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HYDRAULIC MODEL STUDIES OF AERATION DEVICES FOR YELLOWTAIL DAM SPILLWAY TUNNEL, PICK-SLOAN MISSOURI BASIN PROGRAM, MONTANA

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Engineering and Research Center
Bureau of Reclamation

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16. ABSTRACT

Prototype operation of the Yellowtail Dam tunnel spillway in 1967 resulted in severe damage to the tunnel. The damage was caused by cavitation initiated by surface irregularities in the tunnel lining. The major damage was concentrated in the vertical bend and in the tunnel just downstream from the bend. An aeration slot to introduce air into the flowing water was to be constructed concurrently with tunnel repairs. A laboratory model of the tunnel was used to study various locations and configurations of aeration slots. As a result of the model study, one aeration slot was designed that was suitable for all spillway discharges. The optimum location for the slot was determined to be just upstream from the vertical bend.

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by

D. M. Colgate

December 1971

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Denver, Colorado

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Secretary

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Commissioner

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The author acknowledges the contribution of the Division of General Research shops for their rapid and accurate fabrication and installation of the many complicated configurations required before a satisfactory design was perfected. Speed was of the utmost urgency since model studies proceeded concurrently with the repairs and modifications of the damaged spillway tunnel.

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Frontispiece. Yellowtail Dam On The Bighorn River, South Central Montana. Photo 459-600-135A

PURPOSE

These model studies were made to develop an aeration device to be installed in a spillway tunnel during repair and modification of the tunnel. Air entrained in the flowing water would aid in the prevention of cavitation damage to the concrete lining of the tunnel.

RESULTS

1. An aeration slot at Station 6+64 entrained air in the model flow; however, as the stream progressed down the inclined tunnel, the bubbles left the invert rather rapidly and none remained near the flow boundaries at the PC of the bend, Station 7+95.08.

2. The air entrained in the flow by an aeration slot at Station 7+79 appeared to remain in the stream and near the flow boundaries throughout the vertical bend.

3. These limited studies failed to produce a satisfactory aeration device in the bend at Station 9+57.67.

APPLICATION

These studies for the aeration of the flow in the Yellowtail Dam spillway tunnel, together with the report of the studies regarding aeration of the spillway tunnel at Hoover Dam[1], should serve as a guide in the design of aeration devices for modification of existing structures. Further studies are needed to define the parameters for determining the configuration and location of aeration devices in both existing and proposed tunnel bends.

INTRODUCTION

The diversion tunnel at Yellowtail Dam in South Central Montana was closed in November 1965, and Bighorn Reservoir behind the dam started to fill. After diversion flows stopped, the entrance, sloping portion, and vertical bend of the tunnel spillway were constructed to intersect the old diversion tunnel 1,200 feet upstream from the exit portal of the tunnel (Figure 1). The debris-laden water of the Bighorn River had roughened and eroded the concrete in the tunnel invert until aggregate was exposed. Also, in the newly constructed portions of the spillway tunnel, the concrete lining contained small aggregate pockets, bugholes, spalls, and other comparatively minor surface irregularities. Repairs throughout the tunnel were made by grinding or bushhammering to eliminate abrupt into-the-flow irregularities. Depressions or gouges were repaired with concrete patches keyed into the original concrete and with epoxy-bonded epoxy mortar.

During the spring of 1967, heavy rains in the watershed of the Bighorn River resulted in large inflows into Bighorn Reservoir. The Bighorn River below Yellowtail Dam flows into the uncontrolled Yellowstone River, and for a time floodwaters were impounded in the Bighorn Reservoir because the Yellowstone was in flood. On June 26, the water surface of Bighorn Reservoir was 9 feet into the exclusive flood control pool and an initial spillway release of 3,000 cfs was made (Figure 2). Spillway discharges were increased to 12,000 cfs on June 27 and varied as flood demands required thereafter. On July 4, the discharge through the spillway was increased to 15,000 cfs and the hydraulic jump swept out of the basin as intended with the jet being "flipped" into the river.

The discharge remained at 15,000 cfs or greater (up to 18,000 cfs) and the flow remained in the flipped attitude, from about noon on July 4 to 5:30 p.m., July 14. At this time, the 15,000-cfs discharge stopped flipping and the toe of the hydraulic jump swept back through the basin and into the tunnel. Several attempts, involving increased spillway discharges to 15,500 cfs and reduced tailwater, were made to again sweep the flow from the basin, but none were successful. The spillway basin would not sweep out. Obviously, some change had occurred in the flow passage which produced a large increase in energy loss in the flow through the tunnel. The discharge was reduced to 8,300 cfs, the minimum allowable for the safety of the dam.

After the spillway flow swept back into the basin, project personnel became aware of distinct vibrations in adits in the dam and abutments. Also, when standing near the radial intake gates, loud "thumpings" could be heard emanating from the spillway tunnel. These physical indications of something amiss in the tunnel may have been present, but remained unnoticed, prior to loss of the flipping action. The spillway discharge was held at 8,300 cfs until July 23, then gradually decreased until complete spillway shutdown was achieved on July 25. A 10-hour shutdown permitted a scuba diver examination of the tunnel lining. Major damage was found in the near-horizontal tunnel and in the elbow. Because additional reservoir evacuation was

[1] "Study of Air Injection Into the Flow in the Boulder Dam Spillway Tunnels," USBR Report No. Hyd-186, October 24, 1945.

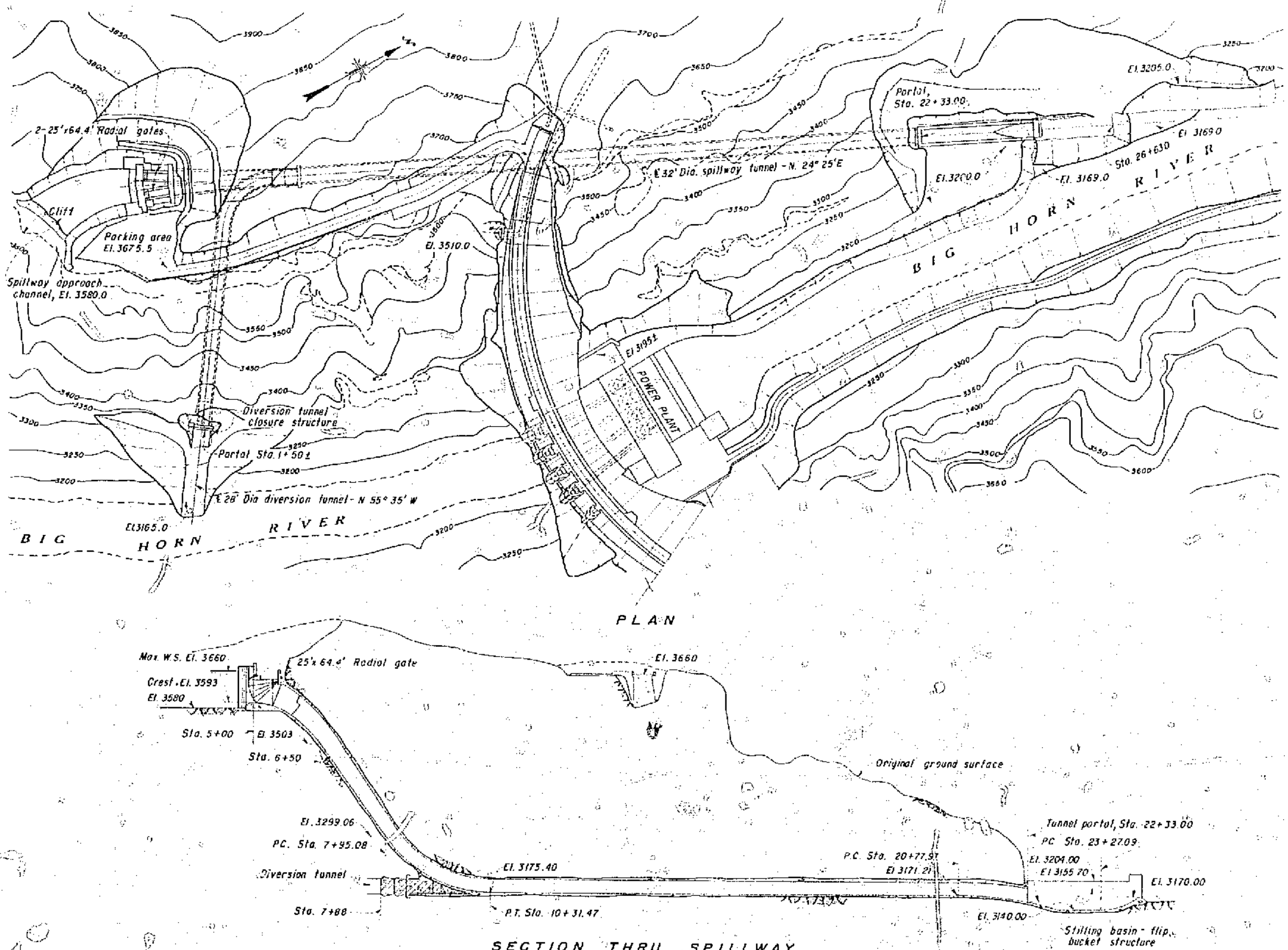

Figure 1. Yellowtail Dam.

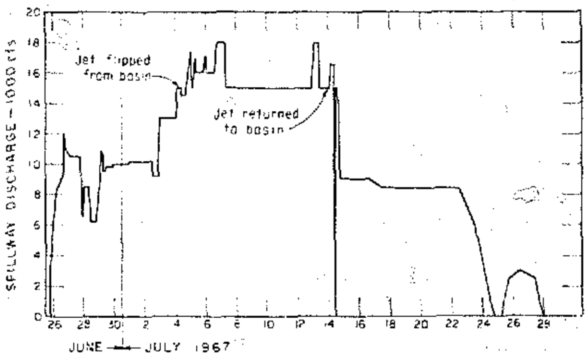

Figure 2. Yellowtail Dam spillway releases between June 26 and July 28, 1967.

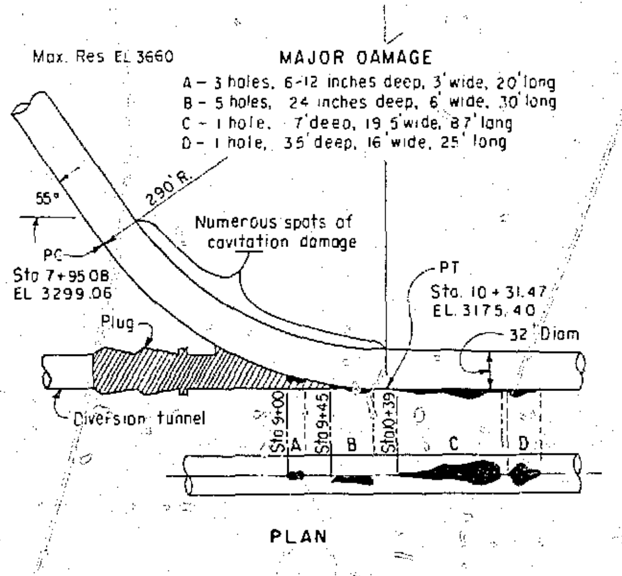

Figure 3. Yellowtail Dam—Section through tunnel spillway bend—Location of major damaged areas, 1967 flood releases.

required, the spillway was again activated and discharged up to 3,000 cfs until final shutdown was achieved on the morning of July 28.

Except for the 10-hour shutdown July 25, the spillway operated continuously from June 26 to July 28. In that period, 650,000 acre-feet of floodwaters had passed through the spillway at variable discharges up to 18,000 cfs.

At 4 p.m. on July 6, the reservoir reached a peak elevation of 3656.43, 3.57 feet below the crest of the dam.

After flood danger had passed, the tunnel was dewatered and the concrete tunnel lining was subjected to a thorough examination (Figure 3). The largest damaged area was centered on the tunnel invert beginning 8 feet downstream from the P.T. of the tunnel bend and extending downstream for 125 feet (Figure 4). A surface discontinuity was responsible for the cavitation that initiated the damage, and a combination of cavitation and jet action continued to erode the concrete and foundation rock downstream. The surface discontinuity resulted from the partial failure of an epoxy patch which had been placed to fill in an eroded area in the tunnel invert before spillway releases were made. The spalled area was 1/4 inch deep, 6 inches wide, and 10 inches long. Remains of epoxy mortar could be seen around the perimeter of the patch. Cavitation damage started immediately downstream from the depression, and damage in the first 25 feet was sufficiently deep to expose reinforcement bars. In the next 100 feet (approximately), the tunnel invert concrete and large quantities of the limestone foundation rock had been removed. The crater reached a maximum depth of 7 feet and a width of 19.5 feet. Portions of the concrete lining along the sides of the damaged area had been undercut as much as 6 feet.

The 1,070 feet of tunnel lining downstream from the large hole was undamaged except for minor gouges probably caused by the movement of large blocks of concrete and rock from the heavily damaged area upstream. (Note: The flow velocity in the spillway tunnel for a discharge of 15,000 cfs is approximately 90 fps at Station 6+50, 140 fps through the bend, and 85 fps at the tunnel exit[2].)

Two areas of major damage occurred in the tunnel elbow (Figure 5). In each instance, the cavitation which resulted in the damage was induced by failure of an epoxy mortar patch within a dry pack mortar patch. One damaged area began at Station 9+00 and extended along the tunnel centerline for 20 feet. The damage consisted of three holes each about 3 feet in diameter, 6 to 12 inches deep, and interconnected by shallow damaged areas. Another area of major cavitation damage in the bend continued for 30 feet downstream from Station 9+45 and was 3 feet to the 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.

[2] Laboratory Report No. Hyd-483, "Hydraulic Model Studies of Yellowtail Dam Spillway," August 7, 1964.

Figure 4. View looking downstream at the large eroded area below the P.T. of the bend. Cavity is about 100 feet long, 7 feet deep, and 19-1/2 feet wide. Photo P459-D-70515

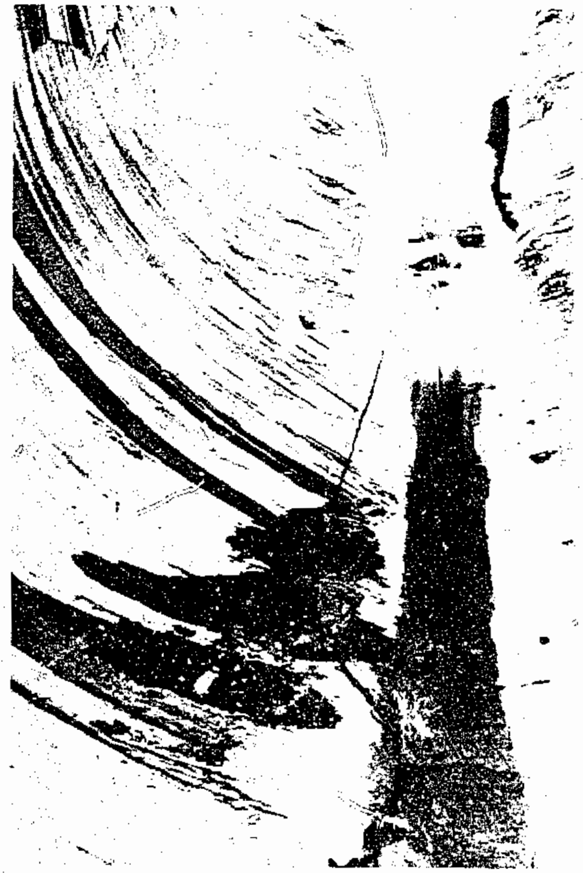

Figure 5. View looking upstream showing the two major damaged areas in the vertical bend. One area is in the left foreground, the other in the invert at the center of the photograph. Note man near the upper damage area. Photo P459-640-4088

In addition to the major damaged zones, many smaller areas of cavitation damage occurred in the vertical bend. The cavitation producing these damaged areas was initiated by comparatively minor surface irregularities resulting from calcium carbonate deposits, failure of cement mortar applied 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 concrete surface. Cavitation damage was noted downstream from surface irregularities extending into the flow as little as one-eighth inch.

In the tunnel reach upstream from the P.C. of the bend numerous surface irregularities occurred where poorly bonded epoxy mortar patches had failed or where concrete had spalled or eroded due to water action or passage of debris through the tunnel.

Specifications were issued for the necessary filling and patching to rehabilitate the tunnel to the original alinement using concrete and epoxy mortar. These specifications were extremely rigid and required very smooth surface finishes and complete elimination of surface discontinuities. 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 cavities.

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.[3] Two such slots were suggested for the Yellowtail Spillway, one at Station 6+64 to protect the sloping conical portion of the tunnel and one at Station 7+79 to protect the vertical bend.

[3]Aeration slots have been installed in all of the intermediate and upper tier river outlets at Grand Coulee Dam. Prior to installation of the slots, all of the concrete troughs downstream from the cones in the steel-lined portions of the tunnels had suffered damage by cavitation. Some of the outlets have operated more than 10,000 hours since installation of the slots without damage to the concrete troughs.

A model study was needed to evaluate various air entrainment devices to determine the optimum design to be installed during repairs to the Yellowtail Dam spillway tunnel. Therefore, a 1:49.5 scale model of the tunnel was constructed in the Bureau of Reclamation's Hydraulics Branch laboratory (Figures 6 and 7).

LABORATORY MODEL STUDIES

Aeration Slot at Station 6+64

Initial model operation indicated that air was drawn into the flowing water at the upstream slot (Station 6+64) for all discharges smaller than 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.[4] 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.

Concurrently with the model study, examinations were continuing at Yellowtail Dam. Upon close inspection and reevaluation, it was determined that no damage by cavitation had occurred at surface irregularities in the conical section of the tunnel. Careful surface preparation and repair in this reach of tunnel would be adequate to prevent future surface distress. Therefore, model studies concerning the slot at Station 6+64 were terminated.

Aeration Slot at Station 7+79

The proper operation of an aeration slot at Station 7+79 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 for all discharges up to the maximum of 92,000 cfs. In addition, the configuration of the slot and all adjacent areas would necessarily be such that the flow would be hydraulically acceptable for all discharges. During these studies no attempt was made to measure the quantity of air entrained in the water.

Preliminary Slot

The preliminary aeration slot at Station 7+79 was uniform in cross section for the entire circumference of the tunnel (Figure 7B). 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 for discharges greater than about 5,000 cfs. As the discharge increased, more of the jet impinged on the downstream edge of the slot and greater amounts of water entered the slot. As more water entered the slot, the amount of air entrained in the flowing water decreased. Air entrainment in the flowing water stopped entirely at a spillway discharge of about 50,000 cfs.

Figure 8 shows the preliminary slot with 92,000 cfs flowing in the tunnel. Note the absence of entrained air downstream from the slot.

Narrow Slot—6 Inches Wide

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 (Figure 9A). 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.

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[4] A similar conclusion was reached during the model study of the aeration of the spillway tunnel at Hoover Dam (Laboratory Report No. Hyd-186):

> "*Record of tests on vertical bends.* The first objective in these tests was to determine the percentage of air remaining in the water at the vertical bend, as a result of entrainment by the sill arrangement shown on Figure 5. Measurements were made at Samplers A, B, and C for discharges of 40,000, 60,000, 80,000, and 100,000 second-feet, but not a trace of entrained air could be recovered at these points in any case. Visual observations confirmed these results as the only air visible in the vertical bend was on the surface of the flow."

(Note: Figure 5 shows sills near the tunnel entrance; Samplers A, B, and C are air samplers in the vertical bend.)

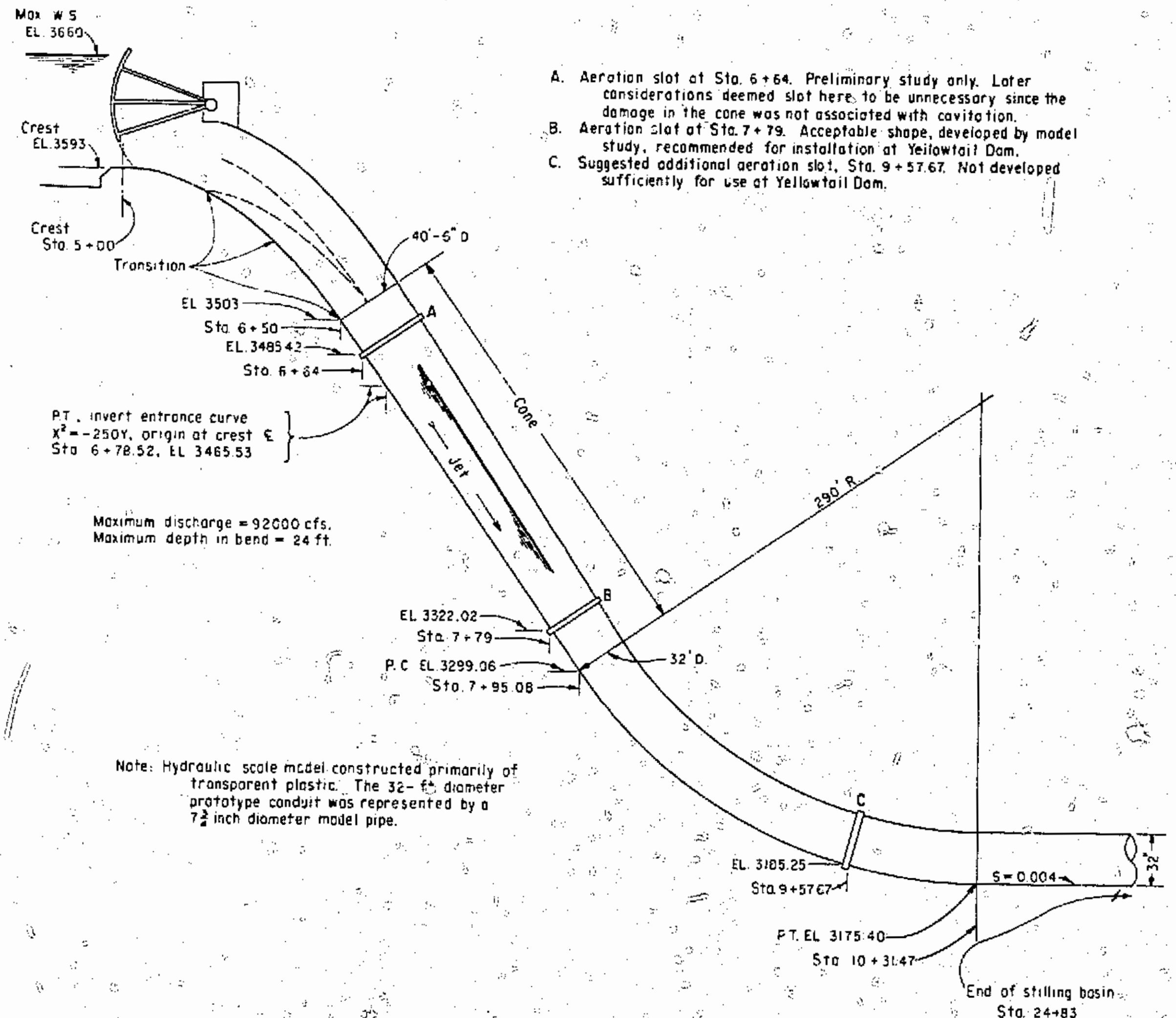


Figure 6. Yellowtail Dam tunnel spillway.

Narrow Slot—12 Inches Wide

The slot width was increased to 12 inches (Figure 9B). 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.

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

Conical Nozzle

A conical nozzle was installed in the tunnel at the upstream face of a 3- by 3-foot aeration slot at Station 7+79 where the tunnel diameter was 33 feet. The nozzle exit was concentric with the tunnel, 32 feet in diameter, and the cone extended 5 feet upstream from the slot (Figure 10). 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 progressively 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 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.

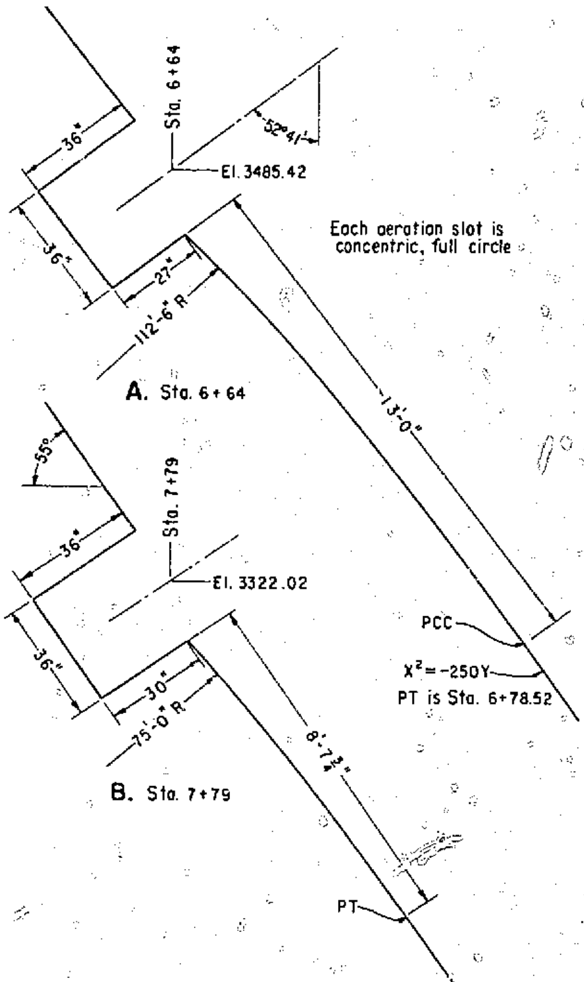


Figure 7. Preliminary aeration slots.

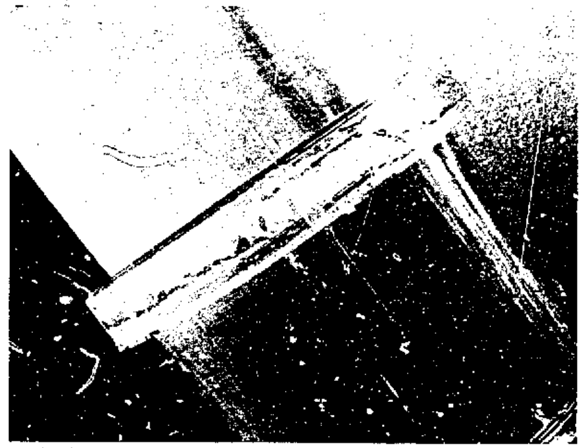


Figure 8. Preliminary aeration slot, Station 7+79. Discharge is 92,000 cfs. The slot has filled with water thus preventing air from entering the jet. Photo P459-D-668807

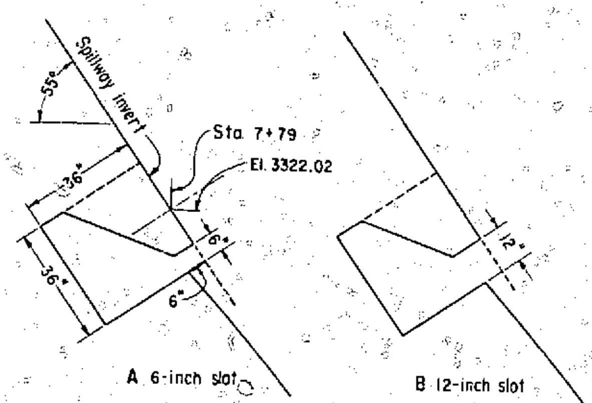


Figure 9. Narrow aeration slots.

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.

Recommended Aeration Slot

The recommended design consisted of a 3- by 3-foot aeration slot at Station 7+79. A ramp, 27 inches long in the direction of flow, 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 was the same radius as the tunnel, with a 3-inch eccentricity in a plane perpendicular to the tunnel centerline. Thus the lift varied from 3 inches at the tunnel invert to 0 at a point 1-1/2 inches above the tunnel springline. The ramp upstream from the lip was a constant 27 inches long (Figure 11).

The lift, or ramp, forced the jet away from the tunnel flow surface and 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 (Figure 12). This type of impingement will not damage smooth concrete surfaces.

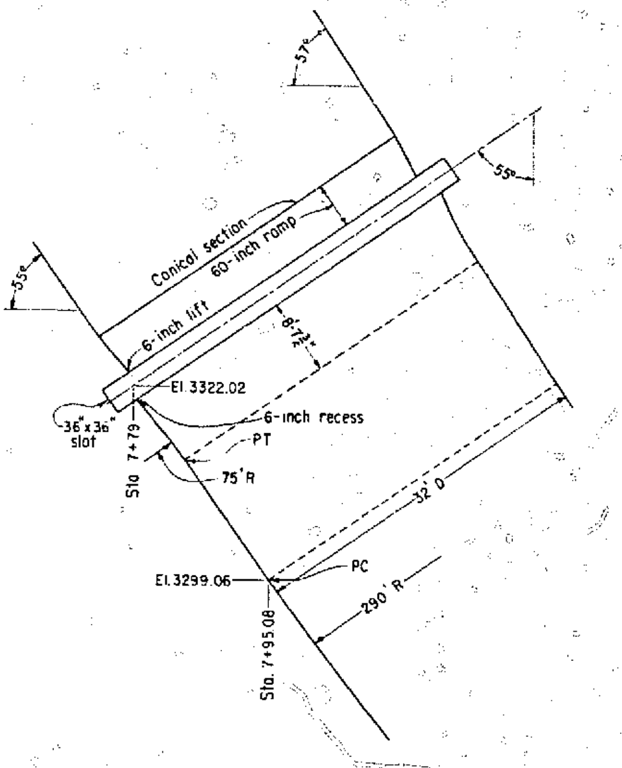


Figure 10. Conical nozzle, 6-inch lift, 60-inch ramp.

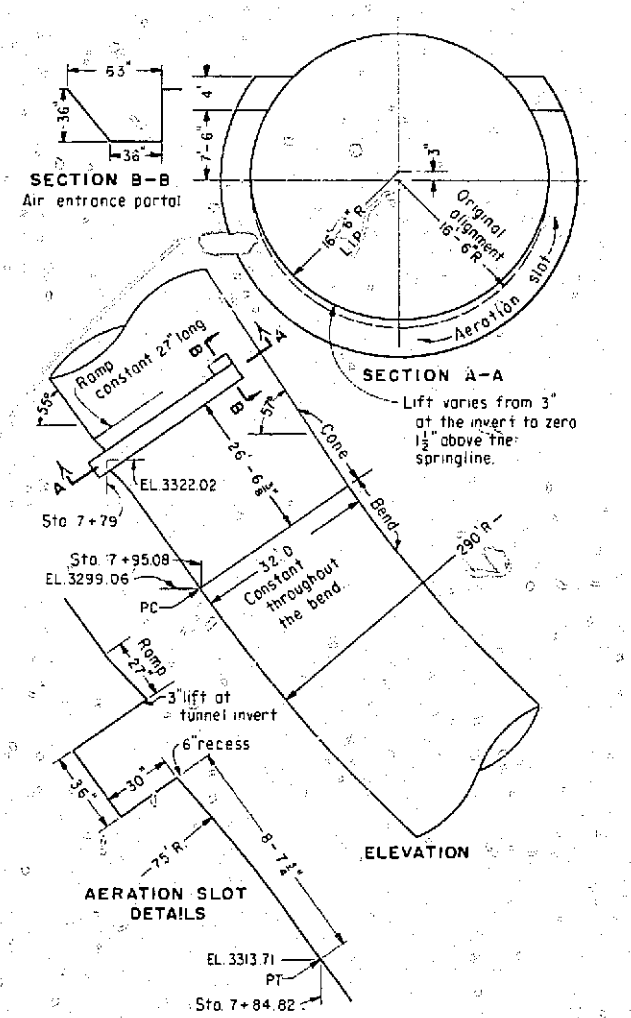


Figure 11. Recommended aeration slot.

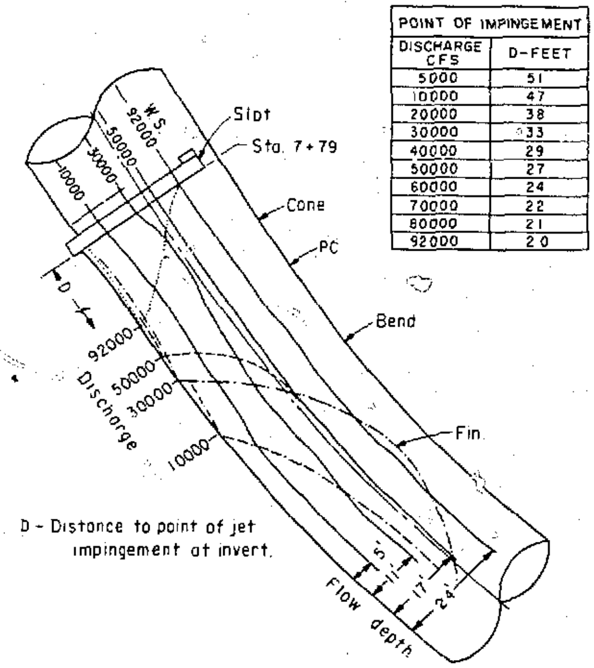
The impingement of the jet on the tunnel invert downstream from the aeration slot caused side fins to form. For discharges less than 50,000 cfs these side fins swept uninterrupted up the walls of the tunnel past the contracted jet. The maximum side fins, which occurred at a discharge of 30,000 cfs, were not objectionable and did not reach the top of the tunnel (Figure 13). Since the lift diminished as it neared the tunnel springline, 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 farther 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 (Figure 14).

The aeration slot remained free of water, and air was drawn into the jet for all discharges. The aeration slot as shown in Figure 11 was installed at Yellowtail Dam during repair and rehabilitation of the tunnel.

Air was visible in the model jet starting at the air slot and continuing well downstream from the P.T. of the bend (Figure 15). 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 unknown. As a further precaution against cavitation damage, it appeared that air should be reintroduced into the jet at some station upstream from the P.T. of the bend.

Aeration Slot at Station 9+57.67

Model studies were continued to evaluate an aeration slot in the downstream portion of the vertical bend at Station 9+57.67 (Figure 16). The centrifugal force of the water in the bend made this location quite different hydraulically from the location in the conical



POINT OF IMPINGEMENT	
DISCHARGE CFS	D-FEET
5000	51
10000	47
20000	38
30000	33
40000	29
50000	27
60000	24
70000	22
80000	21
92000	20

Figure 12. Trace of side fins and jet impingement point. Recommended aeration slot.

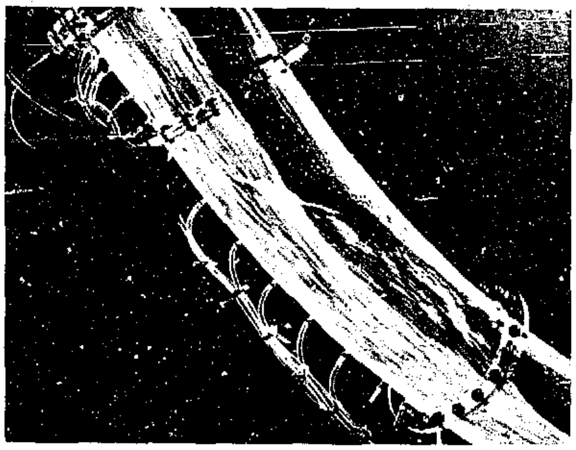


Figure 13. Recommended aeration slot, Station 7+79. Discharge is 30,000 cfs. These maximum side fins, one each side of the jet, do not reach the crown of the tunnel. Photo P459-D-68809

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 discharges

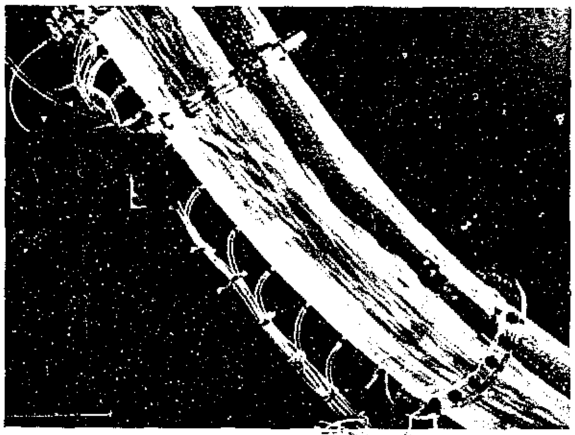


Figure 14. Recommended aeration slot, Station 7+79. Discharge is 50,000 cfs. The upper portion of the jet has spread to the tunnel walls and suppressed the side fins. Photo P459-D-68810

greater than 15,000 cfs water filled the slot and no air was 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. Figure 17 shows the fin produced by one configuration with a discharge of 60,000 cfs. This fin choked the tunnel downstream.

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. However, an aeration device could undoubtedly be developed for installation in a bend during initial construction of a spillway tunnel.

Prototype Tests and Instrumentation

The adequacy of the aeration slot in providing protection to the flow surfaces in the tunnel could be determined only by prototype spillway operation after completion of tunnel repairs and modification.

Consequently, prototype tests of preassigned discharges and duration, with pre- and post-operation inspection, were made to determine the adequacy of the protection. Visual and audio surveillance was maintained during spillway operation of the flow into, through, and out of the stilling basin and audio surveillance maintained at the entrance to the spillway

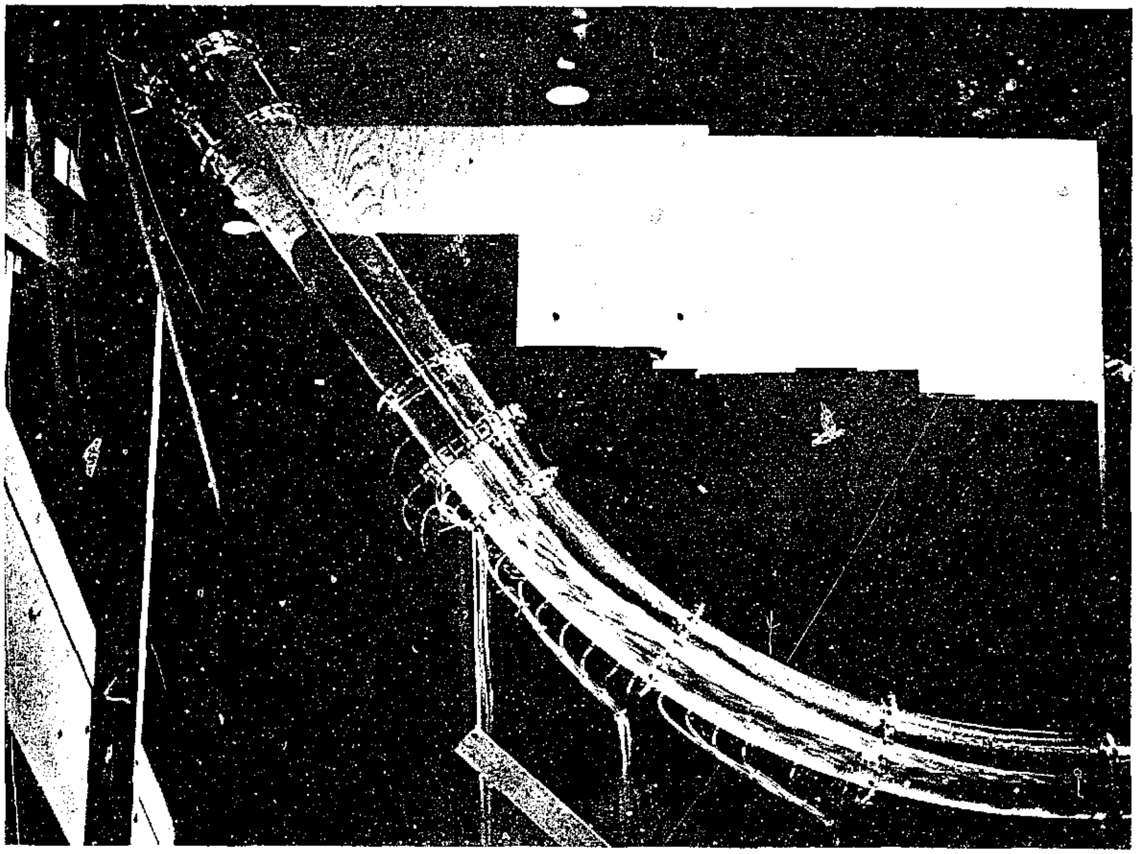


Figure 15. Overall view of the spillway model. Recommended aeration slot at Station 7+79. The slot at Station 6+64, upper left, has been closed. Air entrained at the aeration slot continues throughout the bend. Mixing tends to reduce the air near the flow surfaces in the downstream portion of the bend. Photo P459-O-68808

tunnel. Electronic surveillance was supplied by two hydrophones and one pressure transducer installed in the aeration slot prior to the start of the first spillway test (Figure 18). The hydrophones were embedded in the concrete in the downstream face of the slot to indicate any change in vibration and the pressure transducer was installed in the slot to monitor the slot pressure during the extended tunnel operation.

The prototype study included three tests: 5 days' spillway operation at 5,000 cfs, 1 day at 15,000 cfs, and 4 days at 14,500 cfs. Examination after each test revealed small areas of surface repair failure, but no indication of cavitation damage. The higher discharges were made with known surface irregularities in the downstream portion of the bend. These irregularities were similar in size, shape, and location to irregularities which caused extensive cavitation damage during the spillway releases in 1967. The prototype testing confirmed the results of the model study relative to the location and configuration of the aeration slot. The final examination indicated that a sufficient volume of air was being supplied to the flow to protect the flow surfaces from cavitation damage.

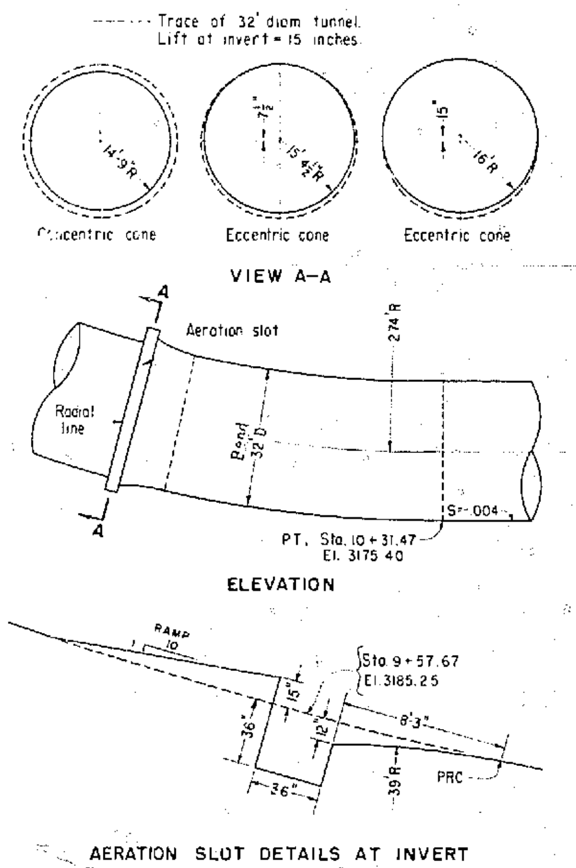


Figure 16. Aeration slot in the bend, Station 9+57.67 (not recommended).

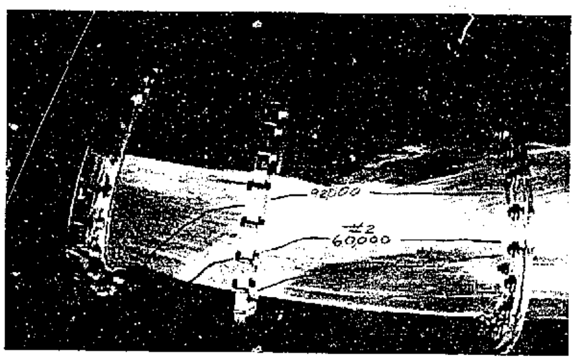


Figure 17. Aeration slot in the bend at Station 9+57.67. Discharge is 60,000 cfs. The side fins choke the tunnel downstream. Photo P459-D-68811

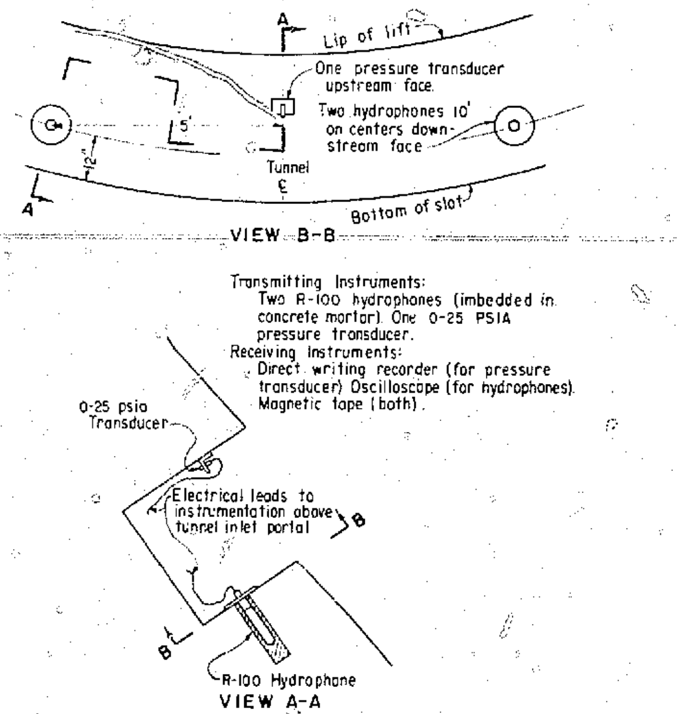


Figure 18. Prototype instrumentation.

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 839-644

ABSTRACT

Prototype operation of the Yellowtail Dam tunnel spillway in 1967 resulted in severe damage to the tunnel. The damage was caused by cavitation initiated by surface irregularities in the tunnel lining. The major damage was concentrated in the vertical bend and in the tunnel just downstream from the bend. An aeration slot to introduce air into the flowing water was to be constructed concurrently with tunnel repairs. A laboratory model of the tunnel was used to study various locations and configurations of aeration slots. As a result of the model study, one aeration slot was designed that was suitable for all spillway discharges. The optimum location for the slot was determined to be just upstream from the vertical bend.

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REC-ERC-71-47
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HYDRAULIC MODEL STUDIES OF AERATION DEVICES FOR YELLOWTAIL DAM SPILLWAY TUNNEL, PICK-SLOAN MISSOURI BASIN PROGRAM, MONTANA
Bur Reclam Rep REC-ERC-71-47, Div Gen Res, Dec 1971. Bureau of Reclamation, Denver, 11 p, 18 fig

DESCRIPTORS--/ *cavitation/ *hydraulic models/ *air entrainment/ test results/ tunnel failure/ tunnel linings/ finishes/ Montana/ aeration/ model tests/ *spillways/ *tunnels/ cavitation control/ prototype tests/ *damages
IDENTIFIERS--/ Yellowtail Dam, Mont/Pick-Sloan Missouri Basin Program

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