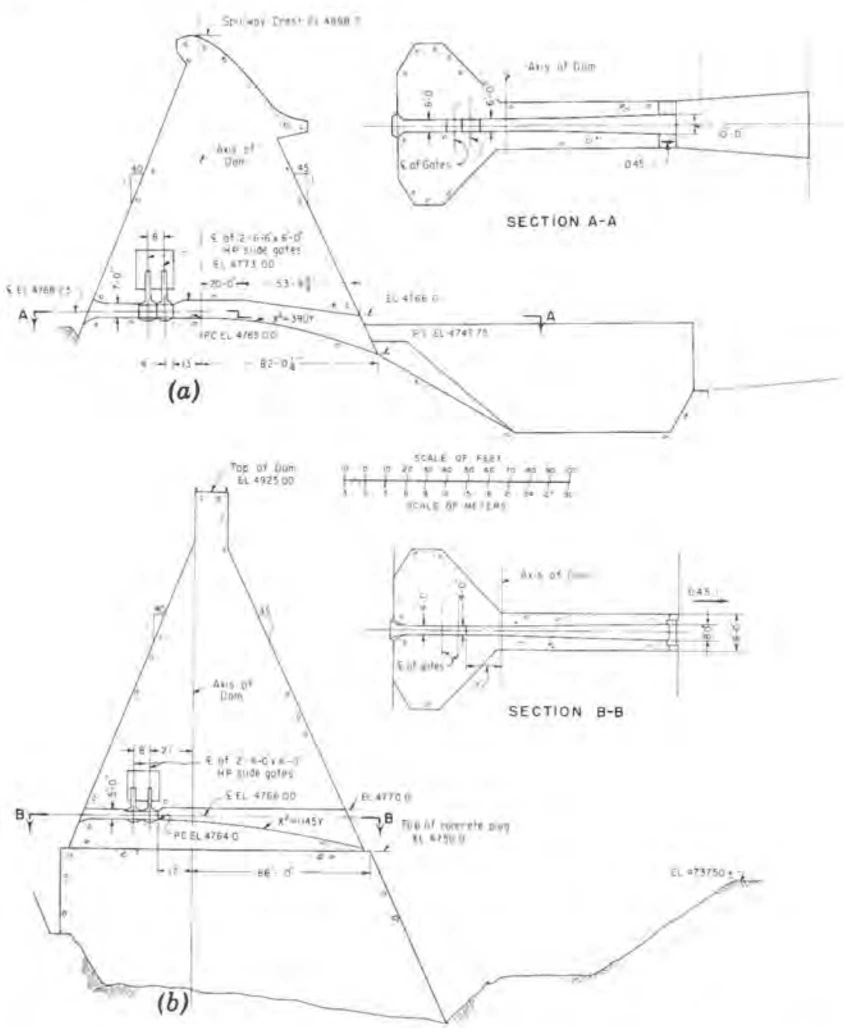

FIG. 6.—Pueblo Dam Preliminary Outlet Works: (*a*) Spillway Outlet Works; (*b*) River Gorge Outlet Works

The preliminary design of the spillway outlet works was modified by offsetting the floor of the conduit 6 in. (150 mm) below the floor of the gate frame and offsetting the walls at that point 3 in. (76 mm) away from the flow. The gate frame extended 4 ft (1.2 m) downstream from the gate, from which point the width of the conduit flared. The offsets failed to aerate except when the gate was operated at near maximum head. By installing at least two 3-3/4-in. (95-mm) diam 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 ft (9 m). The space under the jets

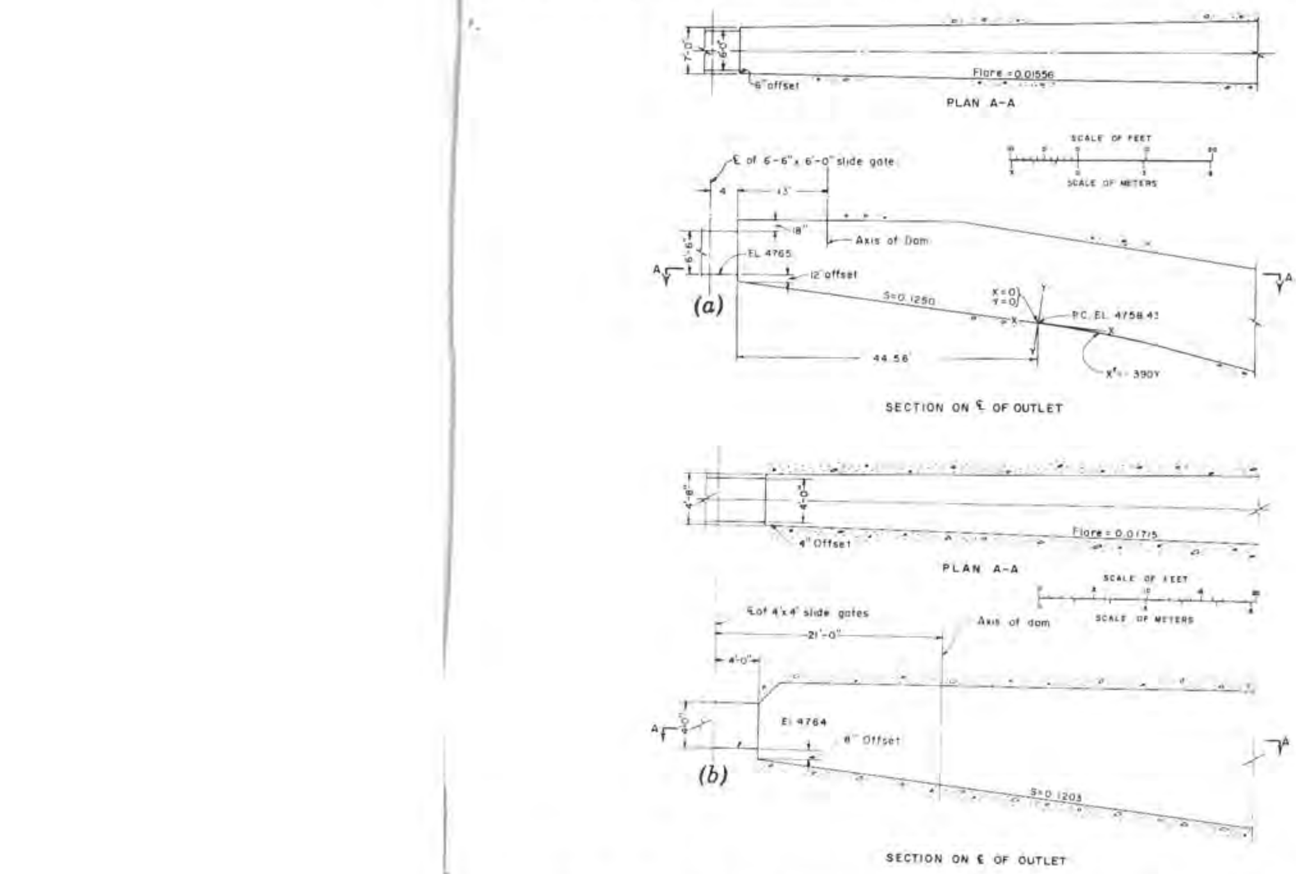

FIG. 7.—Pueblo Dam Recommended Outlet Works: (*a*) Spillway Outlet Works; (*b*) River Gorge Outlet Works

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.

Recommended Design of Spillway Outlet Works.—A better method of aerating the undernappe was found by increasing the side offsets from 3 in. (76 mm) to 6 in. (150 mm) and the floor offset from 6 in. (150 mm) to 18 in. (460 mm). 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.

The final step in the development of the recommended design [Fig. 7(*a*)] was to slope the floor away from the offset at the rate of 1:8. To accomplish this, the floor at the offset was raised to provide only a 12-in. (300-mm) offset at the gate frame, from which point the floor sloped to the point of curvature of the trajectory. The hydraulic performance of this recommended design was satisfactory. The jet was quite stable, the subatmospheric pressure below the nappe at the offset was nominal and steady for all flows, and normal pressures were recorded on the trajectory of the conduit floor.

Recommended Design of River Gorge Outlet Works.—The preliminary design of the river gorge outlet works was modified to include aeration offsets. The recommended design [Fig. 7(*b*)] 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 was 1/6 the gate frame width, which provided offsets of 4 in. (100 mm) and 8 in. (200 mm), respectively, for the 4-ft by 4-ft (1.2-m by 1.2-m) gate. The slope of the rectangular conduit floor away from the offset was slightly less than for the three spillway outlets, to meet a minimum elevation requirement at the outlet end of the flow passage. The flare of the walls was slightly more because of the wider buttress which permitted additional flare. The hydraulic performance of the river gorge outlet was satisfactory as designed except for some climbing of the walls by water fins 10 ft–20 ft (3 m–6.1 m) downstream from the offsets. Upon analyzing the performance of the two Pueblo outlet works, it was concluded that the wall fins were more prominent for the river gorge outlet than for the spillway outlets. The wall offset at the river gorge outlet is only 2/3 that at the spillway outlets, yet the heads and wall divergences are nearly identical. Therefore, a minimum wall offset of 4 in. (100 mm) is suggested for any head to width ratio greater than that for the spillway outlet works (21.6:1). Additional studies would be necessary to allow a statement of a specific recommendation. Pressures were not recorded in the river gorge outlet because there was no curvature in the chute floor. Flow conditions were stable and steady.

Crystal Dam Outlet Works

The outlet works at Crystal Dam (designed as an earth dam when these tests were conducted and later redesigned as a concrete dam) was proposed with two 3-1/4-ft (1.0-m) square high-pressure slide gates (Fig. 8) installed side by side. Each gate was designed to release up to 980 cfs (28 m^3/s) when the gates are operating together or up to 1,060 cfs (30 m^3/s) when operating alone under a total head of 221.82 ft (67.6 m). The gates were tilted downward 5° more than a 2:1 sloping chute and discharged into a stilling basin with a center dividing wall. The 2:1 chute was lined with stainless steel in the upstream 10 ft (3 m). The walls of the gate frame and metal chute flared to a width of 3 ft 11-3/8 in. (1.2 m) at which point there were 4-1/2-in. (114-mm) aeration offsets in the walls and a 9-in. (230-mm) offset in the floor. The offsets were recessed 9 in. (230-mm) into the concrete portion of the chute under and around the steel lining. The concrete chute walls flared 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. Although this structure will not be built, the model tests add data for generalization of design criteria.

The investigation was concerned with the range of discharges up to 950 cfs (27 m^3/s) for one valve. The tailwater elevation varied depending upon whether

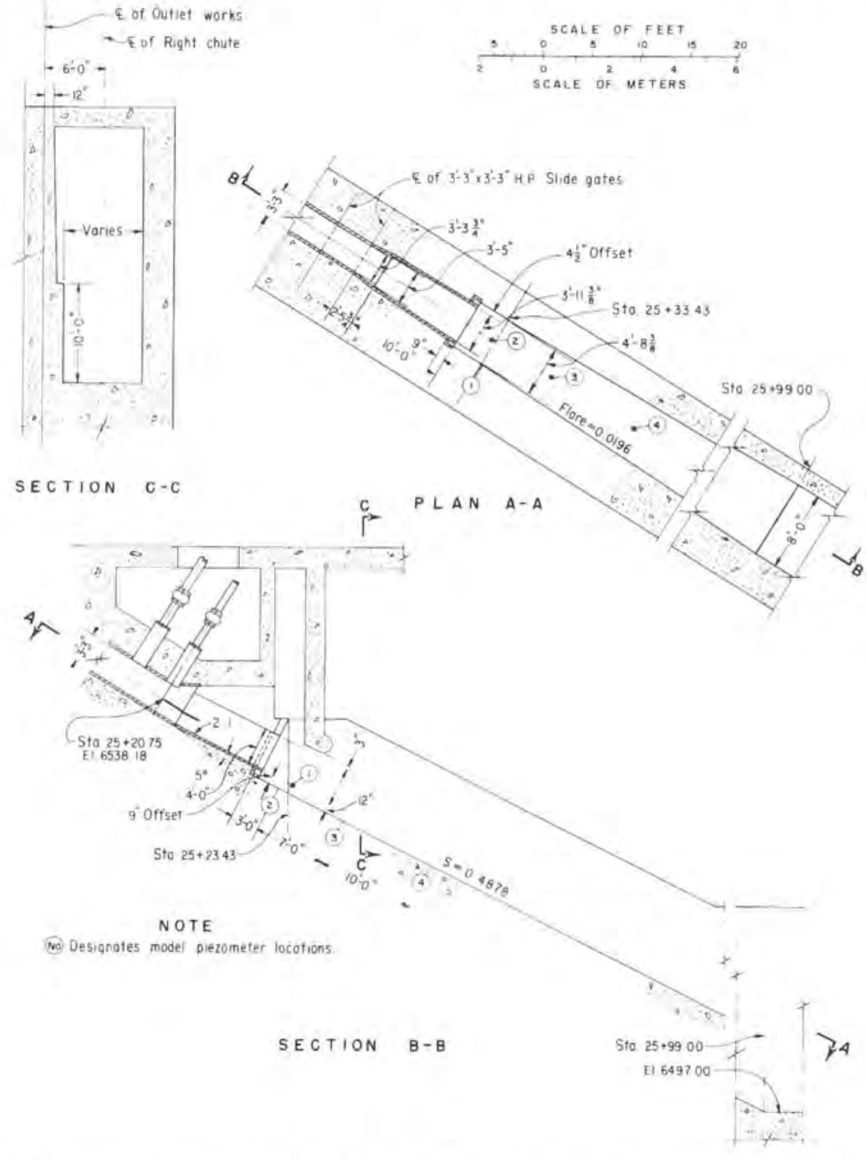

FIG. 8.—Crystal (Earth) Dam Outlet Works; Recommended Air Vent Offsets in Chute

or not the spillway was operating. Operation of the outlet works with spillway flows up to about 12,000 cfs (340 m^3/s) before the hydraulic jump swept out of the spillway 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 ft (3 m) downstream before offsetting for air entrainment. This arrangement required the installation of cavitation-resistant stainless steel walls from the gate to the offset.

The studies described herein indicated that offsets of 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 in. (100 mm) and 8 in. (200 mm), respectively, since the chute width at this point was 3 ft 11-3/8 in. (1.2 m). However, because the space was available, minimum offset recommendations were exceeded slightly. The offsets were made 4-1/2 in. and 9 in. (114 mm and 230 mm), respectively; and were recessed 9 in. (230 mm) behind the steel lining, as previously described.

Recommended Design.—The initial design of the chute and aeration offsets as tested was not modified and became the recommended design (Fig. 8). Observation of the hydraulic performance showed the jet to be fully aerated at the offset even at the highest tailwater conditions. Slight subatmospheric pressures were recorded at those piezometers that were not in contact with the flow, which verified that adequate air was present to provide good aeration of the flow. A test run at 28% gate opening and high tailwater 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. A test using the offsets without the 9-in. (22.9-cm) recesses showed the hydraulic performance to be equally satisfactory at the low tailwater condition but not quite as good with high tailwater because of surges extending upstream to the offset.

Teton Dam River Outlet Works

The river outlet works at Teton Dam (Fig. 9) (under construction) will have two 4-ft (1.2-m) square slide gates installed side by side, each discharging down a chute into a stilling basin. The flows from the two gates 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 m^3/s) each under a maximum head of about 300 ft (91 m). Each valve is tilted downward at a 2:1 slope and parallels the slope of the chute. The gate frame extends downstream from the center line of the gate, at which point the chute floor is offset 9 in. (230 mm) and the sidewalls 4-1/2 in. (114 mm). The gate frame width at the offset is 4 ft 2 in. (1.3 m). The chute walls flare from the gate frame at the rate of 0.0968.

The test facility provided a 1:10.1 scale model. 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 since the aeration offsets could not be submerged for any flow release.

Recommended Design.—Observation of the hydraulic performance showed the jet to be fully aerated at all operating heads from the minimum of about 120 ft (37 m) to the maximum of about 300 ft (91 m). At the high tailwater condition for the maximum flow discharging at maximum head, the basin water surface surged to the chute offsets but the jet remained fully aerated.

Pressures were recorded at three piezometers on the floor of the chute. The two piezometers nearest the offset were quite steady and only slightly subatmospheric, indicating a normal demand for air. The third piezometer was usually

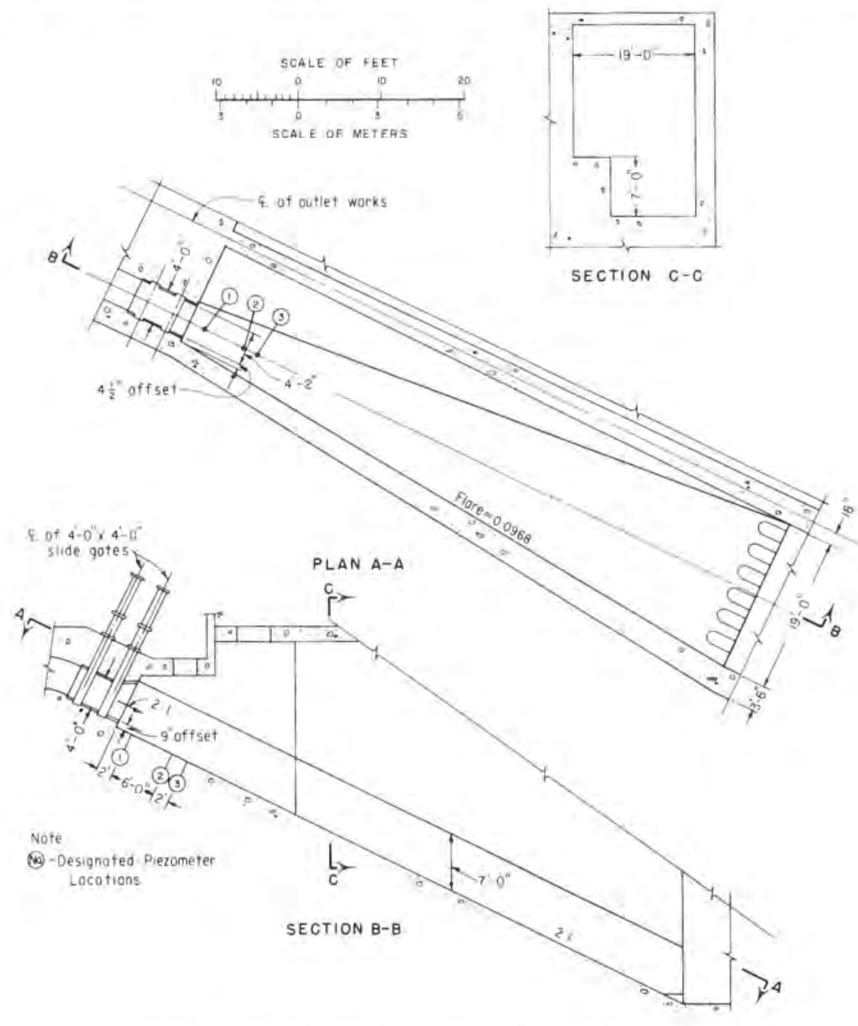

FIG. 9.—Teton Dam Recommended River Outlet Works

above atmospheric pressure, indicating that impingement of the jet on the floor of the chute had occurred.

This design was appreciably assisted by the experience gained from the previous investigations. The operation was fully satisfactory and no additional explanation is required.

Teton Dam Auxiliary Outlet Works

The auxiliary outlet works at Teton Dam (Fig. 10) is a proposed facility designed to release up to 850 cfs (24 m^3/s) from one 4-ft (1.2-m) square slide gate into a 7-1/4-ft (2.2-m) diam tunnel, 625 ft (191 m) long. The design flow can be released under heads ranging from 100 ft (30 m) at full gate opening to 279 ft (85 m) at maximum reservoir elevation. Flows as low as 150 cfs (4.2 m^3/s) may be released to any head up to 279 ft (85 m). In the recommended design, the downstream gate frame is 4 ft 3/4 in. (1.2 m) wide by 6 ft (1.8 m) high and extends 3 ft 8 in. (1.1 m) from the gate leaf. The downstream tunnel has a slope of 0.0124.

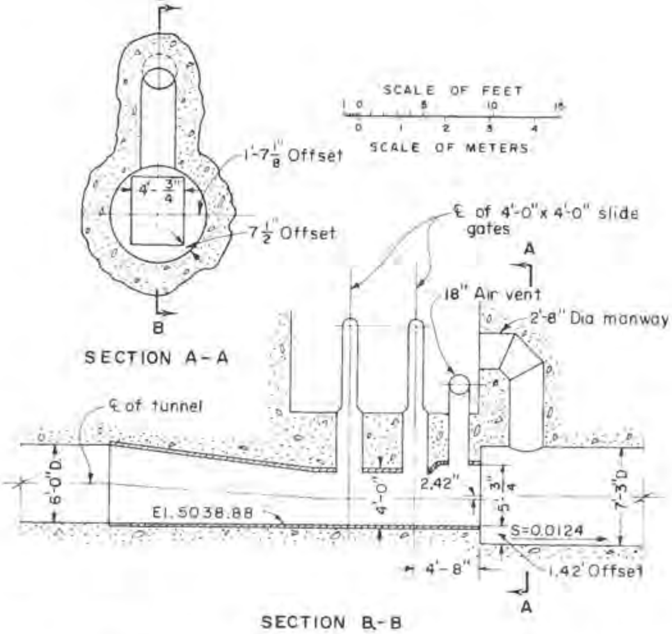

FIG. 10.—Teton Dam Recommended Auxiliary Outlet Works

The test facility provided a 1:10.1 scale model. It included the gate and approx 115 ft (35.1 m) of the tunnel.

The preliminary design included a 3-in. (76-mm) offset in the walls of the gate frame, 2-1/2 in. (64 mm) from the gate leaf for the purpose of aerating the sides of the jet through the gate frame section, where the possibility exists of cavitation under high heads. This increased the gate frame width to 4 ft 6-3/4 in. (1.4 m).

At full open gate discharging the design flow of 850 cfs (24 m^3/s) at a head of 100 ft (30 m), the sides of the jet through the gate frame were aerated as intended, with impingement of the jet on the walls at the lower downstream corner of the frame. However, with slight closure of the gate, this impingement point moved upstream. At 96% open, ventilation to the floor of the frame ceased. At 90% open, the offset was completely filled with water when the gate was discharging at 100 ft (30 m) head. Extremely high pressures were recorded on the wall of the gate frame at these high head flows. Experience has shown that the rapidly expanding jet, as evidenced by the high impact pressures on the wall, may cause formation of vortex trails into the region, resulting in cavitation erosion in the walls of the offset.

At smaller gate openings, generally in the vicinity of 30% 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. Because the sheets of water on the walls appeared to fill the tunnel with spray, hampering ventilation from the downstream portal, and because at the larger gate openings there was no ventilation of the jet at the gate frame offset, the idea of an offset in the gate frame near the gate leaf was abandoned.

The preliminary design also included a transition section from the rectangular gate frame to the round tunnel, over a distance of 7.58 ft (2.3 m). The floor offset at the gate frame was 9 in. (230 mm) and the wall offset was 1 ft 7-1/8 in. (49-m) on each side. At maximum head of 277 ft (84.4 m), the flow of 860 cfs (24 m^3/s) impinged on the sides and bottom surfaces of the transition at about 3/4 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. This is believed to be due to the unique geometry of the flow passage and does not imply that the side offsets were not supplying air.

Recommended Design.—In the recommended design, the offset in the walls of the gate frame [other than 3/8 in. (10 mm) across the gate slot] and the transition section downstream from the gate frame were eliminated. 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 in. (190 mm) at the corners of the gate frame. Aeration was satisfactory for the full range of discharges. Pressures on the gate frame and the circular tunnel showed the high-pressure areas expected on the gate frame walls and the slightly subatmospheric pressures caused by the air demand in the circular tunnel.

Summation of Project Studies

Air Vent Slots.—In existing structures, the results imply that a 12-in. (300-mm) square air slot is sufficient for flows from outlet works gates in conduits ranging from 4 ft-7-1/2 ft (1.2 m-2.3 m) wide discharging at heads up to 330 ft (101 m). The 7-1/2 ft (2.3 m) wide conduit was not tested at heads to 330 ft (101 m); therefore, some caution is necessary in interpretation.

Floor Deflectors.—The floor deflector for Palisades Dam gained a height of 2-1/2 in. (64 mm) in a length of 30 in. (760 mm). For Navajo, the deflector was 2 in. (51 mm) high in a length of 18 in. (460 mm). Floor deflectors, 3 in. (76 mm) and 4 in. (100 mm) high, were tested in the Palisades model, but a fin of water formed on the center line 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 [16-1/3 ft (5.0 m) downstream] for gate openings less than 50% at high heads. Also, the close proximity of the deflectors to the gate leaf substantially reduced the discharge coefficient and the higher deflectors are therefore not recommended.

Generally, the upward slope of the floor deflectors should begin at the end of the gate frame, which is usually 4 ft (1.2 m) or more downstream from the gate leaf. The deflector should have a rise of at least 2 in. (51 mm) and a slope of not more than 1 on 9.

Wall Deflectors.—Wall deflectors converging inward 1 in. (25 mm) were used at Palisades. The deflectors were 30 in. (760 mm) long beginning at the gate frame, extending to the air vent slot, the same length and station as the floor deflector. Larger wall deflectors were not tested because of reduction in the discharge coefficient of the gate and because of the center fin that formed as previously described.

At Navajo, wall deflectors were not necessary because the walls diverged downstream from the gate frame. Therefore, the 18-in. (460-mm) 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. Generally, 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 in. (25 mm) 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 in. (51 mm) and the walls were parallel until they intersected the original divergent walls. Generally, the walls downstream of the slot should be offset at least 1 in. (25 mm) when a wall deflector is used upstream of the slot and 2 in. (51 mm) 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 (1).

Proposed Structures.—In the design of the proposed structures, 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 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 studies of the two Pueblo outlet works, 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; however, one discharged from a 6-ft (1.8-m) wide gate frame while the other discharged from a 4-ft (1.2-m) wide gate frame. The wall offsets were 6 in. (150 mm) and 4 in. (100 mm), respectively, 1/12 of the gate frame width. Because the head was nearly the same in both cases, the spreading jet from the gates impinged on the 4-in. (100-mm) wall offset sooner than on the 6-in. (150-mm) 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 in. (100 mm), unless the head-to-width ratio is less than about 20:1 as at the 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 bottom of 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 1/6 of the gate width, which is similar to that used for Teton Dam auxiliary outlet works. However, a hydraulic model study should be made to verify the design.

Conclusions

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 because 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-ft (300-mm) square. Larger slots should maintain a square or nearly square configuration. No data are available for sizing larger slots.

3. The downstream edge of the slot should be offset 1 in.–2 in. (25 mm–51 mm) 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 fps (12 m/s), 1:50 for velocities exceeding 90 fps (27 m/s), and 1:100 for velocities exceeding 120 fps (37 m/s) (1).

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 in. (25 mm) 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 will not reduce the discharge capacity by forming a restriction in the tunnel.

5. If a floor deflector is used, its rise should be determined from the jet velocity and the resulting jet trajectory. In the cases tested, the rise was 2.5 in. and 2 in. (64 mm and 51 mm), with respective slopes of 1:12 and 1:9. Jet velocities were approx 100 fps and 112 fps (30 m/s and 34.1 m/s), 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 in. (100 mm). Floor offsets should be twice the wall offsets, or 1/6 of the gate frame width.

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.

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Appendix.—References

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11462 CAVITATION CONTROL BY AERATION OF JETS

KEY WORDS: **Aeration; Cavitation; Deflectors; Gates; Hydraulics; Jets;** Offsets; **Outlet works;** Research; Slots

ABSTRACT: To prevent cavitation erosion, air may 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 tests, formed the basis for guidelines developed for design of future air-entraining devices to protect flow surfaces from cavitation erosion.

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