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Performance of Glen Canyon Dam Diversion Tunnel Outlets

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PERFORMANCE OF GLEN CANYON DAM
DIVERSION TUNNEL OUTLETS
By
William E. Wagner,[1/] F. ASCE

SYNOPSIS

The operational history and performance of the tunnel outlets at discharges to 29,800 cubic feet per second and heads of 360 feet are discussed. Extensive abrasive damage to the concrete tunnel lining was experienced early in the operation. After the abrasive material was flushed from the tunnel, no significant additional damage to the roughened concrete lining was noted. Progressive cavitation damage was experienced downstream from the gate slots and at surface irregularities in the conduit steel liners. Probable causes of the damage and precautions to be considered in designing future structures are presented.

INTRODUCTION

This paper discusses the performance of the left diversion tunnel outlets, Glen Canyon Dam, during the period from March 1963 to July 1965 when the outlets were permanently closed to complete the spillway tunnel. In this period, about 5.7 million acre-feet of water was released through the outlets at flow rates up to 29,600 cubic feet per second and heads to 360 feet.

Glen Canyon Dam is the largest and most important feature of the Colorado River Storage Project and is located on the Colorado River

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in Arizona, 13 miles south of the Utah border, Figure 1. It is a concrete-arch dam, rising 710 feet above the bedrock foundation, Figure 2. The reservoir, Lake Powell, has a total capacity of 27 million acre-feet, and when filled, will extend about 186 miles up the Colorado River and 71 miles up the San Juan River. The stored water will be used for river regulation, development of power at the dam's 8-unit, 900,000-kw powerplant, recreation, and fish propagation. About 6 million acre-feet of the total reservoir capacity will be inactive storage to provide power head at the dam. This space will be available for sediment accumulation.

Identical spillways in each rock abutment of the dam, will discharge into an inclined tunnel connecting with each diversion tunnel downstream from the plug, Figure 3. The total spillway capacity of 276,000 cubic feet per second (cfs) is controlled by two 40- by 52.5-foot radial gates in each spillway. Four river outlets located near the left abutment, have a total capacity of 15,000 cfs and discharge freely into the downstream river channel through four 96-inch hollow jet valves.

During the construction period, the river flow was diverted around the damsite through a 41-foot-diameter tunnel in each abutment. After construction of the dam had advanced sufficiently, the portions of the diversion tunnels upstream from the spillway tunnel junctions were closed by permanent plugs.

Plans for filling Lake Powell required early storage of water before completion of the dam and powerplant. As the intakes to the river outlets are located at elevation 3374, or 245 feet above the river bed, and the penstock intakes are located at elevation 3470, a temporary outlet works (Figure 4) was built into the left diversion tunnel plug to provide the necessary river control during the early filling period required for the reservoir to reach the minimum power operating level of elevation 3490. After the reservoir reached this service level and the river outlets and turbines could be operated, the tunnel outlet gates were permanently closed and the conduits were filled with concrete. The remaining section of the tunnel plug was concreted to complete the plug and make the final connection to the sloping portion of the left spillway tunnel.

The left diversion tunnel outlet works was provided with three 7-foot wide by 10.5-foot high conduits having rectangular bellmouth inlets in the upstream face of the tunnel plug. Each conduit was equipped with 7- by 10.5-foot tandem slide gates that discharged into a 7-foot wide by 14.5-foot high conduit and into the downstream diversion tunnel, Figure 4. The upstream gate was provided for emergency or guard use and the identical downstream gate was used for regulation. The conduits upstream from the gates were lined on all four sides, but only the bottom and sides of the downstream conduits were lined. The conduit linings were 3/4-inch steel. Air to each regulating gate was supplied through the space above the free water surface in the downstream conduits.

This air supply was augmented by 24-inch vent pipes from a 7- by 5-foot adit between the gate chamber and the diversion tunnel. Aeration in the 41-foot downstream tunnel was provided through an opening to the partially completed sloping spillway tunnel and from the downstream end of the tunnel.

The 41-foot-diameter diversion tunnel was lined with 1.25-foot-thick unreinforced concrete from the intake to the P.T. of the vertical spillway bend at Station 26+11.72. From this station to the downstream portal, the tunnel lining was reinforced concrete with a minimum thickness of 2.75 feet.

PERFORMANCE OF TUNNEL OUTLETS

Operation--March 1963 to February 1965

On March 13, 1963, the right diversion tunnel was permanently closed and releases through the left diversion tunnel outlets were started. Figure 5 charts the outlet discharges, number of gates operating, and the corresponding reservoir elevation for the period from March 13, 1963, to February 23, 1965, when the downstream tunnel was unwatered and inspected. In this period, nearly 2.9 million acre-feet of water were released at discharges up to 19,600 cfs and heads ranging from 43 feet to 336 feet. About 20 percent of these releases were made at heads less than 240 feet; 60 percent were made at heads ranging between 240 to 260 feet; and the remaining 20 percent of the releases were at heads from 260 to 336 feet. Gate openings at which the outlets operated can be determined from the head-discharge curves shown in Figure 6. In September 1964, the reservoir reached the minimum level for power operation and, except for two short periods in December 1964 and February 1965, the outlets were closed and the inflow to the reservoir was passed through the power generating units.

Tunnel Inspection--February 1965

Previous inspections of both diversion tunnels had indicated that the tunnel inverts were eroded by sediment in the diversion flows before the outlets were installed. This damage consisted of exposed aggregate at the invert centerline. The damage feathered to the original surface finish at about 5 feet on each side of the centerline. Since specifications to complete the left spillway tunnel were about to be prepared, the left tunnel downstream from the plug was unwatered and inspected on February 23, 1965, to determine the condition of the tunnel and what repairs, if any, should be covered in the contract.

Concrete Lining from Plug to Flip Bucket.--The inspection revealed considerably more erosion damage had occurred to the lining since the diversion tunnel outlets were placed in operation in 1963. The surfaces of the unfilled plug keyway immediately downstream from the tunnel plug were eroded sufficiently to expose the aggregate (Figure 7A). This damage extended nearly to the springline of the tunnel and up the downstream face of the plug. Loose aggregate and foreign material were deposited in this location to a depth of about 5 feet. For a distance of about 200 feet downstream from the unfilled keyway, aggregate was exposed for approximately 10 feet either side of the invert centerline (Figure 7B). The texture of the eroded surface was generally smooth.

The most severely damaged area was located between Stations 26+40 and 27+20 (Figures 8 and 9). In this area, the invert was eroded to a maximum depth of 0.8 foot and many reinforcement bars were exposed or missing. Laterally, the damage decreased almost uniformly to the original lining surface at a maximum height of 5 to 10 feet above the tunnel springline. Exposed reinforcing bars and stubs of missing bars were worn smooth indicating that an abrasive material had caused the damage. No deposits of foreign materials were found in the tunnel downstream from the unfilled plug keyway.

Downstream from this severely damaged area to the point of curvature of the flip bucket, the lining surface was generally smooth and only minor erosion on the invert for a width of about 10 feet was noted. This damage probably occurred during diversion before the outlet works was installed. This premise is supported by the absence of damage to surfaces of the flip bucket which was constructed at the time the diversion tunnel plug outlets were installed.

Regulating Gates and Downstream Conduit Steel Liners.--At the time of installation, all exposed steel surfaces in the gates and liners were painted with a heavy-bodied, cold-applied coal tar to prevent corrosion. Generally, the surfaces of the gates and liners were in good condition except at points of surface irregularities. Figure 10A shows the bottom of the service gate and the narrow gate slot about 5 feet above the invert. Removal of the paint by cavitation action was evident immediately downstream from the slot edge. Similar, but more severe, damage was observed at the base of the slot (Figure 10B). Here the steel was pitted to a maximum depth of 3/8-inch about 6 inches from the edge of the slot. The two bands of spotted liner are rust spots where the paint was removed from the vicinity of rows of piezometers located 3/4 inch and 23-3/4 inches above the inverts, prior to operating the outlets.

Two significant areas of cavitation damage to the sidewall steel liners were noted. Figure 10C shows cavitation damage to the sidewall liner about 20 feet downstream from the service gate. This damage consisted of paint removal for a length of 1 foot in the direction of flow and a height of 6 feet above the floor and was triggered by a depression that extended the full height of the liner and which gradually increased in depth to 1/8 inch and faired back to the true longitudinal alinement in about 8 inches. The other damaged area was located about 50 feet downstream from one gate where a misalinement of the side liners resulted in a 1/8-inch offset into the flow. Downstream from this joint, an area about 8 inches long and 12 inches above the invert was damaged to a maximum depth of 1/4 inch.

Operation--March 1965 to July 7, 1965

The filling criteria for the Colorado River Storage Project reservoirs required filling Lake Powell to its minimum level for power operation, after which all inflow had to be passed to the river below Glen Canyon Dam until Lake Mead behind Hoover Dam was raised to its rated power operating head. Since Lake Powell was at its minimum power operating head, there was considerable concern whether the damaged concrete lining would withstand prolonged, near-maximum discharges through the diversion tunnel outlets. The combined capacity of the diversion tunnel outlets, the river outlets, and power generating units was needed to pass the expected above-average spring runoff to Lake Mead. Extensive damage would have destroyed the tunnel lining, exposed the highly vulnerable sandstone, and conceivably could have endangered the left dam abutment and powerplant.

Because there was insufficient time to repair the tunnel lining before the spring runoff, the decision was made to make successive 48-hour test releases of 12,500, 19,800, and 29,600 cfs through the tunnel outlets, Figure 11. Following each test, soundings from a boat and underwater inspections by divers were made to determine the condition of the tunnel lining. Although a few additional exposed reinforcement bars were missing, no significant further damage to the lining during the tests was noted.

As these inspections showed no additional damage, the tunnel inspection periods were increased to 1-week intervals and later to 2-week intervals during the large releases from mid-April to June 23, 1965, when the need for operating the tunnel outlets was no longer required. None of these underwater inspections disclosed any further critical damage to the tunnel lining.

A total of 2.8 million acre-feet of water was released through the tunnel outlets during this period. Most of the releases were made at discharges of 29,600 cfs under a head of 336 feet.

When use of the tunnel outlets for mandatory releases was completed in late June, a test release of 3,600 cfs for 1 week was made to learn whether the dynamic forces of a hydraulic jump in the tunnel would cause extensive damage to the lining. The results of this test are discussed on page 20.

Tunnel Inspection--July 1965

The tunnel was unwatered and a detailed inspection of the gates, steel liner, and tunnel was made on July 15, 1965. In general, the condition of the damaged concrete lining was remarkably similar to that observed on February 23, 1965, when the tunnel was previously unwatered. The service gates and steel liner, however, showed additional progressive-type cavitation damage in the gate bodies, gate leaves, and at surface irregularities in the steel liner.

Concrete Lining from Plug to Flip Bucket.--Figure 12 shows the condition of the concrete lining in the most severely eroded section near Station 26+70. Although additional reinforcement bars (which were exposed prior to the February inspection) had been torn loose, a surprisingly small amount of aggregate was eroded during the March-July operation.

Comparative field surveys of the tunnel in February and July (Figure 13) showed no appreciable additional damage at the invert centerline. The additional damage indicated on the left side of the eroded area probably resulted from spalling where the exposed reinforcement bars were torn out by the high-velocity flow.

A comparison of the tunnel lining at Station 26+51 in February and July is shown in Figure 14. Except for the loss of the two longitudinal bars (near the bottom of the July picture), the condition of the concrete is similar. Many individual pieces of aggregate and reinforcement bars (A and B) can be identified in both photographs. Longitudinal stripes (C and D) were painted on the sides of the conduit in February as an aid in determining possible progressive damage in later inspections. The fact that remains of these stripes were clearly visible in July indicates the minor concrete erosion that occurred during the period.

The remainder of the tunnel lining, including the area where the outlet jets from the tunnel plug impinged, showed no evidence of additional erosion.

Regulating Gates and Conduit Steel Liner.--Progressive-type cavitation damage was noted on the flow surfaces of the gate bodies, particularly downstream from the gate slots and in the vicinity of the gate recesses, and at surface irregularities in the conduit lining. Cavitation damage was evident in all three conduits in varying degrees depending on the location, size and shape of the surface irregularities, and the length of operation. Damage to the surfaces varied from paint removal in most instances to pitting of the metal downstream of the gate slots and at other critical surface irregularities.

The most severe damage was found in the top of the left fluidway between the guard and service gates (Figure 15), where cavitation produced pitting over a large part of the upstream body of the service gate and eroded a hole through the 1-inch steel plate. The maximum dimensions of the hole were about 3 feet transversely and 8 inches longitudinally in the direction of flow. The embedding concrete behind the steel plate was eroded to a depth of about 8 inches. This extensive cavitation damage was triggered by a 1/8-inch offset protruding into the flow superimposed on the 65:1 slope between the guard gate recess and the body joint. The offset had been slightly rounded by grinding at the time of installation but was sufficiently pronounced to produce damaging cavitation. Paint was entirely removed from the top and about halfway down both sides of the fluidway between the two gates. A similar cavitation damage pattern was observed in the center and right conduit, but the damage covered about 50 to 60 percent less area and was limited to paint removal. The paint on the sides of the right fluidway was undamaged.

The condition of the left service gate and slot is shown in Figure 16. The damage consisted mostly of paint removal, but mild pitting was noted immediately downstream from the gate slot. An unexpected area of damage was found on the sloping bottom of the gate leaf. The lower 5 inches of the sloping face and the sealing surfaces are stainless steel inlay and showed no damage. Immediately above the stainless steel inlay, the cast steel was pitted about 1/16-inch in depth. The damage feathered to the original painted surface in 6 to 15 inches. To a lesser extent, similar damage was found on the other two service gates.

Figure 17 shows the condition of the center service gate just downstream from the seating surface in the slot. There was no apparent damage to the 1/8-inch-thick Monel cladding on the gate seat. Immediately downstream from the cladding, the steel was pitted about 3/8-inch deep. At the joint between the seat and the cast steel gate body, there was a 3/8-inch-wide crack which tapered inward about 1-1/2 inches from the original fluidway surface. The pitted area extended about 12 inches above the conduit floor and about 10 inches downstream from the slot. Both sides of the center gate showed similar damage; however, less severe damage in a similar pattern was noted downstream from the slots in the other two gates, where the damage was limited to paint removal and slight pitting.

Numerous other areas of minor cavitation damage were noted in the conduit liner downstream from the gate. Cavitation in these isolated areas, which were found throughout the 68-foot length of liners, was caused by poor alinement of the liner joints, projecting joint welds, and minor ridges and depressions in the paint coating. While the larger offsets of 1/8- to 1/4-inch resulted in some pitting of the metal, most of the damage to the liners was limited to paint removal. It was noted that offsets protruding as little as 1/32 inch into the flow produced marked damage and the degree of damage increased with larger offsets. Depressed offsets in the surface appeared to cause no damage until they were about 1/8 inch in depth, while 1/4-inch depressed offsets produced paint removal and minor pitting. Typical cavitation-damaged surfaces with a sketch of the irregularity producing the cavitation are shown in Figures 18 and 19.

The damaged area downstream from the 1/8-inch offset noted in the February inspection and described on page 7 showed very little change; the maximum depth of pitting remained at 1/4 inch and paint was removed for 2 inches farther downstream (Figure 19).

DISCUSSION OF OPERATION AND DAMAGE

The operation of the diversion tunnel outlets provided an unusual opportunity to evaluate the performance of the high head gates and steel liners in the tunnel plug outlet conduits, and the resistance of the concrete surfaces of the tunnel lining when subjected to maximum flow velocities of about 135 feet per second. Although sufficient damage was experienced in the structure to require repairs in a permanent installation, the performance verified the soundness of the basic design of the outlets. The performance also demonstrated that further improvements can be made and certain precautions must be exercised in the design and operation of high head outlet works.

Regulating Gates and Conduit Liner

The major damage to the gates and conduit liner can be attributed to irregularities or misalinement of the fluidway surfaces. These irregularities included offsets at joints, improperly ground field welds, and ridges or depressions in the paint coating. Although irregularities protruding into the flow were more critical than depressed offsets, both types of irregularities must be controlled by rigid manufacturing and installation tolerances when surfaces are subjected to high-velocity flows.

Laboratory studies have been conducted by the Bureau of Reclamation to establish the velocity-pressure relationship for incipient cavitation at offsets with rounded corners and sloped surfaces that protrude into the flow[1/]. These relationships (Figure 20) may be used as guidelines for establishing tolerances for surface irregularities in fluidways and for specifying maximum slopes that may be permitted in removing irregularities by grinding. The experience at Glen Canyon Dam supports the validity of these curves for predicting the type of irregularity that may cause cavitation damage. For example, the 1/8-inch offset superimposed on the 65:1 slope in the left outlet (Figure 15) caused extensive damage to the gate body while no significant damage was experienced at the break in the 65:1 slope in the other two conduits. The average flow velocity through the tunnel outlets was about 135 feet per second for most of the March-July releases. Although the curves appear to be valid for carbon steel, more stringent tolerançes may be required for less cavitation damage resistant materials, such as concrete.

The slide gate design used in the tunnel outlets was developed in the early 1950's for use in the Palisades Dam outlet works. While this type of gate has operated successfully at several previous installations, the operation at Glen Canyon Dam was the first use at heads above 235 feet. The fact that the gates controlled the release of over 2 million acre-feet of water at heads of 350 feet without major damage

1/ "Construction Finishes and High-velocity Flow," by James W. Ball, _Journal of the Construction Division_, ASCE, Vol 89, No. CO2, Proc. Paper 3646, September 1963 is considered to be remarkably good performance. However, the damage to the bottom of the gate leaves and the damage downstream from the gate slots, although not critical, indicates further study of the gate-slot geometry is desirable. The fact that none of the stainless steel in the gates had any apparent damage indicates that materials more resistant to cavitation damage should be used in critical flow regions. The damage to the sloping bottom of the gate leaves, which occurred when the gates were fully open, can be prevented by extending the stainless steel inlay farther upstream. It is also significant that the Monel cladding on the gate seating surface (Figure 17) was undamaged; the use of Monel metal or stainless steel downstream from this critical flow region may be justified in future installations. Stainless steel surfaces in these critical regions have been used on all Bureau high head slide gate designs since the gate performance observations were made at Glen Canyon Dam.

The experience at Glen Canyon Dam also showed that protective paints must be carefully applied to avoid surface roughnesses that may trigger cavitation. Relatively small ridges and peaks in the paint surface were the focal points for the chain type of damage shown in Figures 10C and 18. Although the damage consisted of paint removal in most cases, costly repairs and maintenance can be avoided by careful selection and application of protective coatings. In critical flow regions, more extensive use of stainless steel with its greater cavitation damage and corrosion resistance would certainly be desirable and might prove to be more economical over the years than maintaining paint on carbon steel which has a lower initial cost.

Concrete Lining from Plug to Flip Bucket

When the extensive damage to the concrete tunnel lining was discovered in the February 1965 inspection of the diversion tunnel, the exact cause of the damage was not known and there was considerable concern whether the damaged lining would withstand large, high-velocity releases that would be required during the spring runoff. Previous experience at Hoover Dam[2/] and other structures has shown that surface irregularities much smaller than the damaged surfaces at Glen Canyon Dam would trigger cavitation, quickly erode, and cause failure of the concrete lining. Whether the exposed aggregate in the jet-impact area of the tunnel would withstand the dynamic forces of the jets impinging on the roughened lining was also questionable.

The general texture of the eroded surface and the exposed reinforcement bars indicated that the lining was damaged by abrasion rather than direct impact of the flow or erosion produced by cavitation. The exposed aggregate and the concrete matrix had a generally smooth

2/"Cavitation in Hydraulic Structures," by Jacob E. Warnock, Transactions, ASCE, Vol 112, Paper 2295, 1947, page 55-58 worn appearance. No evidence of aggregate being plucked from the concrete or of ragged-edged pockets typical of cavitation damaged concrete surfaces was found. The surfaces of the exposed reinforcement bars also were worn smooth indicating a grinding action. These observations suggested that the initial damage was caused by foreign material, either left in the tunnel when the gates were installed or dropped through the tunnel riser from the sloping spillway tunnel. This material together with aggregate and steel from the eroded concrete probably tumbled and circulated in the hydraulic jump in the tunnel and acted like a ball mill to continually abrade the tunnel concrete.

An analysis of the flow conditions in the tunnel for typical releases during the March 1963-February 1965 operation was made. This study (Figure 21) showed that for flows less than 3,000 cfs and reservoir elevations up to 3,490, a pool of water existed in the tunnel from the plug to the flip bucket. As the releases increased above 3,000 cfs, a hydraulic jump formed in the tunnel and moved downstream until it swept out at a discharge of about 10,000 cfs and reservoir elevation, 3,490. These computed flow conditions were verified later by a field test which showed that sweepout occurred at 9,400 cfs and reservoir elevation, 3,492.

Assuming that foreign material was in the tunnel during the initial operation of the outlets, the damage in the unfilled keyway and tunnel downstream to about Station 25+00 probably occurred during the first 11 months of operation at 1,000 and 2,570 cfs (Figures 5 and 21). On February 1, 1964, the discharge was increased, and a constant discharge of 4,300 cfs was released until March 26, 1964. During this period, the reservoir elevation also remained constant at 3,415 and a hydraulic jump formed in the tunnel in the region of maximum damage. The "ball-mill" action of the foreign material in the hydraulic jump probably was the cause of the maximum damage to the tunnel lining between Stations 26+00 and 28+00. This conclusion is supported by the fact that damage was observed high on the sides of the tunnel (Figure 9). Also, laboratory model tests (Figure 22) showed that foreign material in a hydraulic jump would damage the surfaces of a circular tunnel in a manner similar to that experienced at Glen Canyon. No additional gravel was added during the 3-hour laboratory test, and the original gravel remained in the region of the hydraulic jump and was continuously circulated by the jump.

From March 28 to May 11, 1964, the releases ranged from 12,000 to 19,600 cfs and rapid flow existed throughout the tunnel length. During this period, all foreign material was swept from the tunnel, which explains why foreign material was found only in the unfilled keyway upstream of the jet impingement region of the tunnel.

Since it was apparent that the tunnel damage resulted from abrasion of debris circulating in a hydraulic jump in the tunnel, the March through June 1965 releases (Figure 11) were made at discharges exceeding 10,000 cfs to avoid operation with a jump in the tunnel and to sweep any abrasive materials from the tunnel.

After storage in Lake Powell was resumed on June 29, 1965, and the tunnel outlets were no longer needed to meet downstream requirements for water, a test for 1 week was conducted with a hydraulic jump in the damaged area of the tunnel. This test was made to learn whether the dynamic forces of a hydraulic jump would dislodge exposed aggregate in the damaged area. Following the test, the outlet gates were immediately closed so that any loose aggregate and reinforcement bars would remain in the tunnel. The condition of the damaged area of the tunnel is shown in Figure 12. Approximately 12-15 reinforcement bars, varying in length from a few inches to 4 or 5 feet, were lying loose on the tunnel invert, and an additional seven bars were loose on one end and embedded on the other end; however, very little loose aggregate was found in the tunnel. The jump forces apparently were sufficient to vibrate and break into small pieces some of the exposed reinforcement bars, but no significant damage to the concrete occurred. No doubt continued operation with loose reinforcement bars in the hydraulic jump would have produced significant concrete damage.

The lack of major additional damage to the concrete lining during the March-July releases is remarkable, considering that flows of 10,000 to 29,600 cfs at velocities of 135 feet per second impinged on and passed over rough concrete with exposed aggregate and abrupt irregularities in the surface. In passing from the tunnel plug to the concrete lining the jets traveled through air about 125 feet, and apparently sufficient air was entrained in the jets to reduce the destructive effects of cavitation as the flow passed over the irregular surfaces.

CONCLUSIONS

Although damage to the structure was experienced, the performance of the Glen Canyon Dam tunnel outlets at capacity discharges for nearly 3 months demonstrated that the basic design concept of this structure is sound. The extensive damage to the concrete lining of the tunnel is attributed to the abrasive action of foreign material circulating in a hydraulic jump that formed in the tunnel early in the operation and during relatively small releases. Precautionary measures are necessary to assure that all foreign material is removed and kept from entering a hydraulic jump stilling basin. Free jets will entrain air that will help to prevent cavitation damage from high-velocity water flowing over irregular surfaces.

The slide gates performed very well in this structure; however, further study and improvements in the gate-slot geometry should be made to reduce the cavitation potential at the gate slots. The use of stainless steel in critical flow regions appears to be desirable to resist the effects of cavitation. Smooth and properly alined surfaces in fluidways and particularly in regions downstream from gate passages are of critical importance. Offsets protruding into the flow as little as 1/32 inch can result in cavitation damage in high velocity flows.

ACKNOWLEDGMENTS

The information contained in this paper represents the cooperative efforts of many individuals in several organizational segments of the Bureau of Reclamation. The Dams Branch was responsible for the outlet works design and the Mechanical Branch designed the slide gates. Hydraulic model studies were conducted by the Hydraulics Branch. Individuals from each of these branches inspected the outlet works and participated in the analysis of the data.

Special thanks are due the Project Construction Engineer and his staff for their assistance and excellent cooperation in furnishing field data and extending the tests to obtain additional information from the outlet works operation.

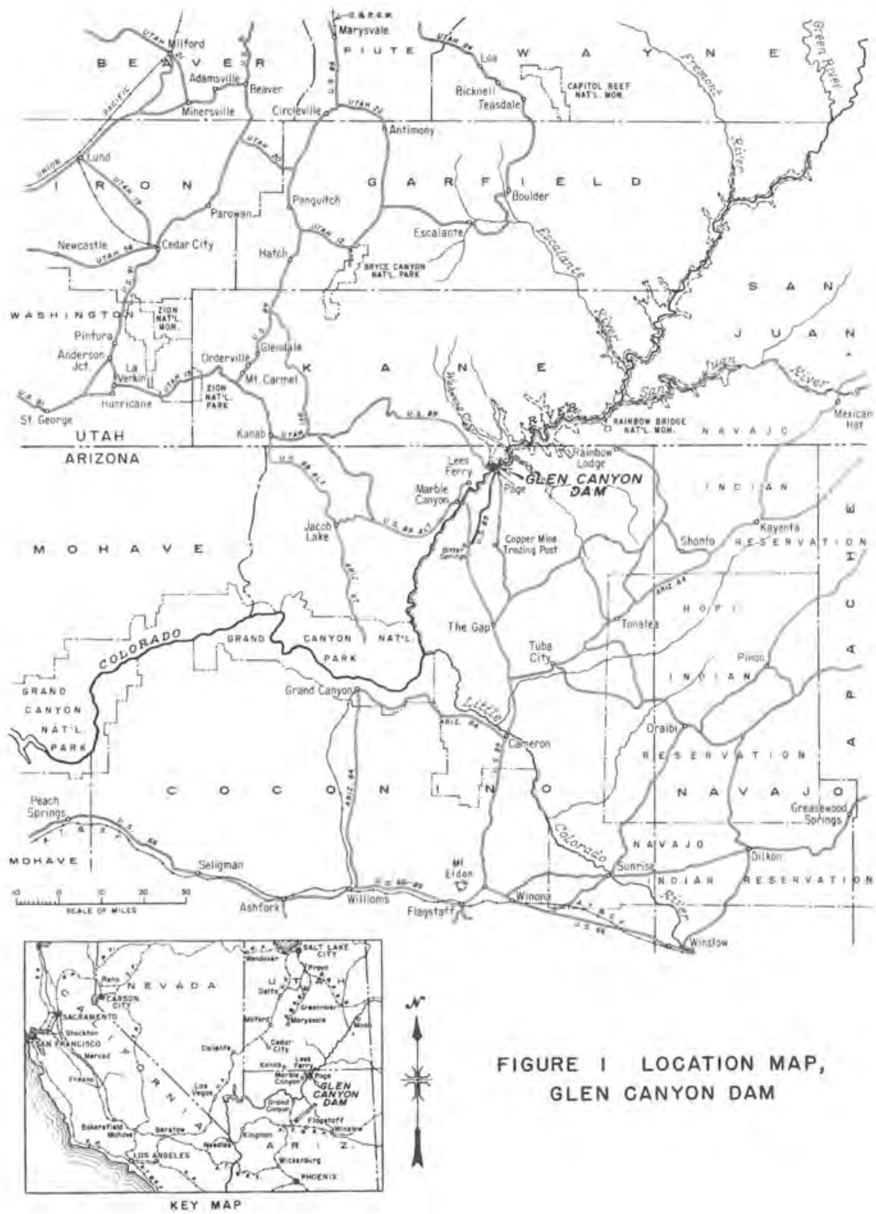


FIGURE 1 LOCATION MAP, GLEN CANYON DAM

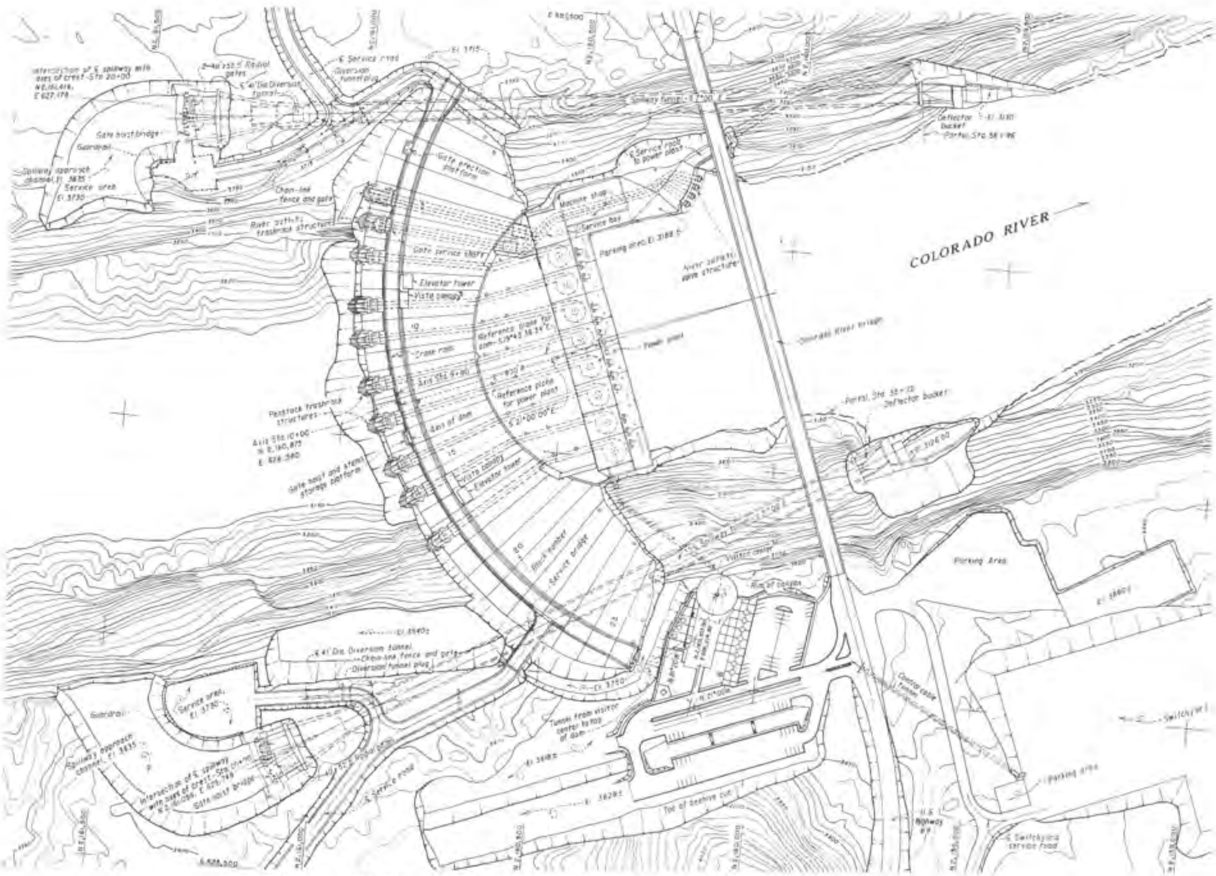


FIGURE 2 PLAN OF GLEN CANYON DAM AND POWER PLANT

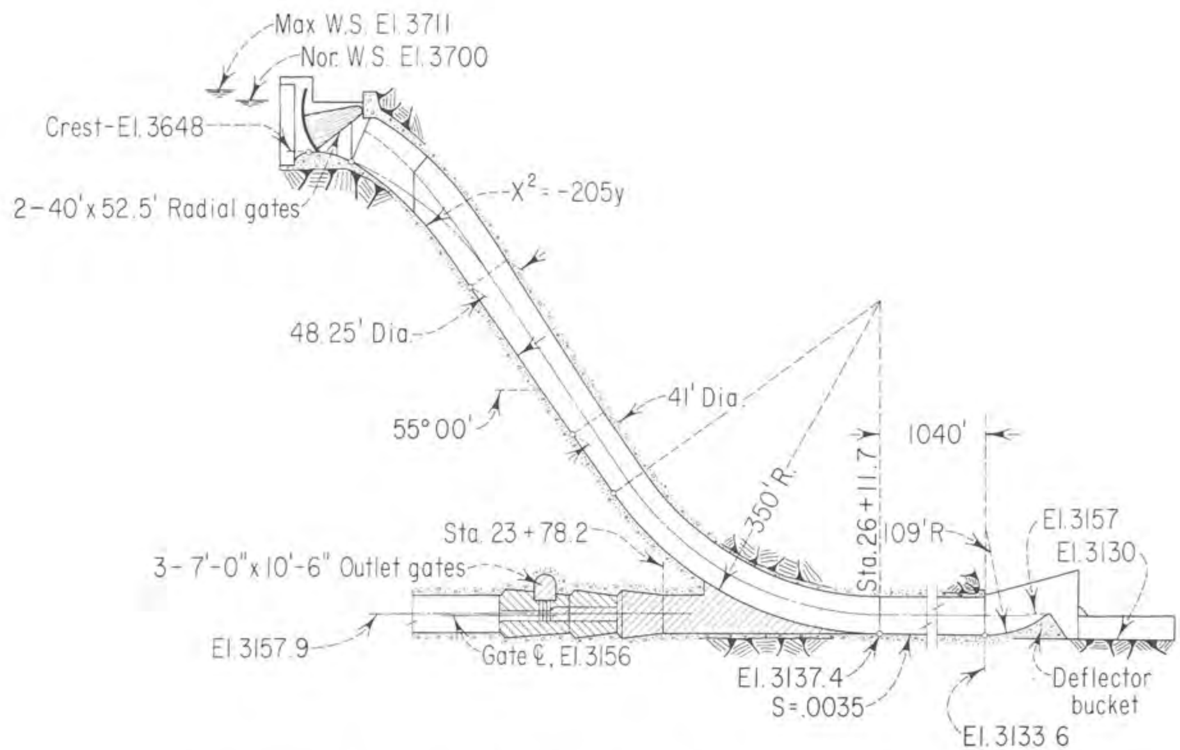


FIGURE 3 PROFILE OF LEFT SPILLWAY AND TUNNEL PLUG

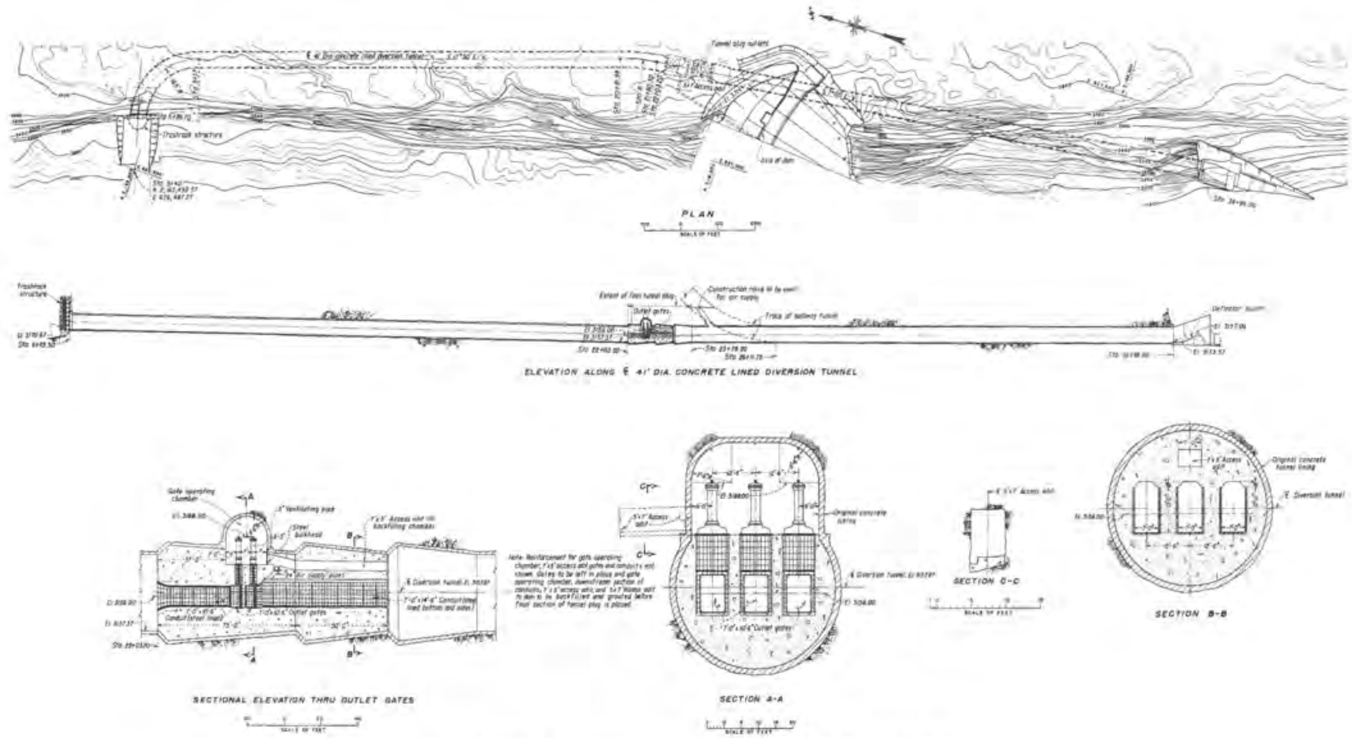
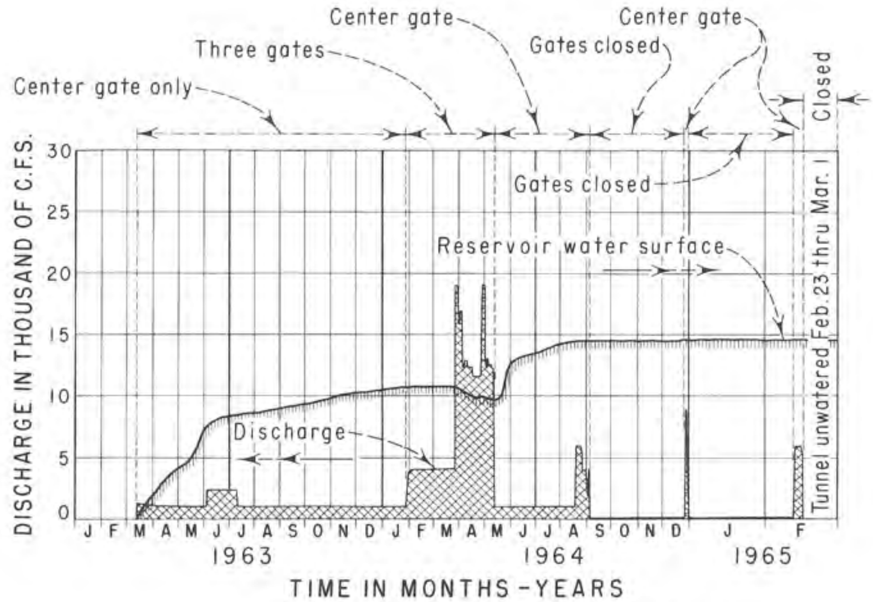


FIGURE 4 LEFT DIVERSION TUNNEL OUTLET WORKS



RELEASES IN ACRE FEET OF WATER

1963	703,460
1964	2,129,160
1965 (Jan. - Feb.)	48,000
TOTAL	2,880,620

FIGURE 5 RELEASES THROUGH TUNNEL OUTLETS
MARCH, 1963 - FEBRUARY, 1965

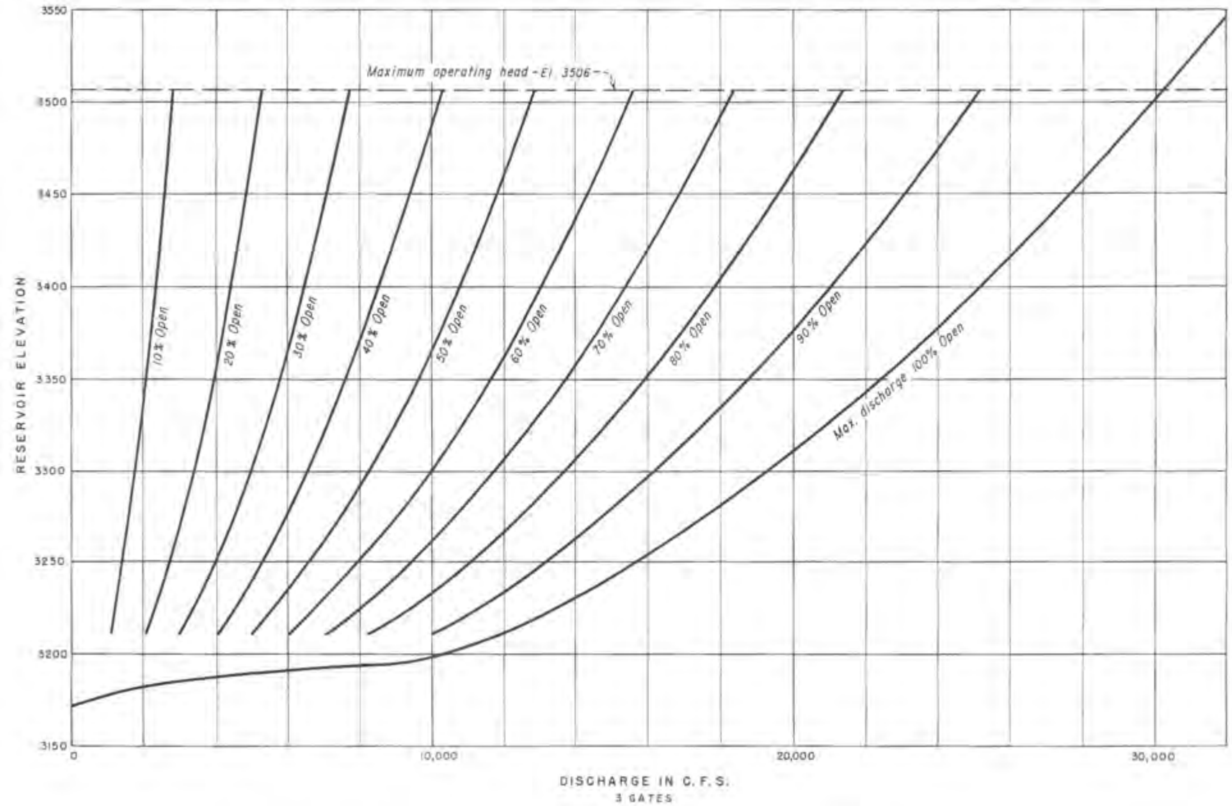


FIGURE 6 HEAD - DISCHARGE CURVES, LEFT DIVERSION TUNNEL OUTLET WORKS

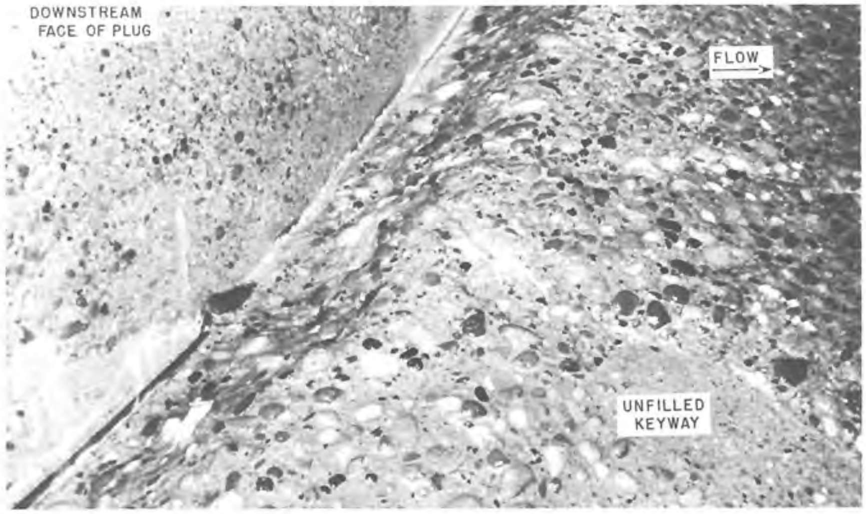


FIGURE 7A CONCRETE SURFACES IN UNFILLED KEYWAY

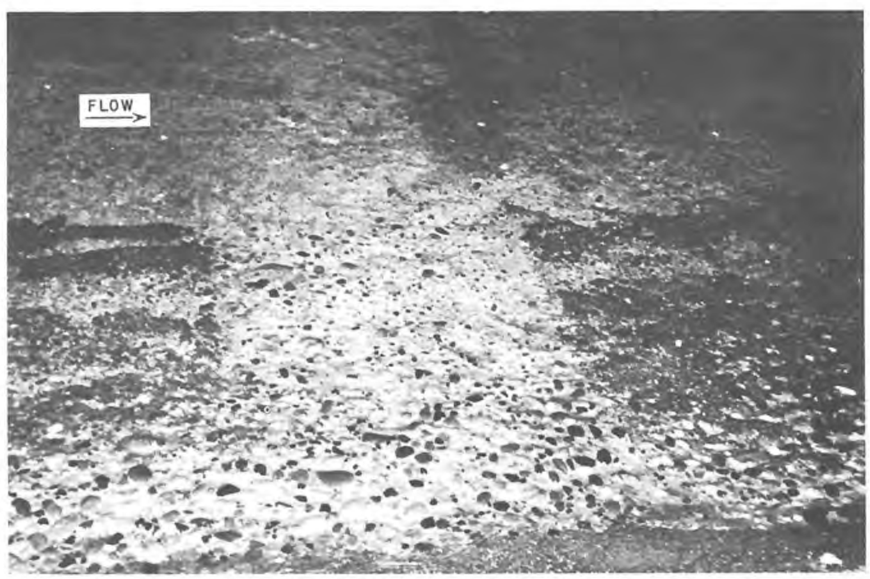


FIGURE 7B CONDITION OF CONCRETE IN JET IMPINGEMENT AREA
NEAR STATION 24 + 55

STA. 26+51

—FLOW—>

FIGURE 8 CONDITION OF LEFT DIVERSION TUNNEL - FEBRUARY 24, 1965

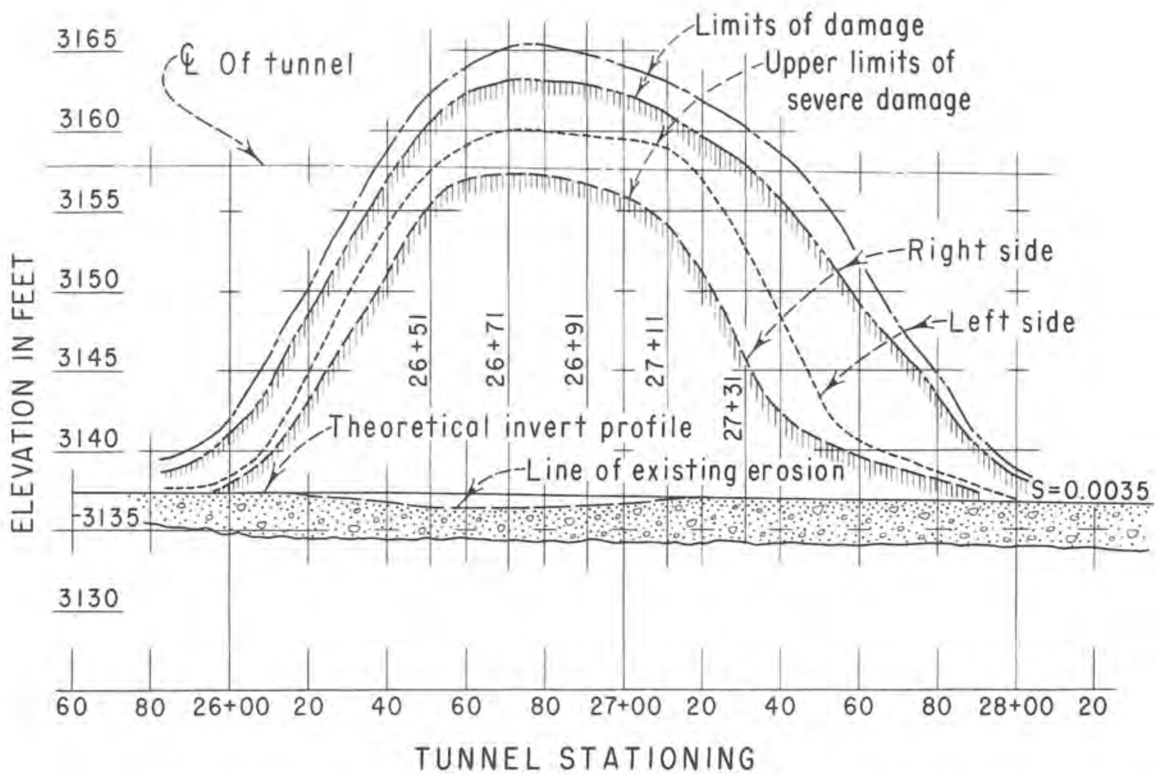


FIGURE 9 EXTENT OF SIDEWALL DAMAGE
LEFT DIVERSION TUNNEL

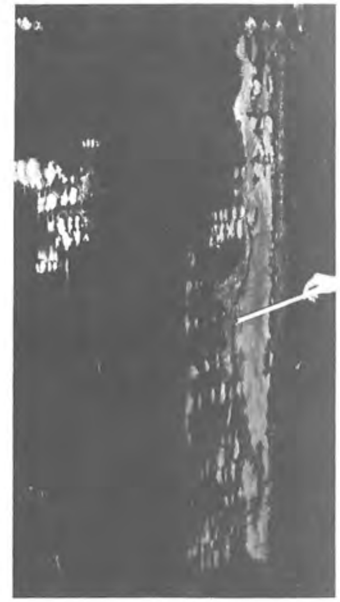
—FLOW→

A. BOTTOM OF GATE LEAF

←FLOW—

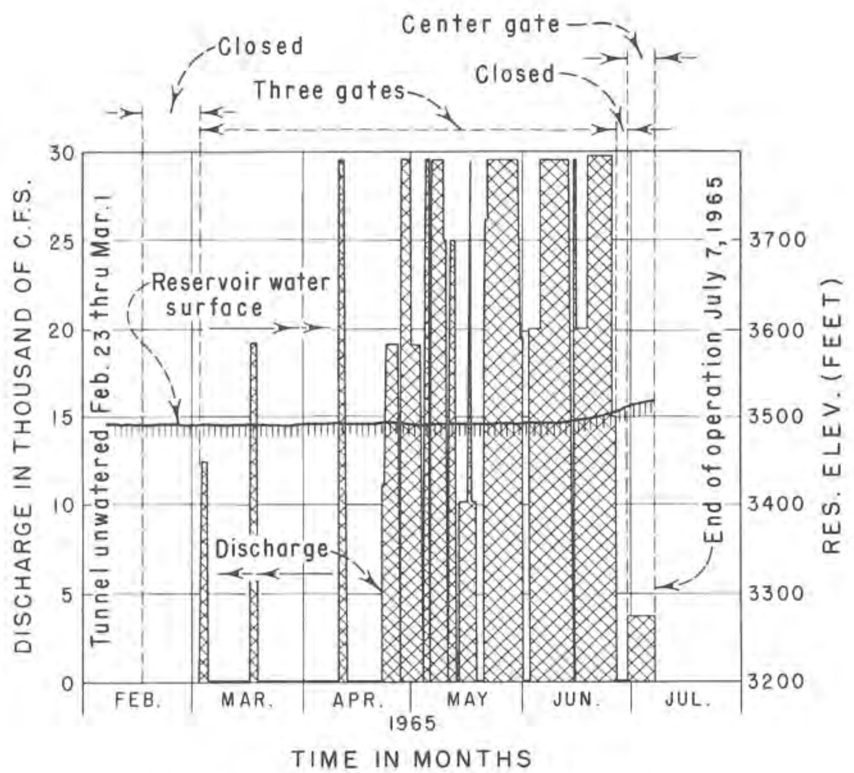
B. PITTED AREA DOWNSTREAM OF GATE SLOT

←FLOW—



C. PAINT REMOVED BY CAVITATION DOWNSTREAM FROM 1/8-INCH OFFSET

FIGURE 10 TYPICAL CAVITATION DAMAGE IN GATE BODY AND CONDUIT LINER



RELEASES IN ACRE FEET OF WATER
1965 (Mar. 2 thru July 7)______2,799,000

FIGURE 11 RELEASES THROUGH TUNNEL OUTLETS
MARCH 2, 1965 – JULY 8, 1965

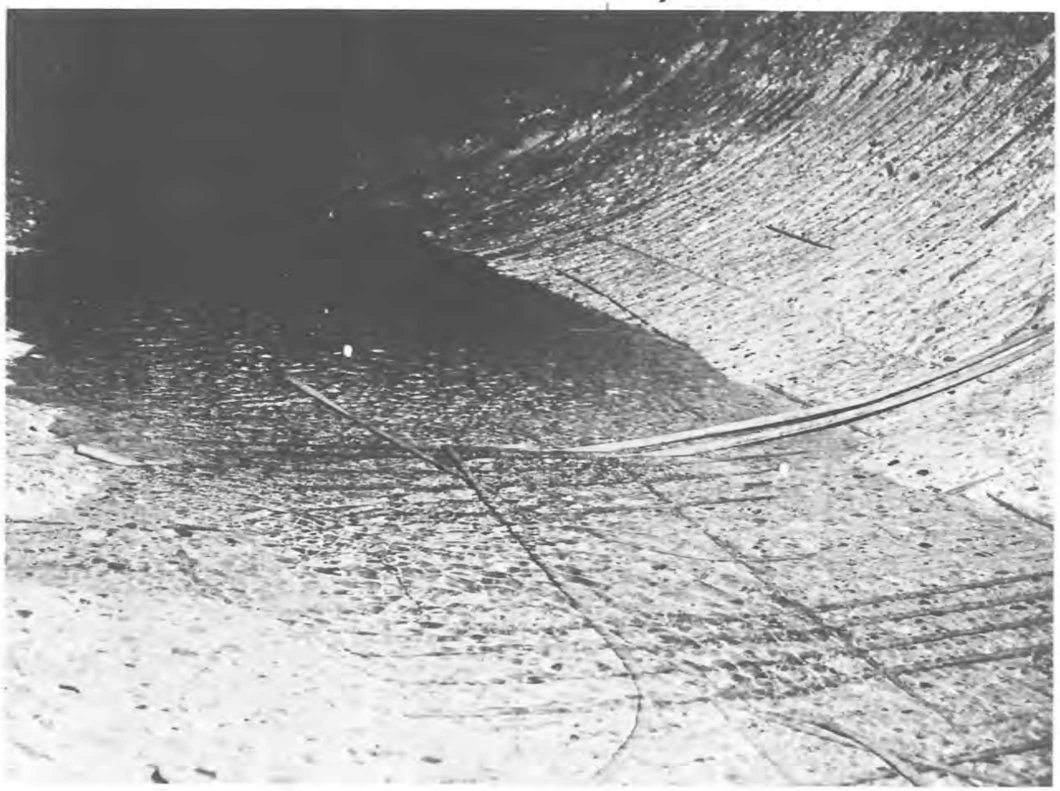


FIGURE 12 CONDITION OF LEFT DIVERSION TUNNEL - JULY 15, 1965

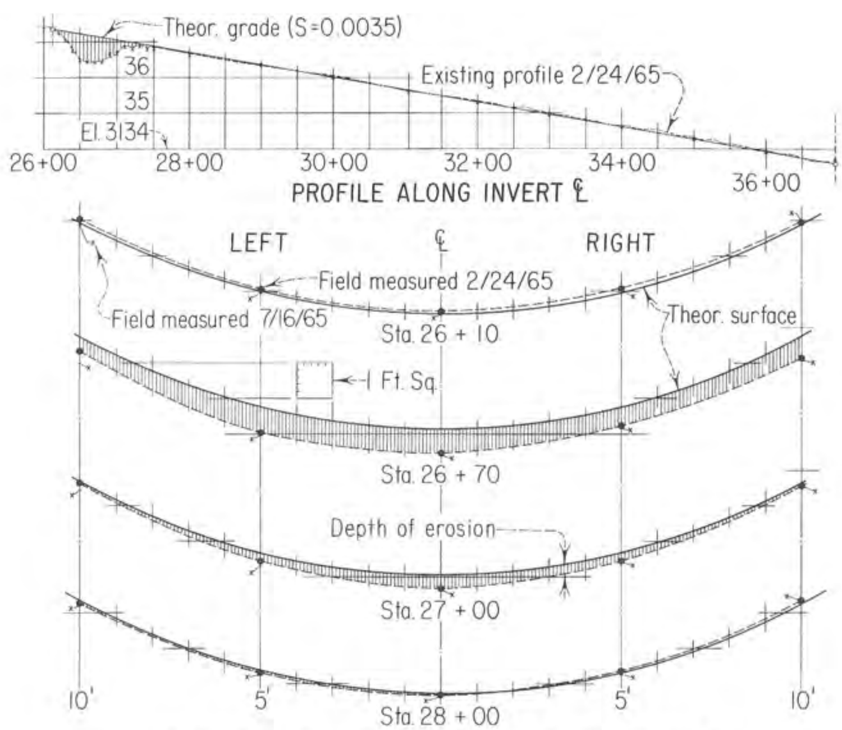
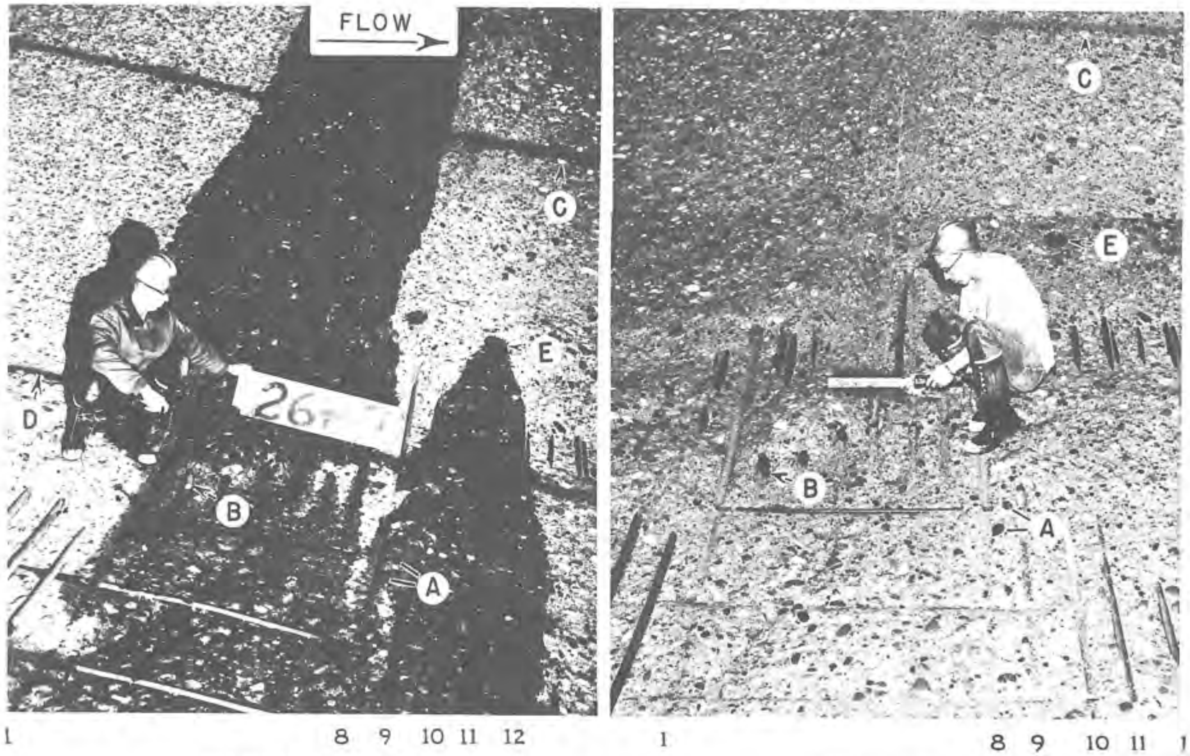


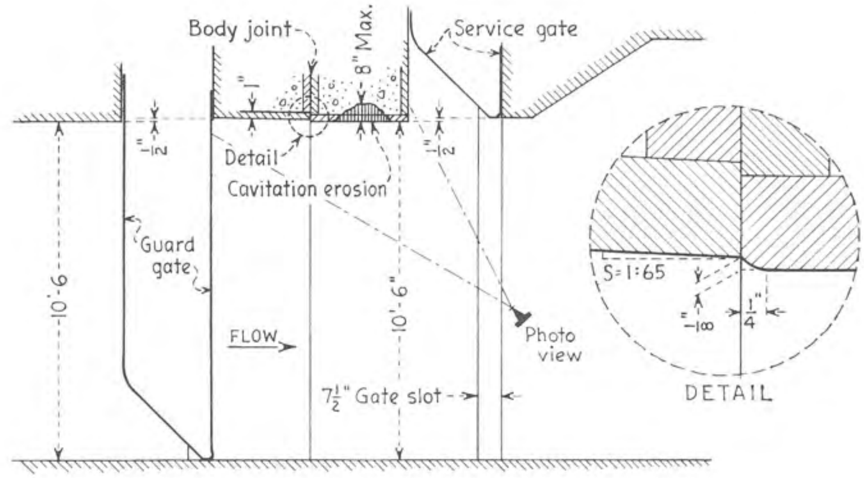
FIGURE 13 EROSION ALONG INVERT OF LEFT DIVERSION TUNNEL



MARCH 1, 1965

JULY 15, 1965

FIGURE 14 COMPARISON OF DAMAGE TO LEFT DIVERSION TUNNEL ON MARCH 1, 1965 AND JULY 15, 1965



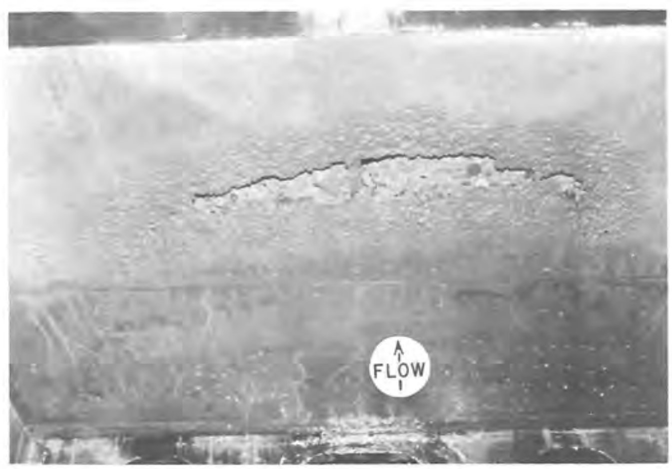
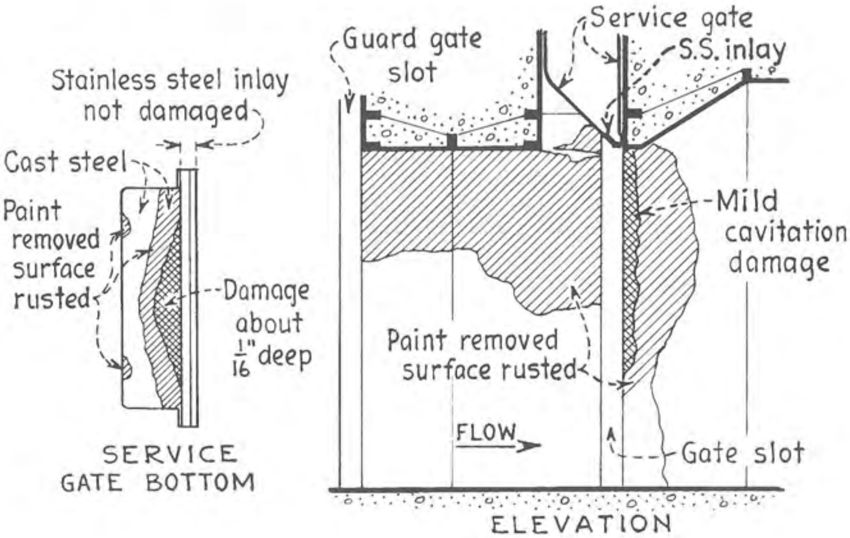


FIGURE 15 CAVITATION DAMAGE IN TOP OF FLUIDWAY UPSTREAM FROM THE SERVICE GATE



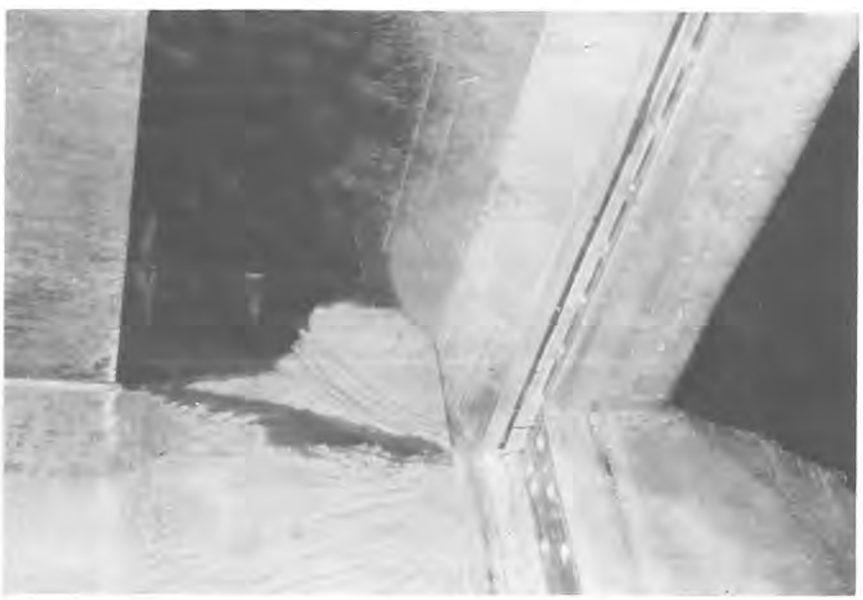


FIGURE 16 CONDITION OF LEFT SERVICE GATE

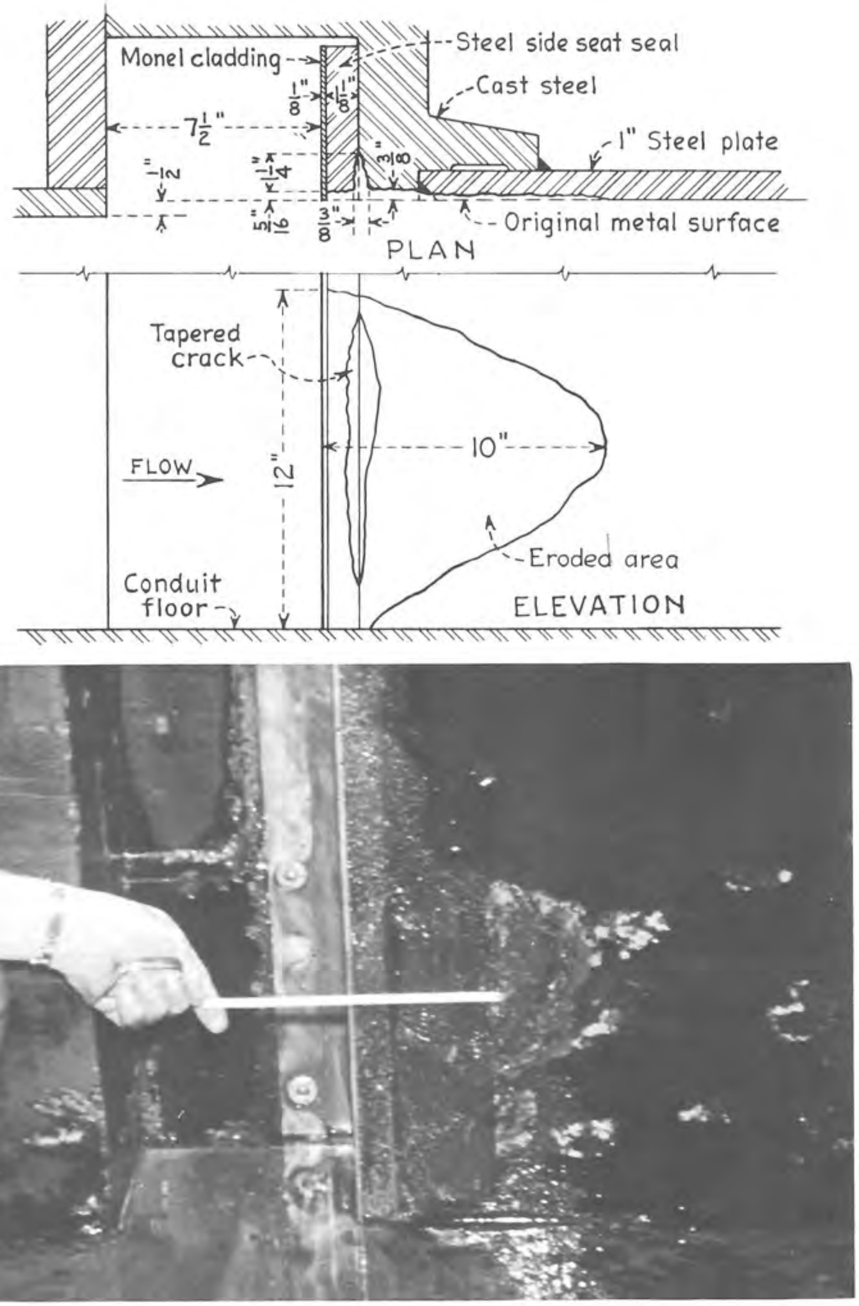
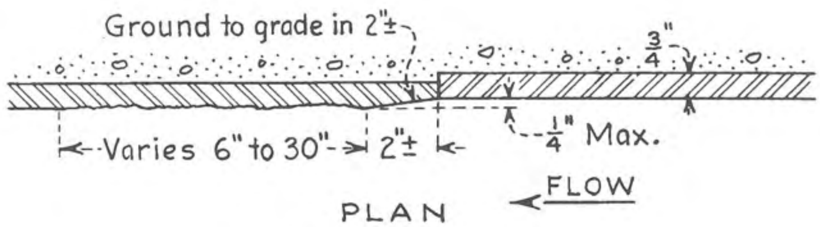


FIGURE 17 CAVITATION DAMAGE DOWNSTREAM OF CENTER GATE SLOT. DAMAGE WAS LESS AT OUTSIDE GATES



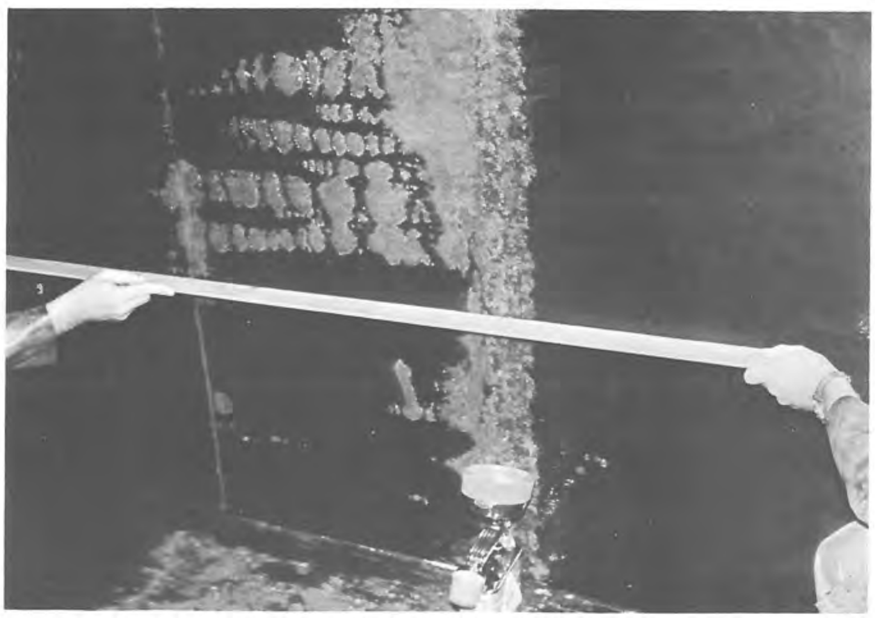


FIGURE 18 DAMAGE AT SLOPED OFFSET 20 FEET DOWNSTREAM FROM GATE

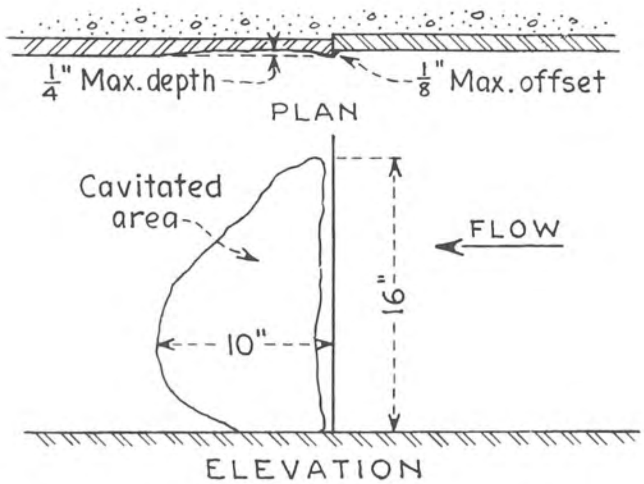
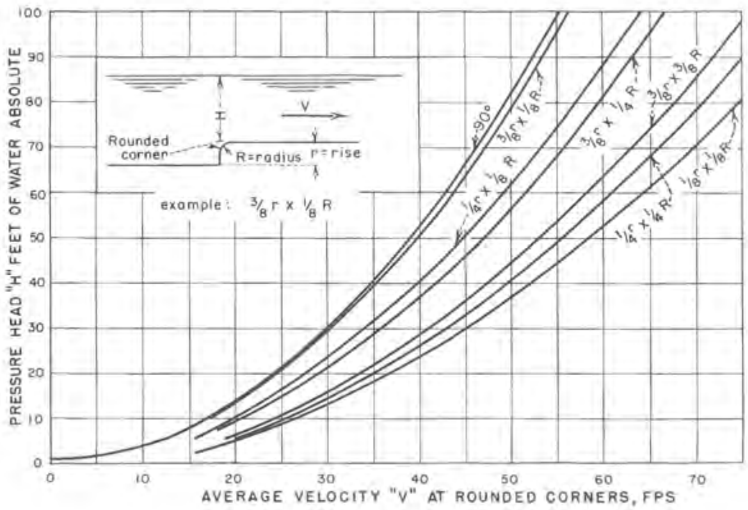
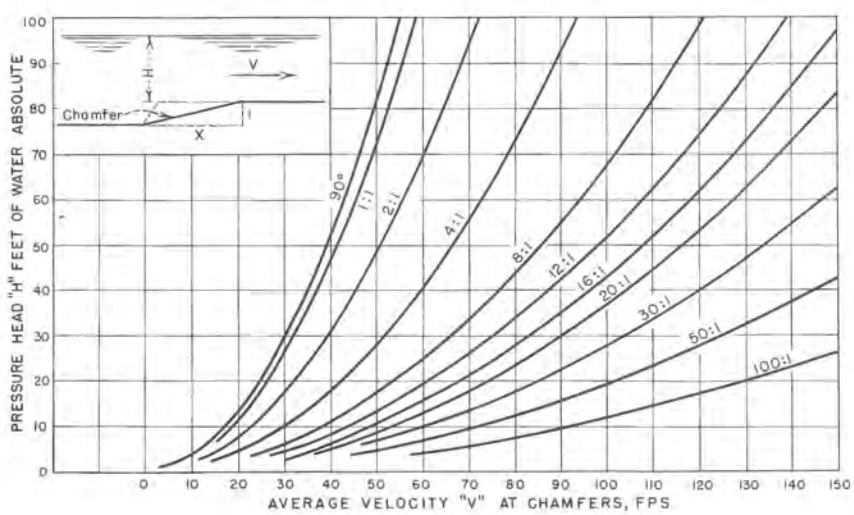


FIGURE 19 DAMAGE AT MISALIGNMENT 50 FEET DOWNSTREAM FROM GATE

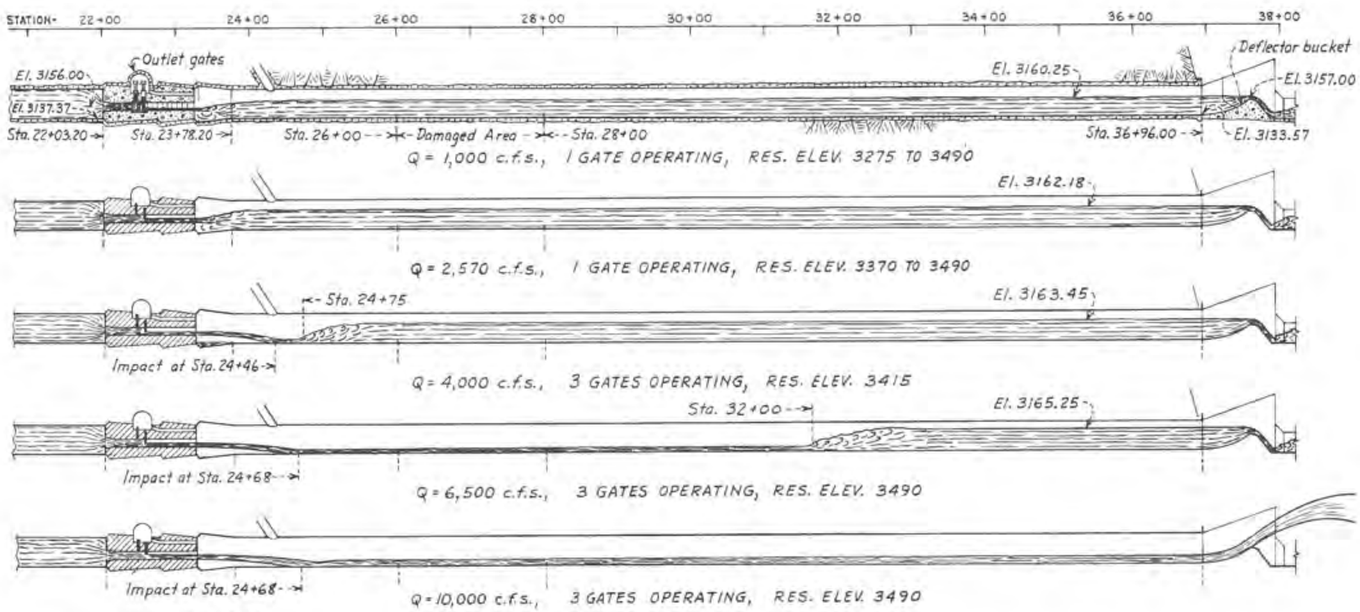


ROUNDED OFFSETS



SLOPED OFFSETS

FIGURE 20 VELOCITY-PRESSURE RELATIONSHIP FOR INCIPIENT CAVITATION AT ROUNDED AND SLOPED OFFSETS PROTRUDING INTO THE FLOW

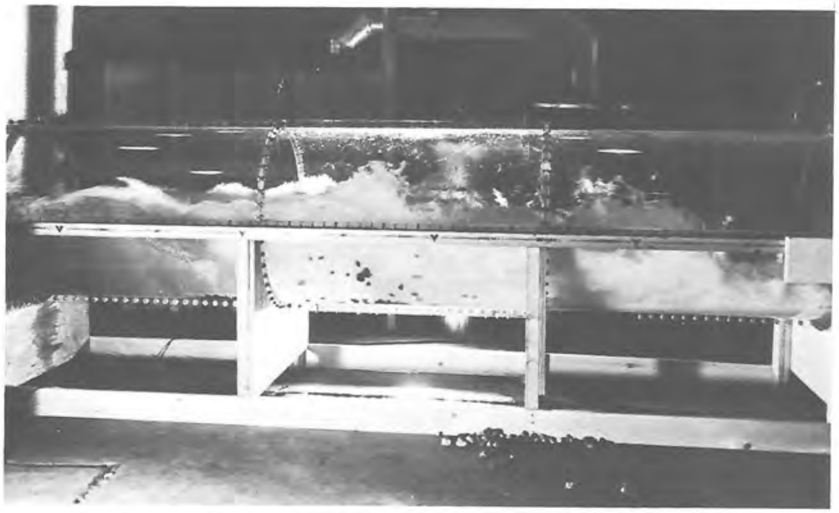


NOTES

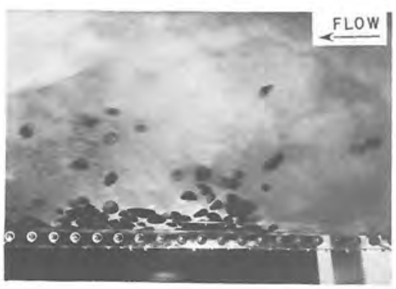
Computations based on uniform velocity distribution at d_1; Manning's n of 0.011, estimated depth of flow over bucket lip, and side weir crest.

Field tests on March 2, 1965 showed sweepout occurred at 9,400 c.f.s. and Res. Elev. 3492.

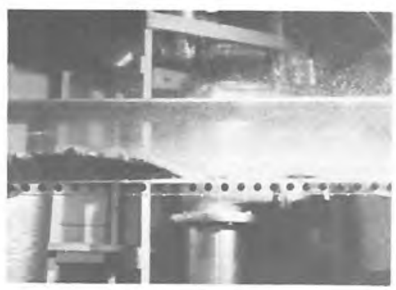
FIGURE 21 COMPUTED FLOW CONDITIONS IN TUNNEL FOR TYPICAL RELEASES BETWEEN MARCH 13, 1963 AND FEBRUARY 15, 1965



A. CIRCULATING ACTION OF 1/4- TO 1 1/2-INCH GRAVEL IN A HYDRAULIC JUMP IN A CIRCULAR TUNNEL



B. MOST OF THE GRAVEL CIRCULATED NEAR THE INVERT



C. AFTER 3 HOURS OPERATION, THE PLASTIC TUNNEL WAS CLOUDED BY THE CIRCULATING GRAVEL

FIGURE 22 MOVEMENT OF MATERIAL IN A HYDRAULIC JUMP