PAP-276

AERATION MITIGATES CAVITATION IN SPILLWAY TUNNEL

ASCE NATIONAL WATER RESOURCES ENGINEERING MEETING
JANUARY 24-28, 1972 ATLANTA, GEORGIA

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PAP-276

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ASCE National Water Resources
Engineering Meeting
January 24-28, 1972 • Atlanta, Georgia $0.50

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Meeting Preprint 1635

AMERICAN SOCIETY OF CIVIL ENGINEERS
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AERATION MITIGATES CAVITATION IN SPILLWAY TUNNEL

By Donald Colgate 1/, M. ASCE and James Legas 2/ M. ASCE

INTRODUCTION

In 1967, sustained operation of Yellowtail Dam spillway tunnel resulted in cavitation damage to the concrete lining and in two areas advanced through the lining and into the foundation rock. This paper describes the condition of the tunnel prior to spill, operation during spill, damage resulting from spill, repairs to the damaged areas, construction of an air slot to introduce air along flow surfaces, use of a laboratory model to optimize the location and configuration of the air slot and subsequent prototype tunnel testing.

GENERAL INFORMATION

Yellowtail Dam is the principal feature of the Yellowtail Unit of the Lower Bighorn Division of the Missouri River Basin Project. The dam, located on the Bighorn River about 45 miles southwest of Hardin, Montana, is a concrete arch structure with a crest length of 1,450 feet and a structural height of 525 feet. Waterways through and around the dam include the spillway, river outlets, and penstocks to a powerplant.

The spillway, an open channel type, is in the left abutment rock and consists of an approach channel, an intake structure, a concrete-lined tunnel section, and a combination stilling basin-flip bucket section.

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The intake structure includes two bays, each controlled by 25-foot-wide by 64.4-foot-high radial gates, and converges into a single tunnel downstream from the gates. The tunnel courses downward through a transition section into a 55° inclined section having a diameter that varies gradually from 40.5 to 32 feet at the beginning of a vertical bend. The vertical bend and the 1,202 feet of near horizontal tunnel downstream from the bend are 32 feet in diameter. The tunnel terminates in a combination stilling basin-flip bucket structure designed as a hydraulic jump energy dissipator for discharges up to about 12,500 cfs and as a flip bucket to project the flow into the downstream river channel for discharges greater than 12,500 cfs.

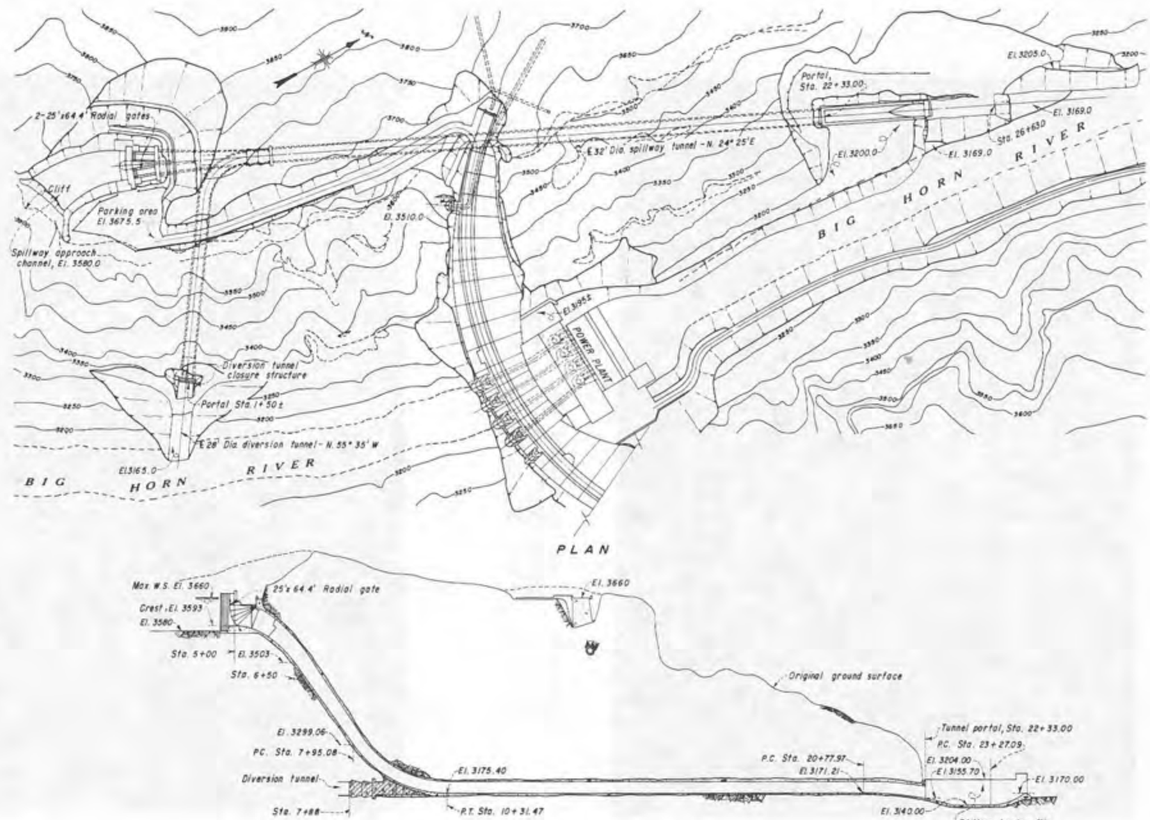
The spillway was designed for a maximum capacity of 92,000 cfs at maximum reservoir elevation 3660. At this maximum discharge the ratio of water depth to tunnel diameter is approximately 0.75.

The completed portion of the spillway tunnel downstream from the P.T. of the vertical bend (Station 10+31.47) was utilized in the diversion of the river during construction. Figure 1 shows the plan and sections of the spillway and diversion tunnels.

CONDITION OF FLOW SURFACES AFTER DIVERSION

During 33-1/2 months of diversion flows, river sediments eroded the invert of the spillway tunnel to a maximum depth of about 1-1/2 inches from the P.T. of the vertical bend to the end of the stilling basin-flip bucket structure.

The eroded tunnel invert was generally smooth, Figure 2; however, some exposed aggregate had popped out, and spalling had occurred at a few construction joints.



SECTION THRU SPILLWAY
FIGURE 1

Figure 2. - Condition of eroded invert in the near horizontal reach of spillway tunnel. Photo No. P459-640-3687 NA

Figure 3. - Eroded invert surfaces of stilling basin. Photo No. P459-D-55582 NA

The condition of the stilling basin invert was excellent considering the amount of silt-laden materials passed during diversion. The surface was sufficiently eroded to expose aggregate, see Figure 3, but the texture of the eroded surfaces was generally smoother than similarly affected areas in the spillway tunnel. Depth of erosion was greatest at the basin centerline and decreased uniformly to the original surface in a distance of 6 to 8 feet from the centerline.

Although not involved with diversion, the lining in the inclined portion and the vertical bend of the tunnel was pitted with surface irregularities resulting from rock pockets, bug holes, spalls, form tie removal, etc. The danger of cavitation damage initiated by the irregularities was of major concern. Maximum spillway flow velocities of about 160 fps will occur at the P.T. of the vertical bend. This area is also most vulnerable to damage because of the presence of secondary flows and the disruption of the boundary layer. Accordingly, restoration and repair guidelines were formulated that required all large depressions or gouges throughout the tunnel to be repaired with epoxy-bonded epoxy mortar or with concrete patches keyed into the original concrete. In addition, a smooth glasslike surface was required in the invert of the downstream portion of the vertical bend and the upstream portion of the near horizontal tunnel reach. For the first 10 feet downstream from the P.T. of the bend the surface was conditioned by bushhammering and grinding, and careful bushhammering continued another 40 feet to transition the surface into the existing eroded surface of the tunnel.

In the 735-foot reach of tunnel starting 130 feet downstream from the P.T. of the vertical bend, six small areas of surface irregularities were not repaired. These areas were for the evaluation of surface irregularities subjected to high velocity flow in a region of developed boundary layer.

SPILLWAY OPERATION IN 1967

During the spring and summer of 1967 the watersheds of south-central Montana and northern Wyoming experienced an above-normal snowmelt runoff. This runoff coupled with heavy rainfall flooded many streams in the area including the uncontrolled Yellowstone River. Releases were restricted from controlled streams tributary to the Yellowstone, including the Bighorn River on which Yellowtail Dam is located, to minimize flooding in the Yellowstone. However, on June 26, the reservoir at Yellowtail Dam was 9 feet into the 17-foot exclusive flood pool and in addition to the powerplant and outlet works discharges, an initial spillway release of 3,000 cfs was made. Spillway discharges were increased to 12,000 cfs on June 27 and reduced to 10,500 cfs on June 28. A rise above flood stage at Miles City on the Yellowstone River was forecast; therefore, spillway releases past the dam were further reduced to 7,000 cfs on June 28 and to 5,000 cfs on June 29. When additional data on inflows to the reservoir became available on June 29, it was decided that the rapidly diminishing flood control space was the critical factor rather than flooding on the Yellowstone River. Accordingly, the spillway discharge was increased to about 10,000 cfs. Inflows into the reservoir continued high and on July 3 spillway releases were increased to 13,000 cfs and to 14,500 cfs on July 4. At 14,500 cfs, and for the existing high tailwater, the jump swept out of the basin and was flipped into the river. The flipping action was good and appeared as predicted from the design and hydraulic model analysis.

During the next 10 days, the discharge through the spillway varied between 14,500 and 18,000 cfs. On July 14, with the spillway discharge at 15,000 cfs, the spillway basin suddenly quit sweeping out. Several attempts involving increased spillway discharges to 15,500 cfs and a decreased tailwater were made to again flip the flow from the basin. None of the attempts were successful. Since a complete spillway shutdown was not possible due to the need to further evacuate the flood control space, the spillway discharge was reduced to 9,000 cfs for 4 days and to 8,300 cfs for an additional 5 days, then gradually decreased until complete shutdown was achieved on July 25. During 10 hours of spillway shutdown, a scuba diver found major damage in the vertical bend and in the horizontal tunnel just downstream from the bend. Since additional reservoir evacuation was required, the spillway was again activated and operated at 3,000 cfs for 3 days. At this time the flood danger had passed and a final shutdown was made.

Except for the 10-hour shutdown on July 25, the spillway was operated continuously from June 26 through July 28. In that period, approximately 650,000 acre-feet of flood waters were passed at discharges that varied from 3,000 cfs to a maximum of 18,000 cfs.

CONDITION OF TUNNEL AFTER SPILL

After shutdown, the tunnel and stilling basin were dewatered to permit a closeup inspection of the lining. As had been reported by the scuba diver examination, the major damage occurred in the vertical bend section and the near horizontal tunnel reach immediately downstream from the bend.

Two severely damaged zones occurred in the vertical bend. The first zone was about 20 feet long and began at Station 9+00±. Damage was centered along the tunnel centerline, and consisted of three concave holes about 3 feet in diameter, 6 to 12 inches deep, and interconnected by shallow longitudinal damaged areas. The second zone originated at Station 9+45±, and was centered 3 feet right of the tunnel centerline. The damage consisted of five distinct teardrop-shaped holes, in line, with a maximum width and depth of 6 and 2 feet, respectively. In both instances, cavitation was initiated by the failure of epoxy mortar patches.

In addition to the major damaged zones, many smaller areas of cavitation damage occurred in the vertical bend from the P.C. Station 7+95.08 to the P.T. Station 10+31.47. The cavitation which caused the damage was initiated by buildup of calcium carbonate deposits, failure of mortar applied in thin layers to bring the original surface up to grade, failure of small epoxy mortar repairs, and loss of aggregate that had been heavily bushhammered and ground to eliminate high spots in the surface. In many cases bushhammering and grinding had either loosened the aggregate from the matrix or resulted in a very thin layer of aggregate that became loose when subjected to high-velocity flow. The ensuing depressions in most cases resulted in minor cavitation damage. Although size and location of the surface irregularities were influencing characteristics, a more controlling influence (in the case of depressions formed by mortar or aggregate loss) was probably the time during the spillway operation at which these failures occurred.

The tunnel reach upstream from the bend was free of cavitation damage; however, at random locations from Station 6+50 to Station 7+75, numerous surface irregularities occurred when poorly bonded epoxy mortar patches failed or when concrete spalled or eroded due to water action or passage of debris through the tunnel. None of these surface irregularities, many of which were 1/2-inch to 3/4-inch deep and about 12 inches in diameter, initiated cavitation damage.

The most severe damage in the tunnel resulted from the failure of an epoxy mortar patch approximately 1/4-inch deep, 6 inches wide, and 10 inches long. Cavitation damage started immediately downstream from the patch failure (Station 10+40±) in the form of a small damaged area about 3 feet long, followed by a large teardrop-shaped area about 20 feet long. Damage in the latter area was sufficiently deep to expose reinforcement. Immediately downstream from Station 10+80± and extending 46 feet down the tunnel, the cavitation-induced damage progressed through the lining and into the limestone foundation. Depth of damage was 7 feet maximum below the invert grade and about 19.5 feet wide in the transverse direction. Downstream from the large hole, the damaged area became progressively less severe and terminated at Station 11+65. The remainder of the tunnel downstream from Station 11+65 and including the stilling basin-flip bucket structure was essentially in good condition and similar in appearance to the surfaces observed after diversion. Surface irregularities that had been left unrepaired to determine their action under high-velocity flow did not change in appearance nor did they initiate cavitation damage. Figure 4 shows the most severely damaged area in the near horizontal tunnel reach.

REPAIRS AND MODIFICATION TO TUNNEL

Restoration of damaged surfaces and areas included repairs with bonded concrete, epoxy-bonded concrete, and epoxy-bonded epoxy mortar. Preparation of the surface for bonded concrete repairs was made by sawcutting around the perimeter of the damaged area to a depth of 1-1/2 inches. Damaged or undercut concrete and all loose rock were removed. Damaged reinforcement was removed and replaced either by welding or lapping new reinforcement in place. All concrete or rock surfaces to receive the concrete were sandblasted, washed clean, and surface dried before placement of the repair concrete. Where the depth of damage was greater than 6 inches, concrete was applied directly to the clean dry surface. Where the depth of damage was between 2 and 6 inches, an epoxy bonding agent was applied to the clean dry surface, and while in a tacky state, overlain with repair concrete.

For damaged areas less than 2 inches deep, the surface was prepared by sandblasting, washing, and drying to receive an epoxy bonding agent, and a veneer of epoxy mortar was then applied to the area. This type of repair with epoxy-bonded epoxy mortar veneer was applied over practically the entire invert surface of the vertical bend.

After the repairs had cured properly, all repaired surfaces not meeting the required specifications for finishes and tolerances were corrected by grinding.

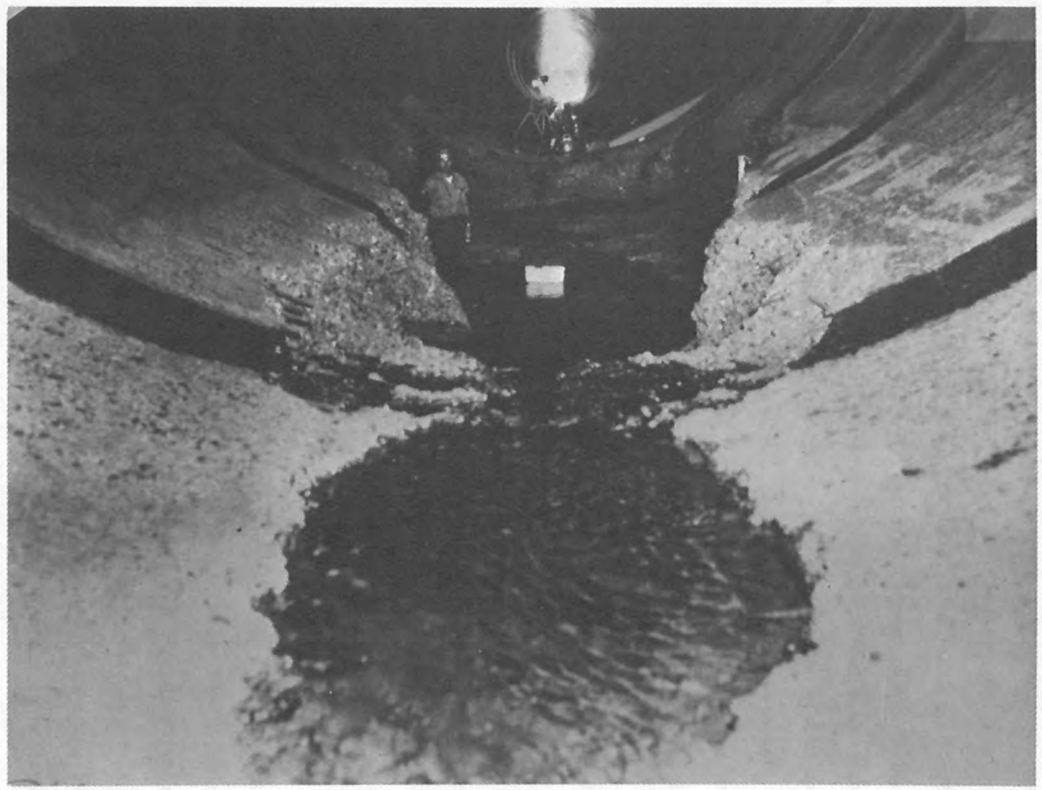


Figure 4. - Damaged area in tunnel approximately 50 feet downstream from the vertical bend. Photo No. P459-640-4042 NA

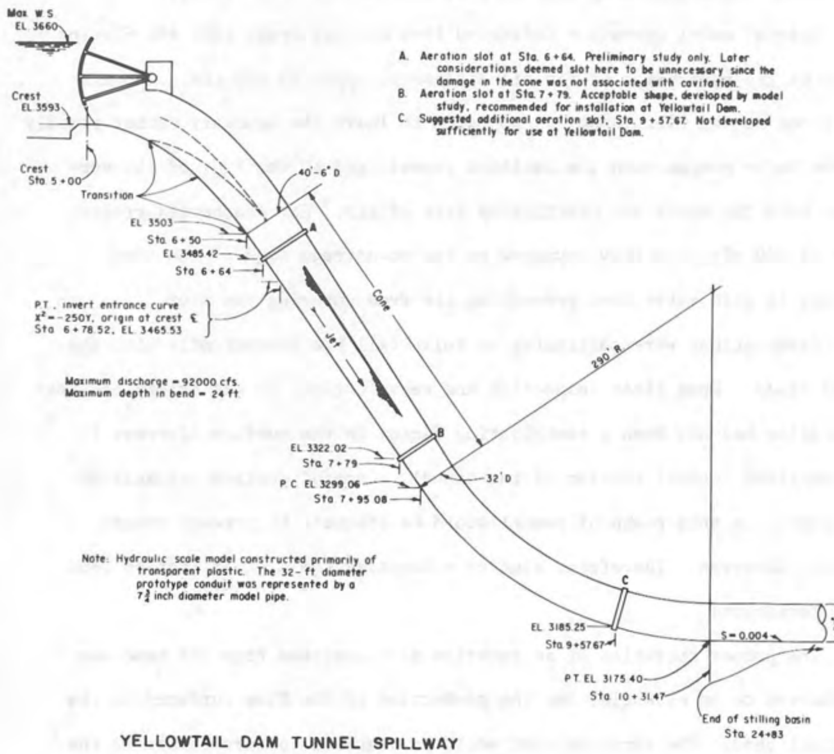
When the flow surfaces were judged to meet all the requirements as to finishes and tolerances, the tunnel reach from Station 7+64 to Station 12+15 extending from spring line to spring line was painted with a two-coat epoxy phenolic paint treatment. The purpose of the paint treatment was to provide a smooth uniform texture to flow surfaces and to cement particles of the materials in the epoxy mortar or concrete to each other. A white pigmented paint was used as the second coat to provide a high degree of visibility to flow surfaces.

The specifications for the tunnel repairs were extremely rigid and required smooth surfaces throughout and elimination of all surface irregularities. As an additional precaution against cavitation erosion, a means was sought whereby air could be introduced into the flowing water to cushion the damaging action of collapsing water vapor cavities. A model study was required to evaluate various air entrainment devices and determine a design that was hydraulically adequate and economically feasible for installation concurrent with the surface restoration repairs.

HYDRAULIC LABORATORY MODEL STUDY

A 1:49.5 scale model of the tunnel spillway was constructed in the U.S. Bureau of Reclamation's Hydraulics Branch laboratory, Figure 5.

A previously used and successful device for entraining air in water flowing in a relatively small tunnel consisted of a slot in the tunnel lining to admit air to the periphery of the jet as it passed over the slot. Three aeration slot locations were suggested for the Yellowtail spillway: (a) Station 6+64, 210 feet downstream from the crest to protect the inclined conical portion of the tunnel, (b) Station 7+79, 200 feet further downstream



YELLOWTAIL DAM TUNNEL SPILLWAY

FIGURE 5

(28 feet upstream from P.C. of the vertical bend) to protect the upper portions of the bend, and (c) Station 9+57.67, 74.65 feet upstream from the P.T. of the 277-foot-long vertical bend to protect the lower portions of the bend and the upstream portion of the horizontal tunnel. The cross section of the preliminary slot at each location was 3 by 3 feet.

Initial model operation indicated that air was drawn into the flowing water at the upstream slot for all discharges up to 55,000 cfs. The air entrained at the slot, however, appeared to leave the boundary rather rapidly as the water passed down the inclined tunnel, and at the P.C. of the vertical bend the water was practically free of air. For discharges greater than 55,000 cfs, the flow impinged on the downstream edge of the slot filling it with water thus preventing air from entering the slot.

Examinations were continuing at Yellowtail Dam concurrently with the model study. Upon close inspection and reevaluation, it was determined that cavitation had not been a contributing factor in the surface distress in the inclined conical section of the tunnel. Careful surface preparation and repair in this reach of tunnel would be adequate to prevent future surface distress. Therefore, studies concerning the slot at Station 6+64 were terminated.

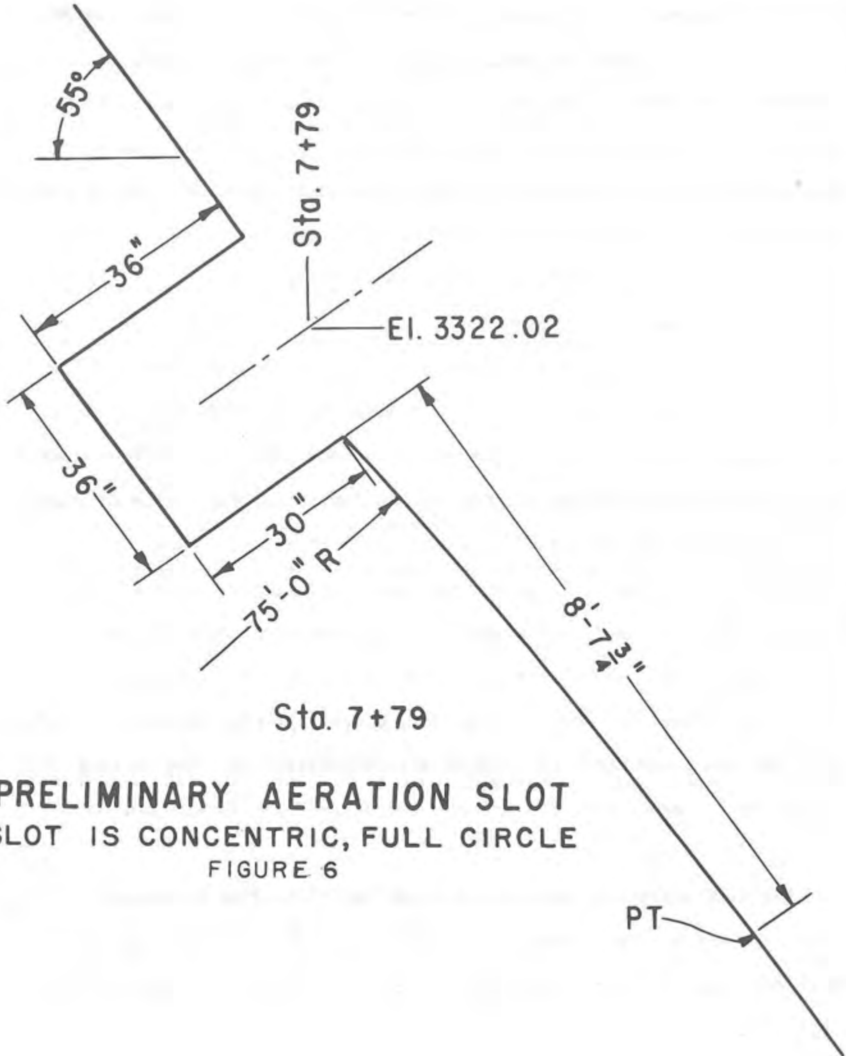
The proper operation of an aeration slot upstream from the bend was considered to be essential for the protection of the flow surfaces in the vertical bend. The aeration slot would be required to furnish air to the flowing water, and be hydraulically acceptable, for all discharges up to the maximum of 92,000 cfs.

A preliminary aeration slot, uniform in cross section for the entire circumference of the tunnel, was installed 28 feet upstream from the P.C.

of the bend (Figure 6). Although air was entrained in the flowing water for low flows, the edges of the jet near the water surface impinged on the downstream edge of the slot and water entered the slot. As the discharge increased, greater amounts of water entered the slot. As more water entered the slot, the amount of air entrained in the flowing water decreased and stopped entirely when the discharge was about 50,000 cfs.

Figure 7 shows the preliminary slot with 92,000 cfs flowing in the tunnel. Note the absence of entrained air downstream from the slot. In an attempt to prevent water from entering and filling the slot, the slot was narrowed to 6 inches, with a 6-inch away-from-the-flow offset downstream. Although some air was entrained in the jet at low discharges, water entered the slot near the water surface for all spillway discharges. For discharges less than 20,000 cfs, water drained down the slot and flowed out into the jet at the tunnel invert, reducing the amount of entrained air as the spillway discharge increased. At a spillway discharge of 20,000 cfs, the water surface in the slot was at the same elevation as the spillway water surface, and no air entered the jet. For spillway discharges greater than 20,000 cfs, the water was forced into the slot at a sufficiently high head to cause it to boil up the slot above the spillway water surface and spill out onto the surface of the jet.

The slot width was increased to 12 inches. The flow with this configuration was similar to that with the 6-inch slot. The discharge at which the water surface in the slot was equal to that of the spillway water surface was 30,000 cfs.



Sta. 7+79

PRELIMINARY AERATION SLOT

SLOT IS CONCENTRIC, FULL CIRCLE

FIGURE 6

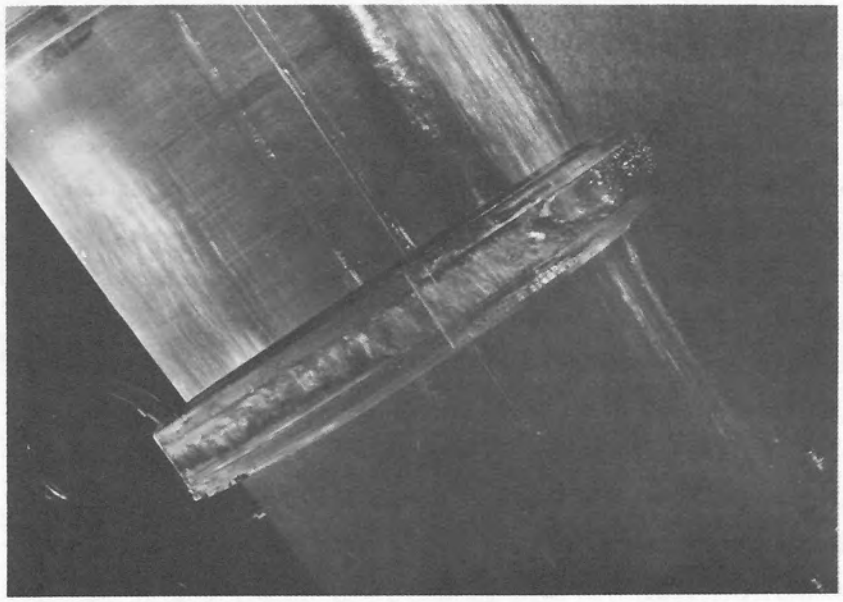


Figure 7. - Preliminary aeration slot, Station 7+79. Discharge is 92,000 cfs. The slot has filled with water thus preventing air from entering the jet. Photo No. P459-D-68807

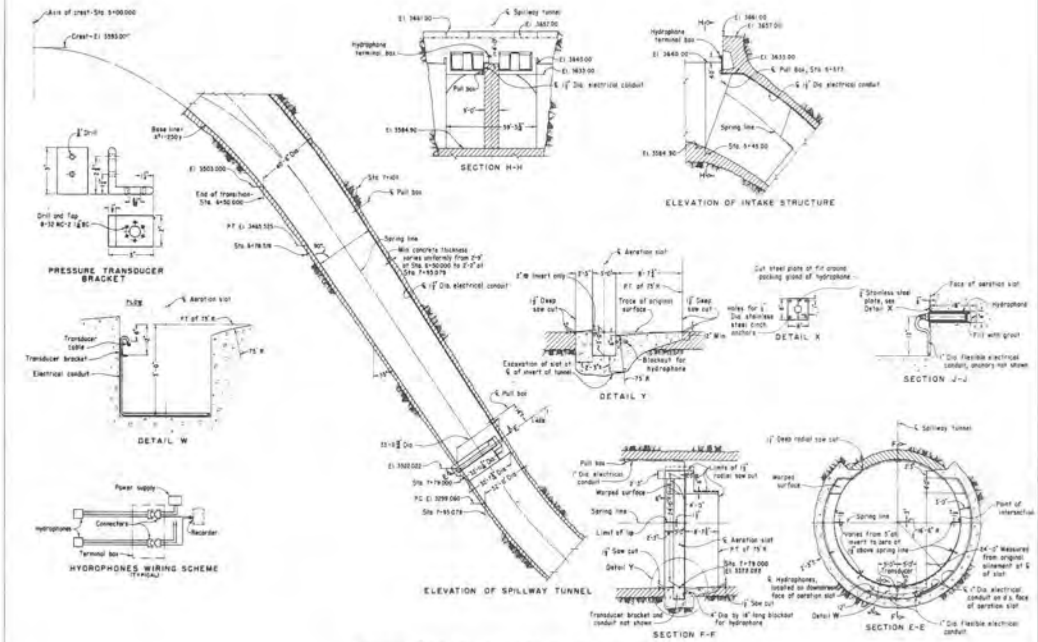
The preceding tests indicated that some type of lift or elevated spring point would be requird to raise the jet over the slot for all spillway discharges so the slot would remain open and furnish air to the jet.

A conical nozzle was installed in the tunnel at the upstream face of the 3- by 3-foot aeration slot where the tunnel diameter was 33 feet. The nozzle exit was concentric in the tunnel, 32 feet in diameter, and the cone extended 5 feet upstream from the slot. Air was entrained in the jet and the slot remained free of water for all discharges. However, a large fin of water formed on either side of the tunnel where the jet from the nozzle impinged in the bend. The fins became progessively larger and arched higher with increasing discharge until, at a discharge of 6,000 cfs, the side fins extended to the crown of the tunnel. For discharges greater than 40,000 cfs, the water folded over the top of the jet and choked the tunnel. This study indicated that the nozzle shape or a ramp-type of lift upstream from an air slot would permit the jet to entrain air for all discharges, but modifications were needed to prevent side fins from choking the tunnel at the higher discharges. Several transitional ramp shapes were evaluated in the model before a configuration was perfected which would operate satisfactorily for all discharges up to the design maximum of 92,000 cfs.

The final design for the aeration slot upstream from the P.C. of the vertical bend consisted of a 3- by 3-foot slot with a ramp, 27 inches long in the direction of flow, which raised the upstream face of the slot 3 inches at the tunnel invert. The intersection of the ramp and the upstream face of the aeration slot were the same radius as the tunnel, with a 3-inch eccentricity in a plane perpendicular to the tunnel invert. Thus the lift varied from 3 inches at the tunnel invert to 0 at a point 1-1/2 inches above the tunnel spring line. The ramp upstream from the lip was a constant 27 inches long (Figure 8).

The lift, or ramp, forced the jet away from the tunnel flow surface, over the aeration slot, and the jet remained free for a considerable distance downstream before it impinged on the tunnel invert. The distance to the point of jet impingement on the tunnel invert reached a maximum of 52 feet downstream from the aeration slot at a discharge of 4,000 cfs. This distance decreased as the flow depth and discharge increased and was 20 feet for a discharge of 92,000 cfs. This type of impingement will not damage smooth concrete surfaces.

The impingement of the jet on the tunnel invert downstream from the aeration slot caused side fins to form. For discharges less than 30,000 cfs, these side fins swept uninterrupted up the walls of the tunnel past the contracted jet. These side fins were not objectionable and did not reach the top of the tunnel (Figure 9). Since the lift diminished as it neared the tunnel spring line, the upper portion of the jet was subjected to less contraction than the lower portion. Consequently, the upper elements of the jet impinged on the walls of the tunnel further upstream and at a much smaller angle as the discharge and flow depth increased. For discharges greater than 30,000 cfs, the upper portion of the jet interfered with and reduced the side fins, and for discharges greater than 50,000 cfs, the side fins were entirely contained by the upper portion of the jet.



TUNNEL AERATION AND INSTRUMENTATION
ELEVATIONS AND SECTIONS
FIGURE 8

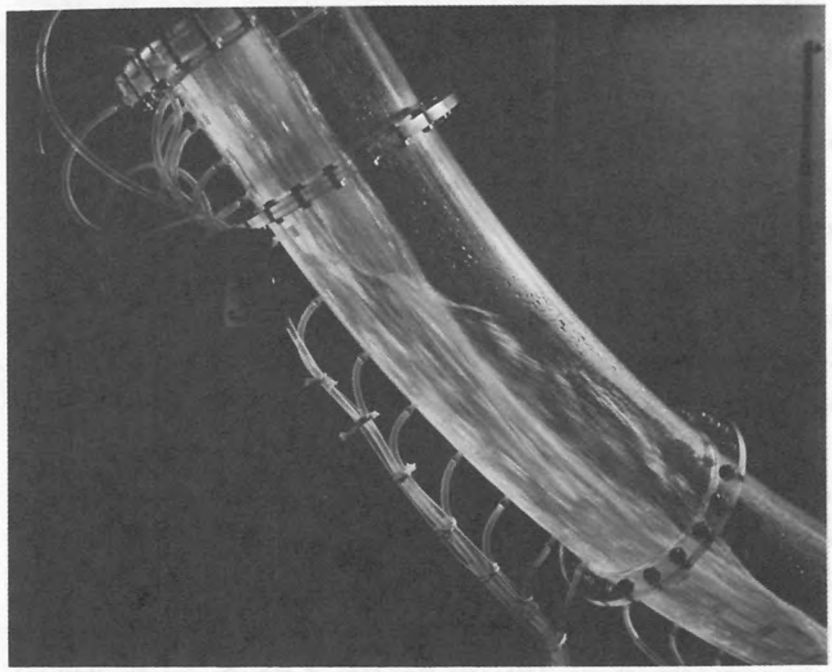


Figure 9. - Recommended aeration slot, Station 7+79. Discharge is 30,000 cfs. These maximum side fins, one each side of the jet, do not reach the crown of the tunnel. Photo No. P459-D-68809

The aeration slot remained free of water, and air was drawn into the jet for all discharges.

Air was visible in the model jet starting at the air slot and continuing well downstream from the P.T. of the bend (Figure 10). However, it was not known whether the amount of air remaining adjacent to the tunnel flow surfaces in the downstream portion of the bend would be sufficient to prevent cavitation damage. The relationship between model and prototype with respect to entrained air is at best poorly understood. Therefore, the model tests were continued to study the proposed aeration slot in the downstream portion of the bend.

The centrifugal force of the water in the bend made this location quite different hydraulically from the location in the conical portion of the tunnel. The initial study was made with no lift upstream from the slot and a 12-inch away-from-the-flow offset downstream. The slot partially or completely filled with water for all discharges. A small amount of air entered the jet for discharges less than 15,000 cfs, but for larger discharges water filled the slot and air was not entrained in the jet.

Various ramps and lifts were installed in the tunnel upstream from the slot. Each design tested produced satisfactory air entrainment and hydraulic operation for a limited range of discharges; however, none would operate satisfactorily over the full range of discharges.

These limited tests indicated that the necessary modifications for a satisfactory aeration device to be installed in the vertical bend of an existing structure would be too extensive to be practical. An aeration device could undoubtedly be developed for installation in a bend during initial construction of a spillway tunnel.

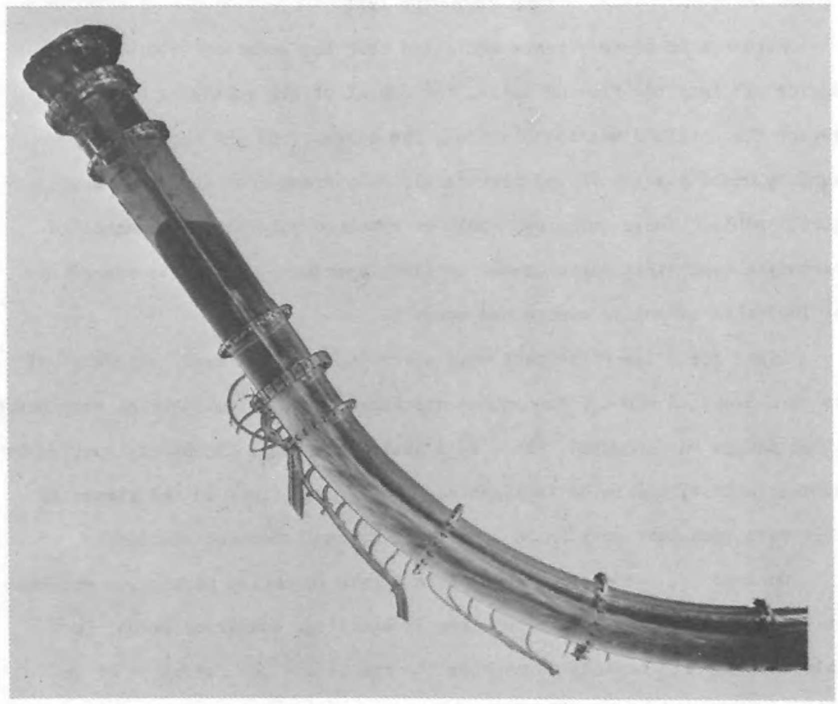


Figure 10. - Overall view of the spillway model. Recommended aeration slot at Station 7+79. The slot at Station 6+64, upper left, has been closed. Air entrained at the aeration slot continues throughout the bend. Mixing tends to reduce the air near the flow surfaces in the downstream portion of the bend. Photo No. P459-D-68808

1969 PROTOTYPE TEST

Although laboratory tests indicated that the aeration slot was introducing air into the flowing water, the amount of air remaining near the invert flow surface was speculative. The adequacy of the epoxy veneer surface beneficiation in and immediately downstream from the bend was also questionable. These questions could be resolved only through controlled prototype tests that approximated spillway operation during the summer of 1967 when extensive damage had occurred.

Plans for a two-phase test were developed early in 1969. Phase 1 was to be a 5-day, 5,000-cfs continuous discharge test, followed by an examination. If no damage was incurred, Phase 2, a sustained 5-day, 15,000-cfs continuous discharge test, was to be implemented. Water conditions in the summer of 1969 were such that only Phase 1 could be accomplished satisfactorily.

On June 16, the entire tunnel from intake to outlet portal was examined in the dry. The tunnel surfaces were in excellent condition except for calcium carbonate buildup throughout the tunnel and the formation of small "blisters" in the epoxy mortar veneer at the upper end of the vertical bend.

Because carbonate buildup had induced cavitation in 1967 and since the efficacy of the air slot was as yet unknown, calcium carbonate deposits were removed from Station 7+75 to Station 12+15 for a distance of 10 feet each side of the tunnel centerline. Blisters in the epoxy veneer were not removed since their location and configuration were thought to be less critical to cavitation. Additionally, repairs of blisters would have been time consuming and could have meant postponement of the test.

For electronic monitoring of the test, two hydrophones were embedded in the downstream face of the slot and one pressure transducer anchored to the upstream face of the slot. Hydrophone outputs were connected to a two-channel oscilloscope for visual readout. A direct writing recorder monitored and recorded the pressure transducer output.

On June 18, the spillway gates were opened incrementally until the 5,000-cfs discharge was reached. Gate openings were adjusted as required during the next 5 days to maintain a constant discharge. The oscilloscope and direct writing recorder were monitored continuously during the early part of the test to establish a background of normal readings. Thereafter, the instruments were monitored at 1/2-hour intervals to determine any deviations from normal.

After completion of the test on June 23, the inclined tunnel section was examined from an inspection cart that traversed the spillway from the intake portal to within 70 feet of the P.T. of the vertical bend. The remainder of the tunnel, still under water, was examined from a boat. The examination revealed several small bonding failures of the epoxy mortar veneer just above lip of the aeration slot and in and downstream from the vertical bend. The largest veneer failure was almost 6 inches in diameter and 1/4-inch deep. Additionally, several areas of paint removal occurred in and downstream from the bend.

The minor failures did not result in cavitational damage normally associated with these types of failures. Although highly encouraging, positive conclusions as to the efficacy of the air slot and the surface restoration could not be made. It was possible that veneer failures occurred late in the test and the resulting surface irregularities subjected to high-velocity flow for only a short time.

Between June 23 and 27, inflows into the reservoir were such that a 1-day, Phase 2 test was feasible. Accordingly, the test started on June 27 with 15,000 cfs discharged for approximately 24 hours. Instrumentation to monitor the test was similar to that developed for the first test. It should be emphasized that the 15,000-cfs test was conducted with existing surface irregularities that occurred during the 5,000 cfs test.

The tunnel surfaces were examined after the 1-day test and the following was noted:

1. Veneer and paint bonding failures in the bend that resulted from the 5,000-cfs test were not affected by the 15,000-cfs test.

2. One relatively large epoxy mortar failure occurred in the bend about 100 feet downstream from the aeration slot and 10 feet right of the tunnel centerline. The resultant depression was approximately 9 inches long, 12 inches wide, and 1 inch deep.

3. Additional paint and epoxy veneer failures occurred in the horizontal reach of the tunnel (examined by boat) with one large paint failure extending from Station 12+04± to Station 12+15. The failure was centered along the invert and was approximately 18 inches wide, maximum. Epoxy veneer failures were small in area and relatively shallow with a maximum depth estimated at one-quarter inch.

The results of the 15,000-cfs test were particularly important in that with a discharge approaching the maximum discharge in the 1967 flood, surface irregularities, similar to those causing damage in 1967, did not initiate cavitation. It was generally concluded that the 15,000-cfs discharge indicated the aeration slot was in fact supplying air to the invert surfaces in sufficient volume to mitigate cavitation damage; however, a sustained 15,000-cfs test was considered as essential before final recommendations could be made relative to future reservoir and spillway operations. Plans for such a test were scheduled tentatively for the summer of 1970.

Since the 1969 test had revealed surface deficiencies in the epoxy mortar veneer, it was decided that these should be corrected in advance of the next test. Of particular importance was the disbondment failures near the lip of the aeration slot. Although these failures were very small in area, any malfunctioning of the air slot could create a potential for cavitation damage far in excess of that occurring in 1967.

These repairs were essentially complete by early February 1970. Later in February a timber ladder used in making the repairs broke loose from its moorings due to an unexpectedly heavy ice load, and skidded along the invert of the vertical bend. The result was a series of gouges in the epoxy-mortar veneer, some of which were as much as 12 inches long, 1/4 inch wide, and about 1/4 inch deep.

1970 PROTOTYPE TEST

Inflows into the reservoir in late June of 1970 were of sufficient magnitude and duration to permit scheduling a sustained 15,000-cfs discharge test. Surface irregularities that occurred due to ladder failure had not been repaired. Since the irregularities were comparatively minor and because a better evaluation of aeration slot efficiency could be made with known surface deficiencies located in critical areas of the bend, it was decided to test the tunnel without repairing the lining irregularities.

The test commenced the morning of July 2 after examination of tunnel surfaces. As in the 1969 test, the aeration slot was monitored by observing and recording the responses from the hydrophone and pressure transducer installations. A discharge varying between 14,000 and 14,500 cfs was maintained until 2:30 p.m., July 6, when releases were reduced to 4,000 cfs. Complete spillway shutdown was made the morning of July 7.

Examination of the tunnel indicated positively the efficacy of the aeration slot in that:

1. Surface irregularities existing in critical areas of the vertical bend prior to testing neither became larger nor did they initiate cavitation damage.

2. Calcium carbonate deposits on the surface did not initiate cavitation damage.

The testing of the tunnel with existing irregularities at critical locations was highly significant in that no evidence of cavitation damage occurred anywhere in the tunnel. The inference is that the aeration slot is providing air which remains sufficiently near the flow surfaces to cushion collapsing water vapor cavities thereby preventing damage to these surfaces. As a result of the 1969 and 1970 prototype tests, all restrictions previously imposed on reservoir and spillway operations were removed.

CONCLUSIONS

Prototpye testing of Yellowtail Dam spillway tunnel confirmed the results of hydraulic model tests relative to the location and configuration of an aeration slot to mitigate the damaging effects of cavitation.

The prototype tests indicated that a sufficient volume of air was being supplied to flow surfaces in the vertical bend of the tunnel and in the tunnel reach immediately downstream from the bend to prevent cavitation erosion. Of particular importance is the fact that the 1970 test was conducted with known surface irregularities, in critical areas of the lining, whose location and size were similar to surface irregularities which initiated heavy cavitation-induced damage during a demand spillway operation in the summer of 1967.

Designers should consider installation of air entrainment devices in the critical areas of newly constructed tunnel spillways where high velocities and disruption of the boundary layer can occur.