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Tunnel Spillway Performance at Glen Canyon Dam

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SUMMARY: Colorado River runoff at the 216-m-high Glen Canyon Dam was 180 percent of normal in the summer of 1983. A high reservoir combined with late spring runoff required the use of both 12.5-m-diameter tunnel spillways. Operating these spillways for 2 months eroded 2150 m^3 of the concrete liner and foundation rock. The tunnels were repaired, an aeration slot installed, and subsequent tests verified acceptable performance.

Introduction

Glen Canyon Dam is located on the Colorado River in northeast Arizona. The 216-m-high concrete arch dam, completed in 1964, is the key feature of the Colorado River Storage Project. Lake Powell, formed by Glen Canyon Dam, provides 33.3 x 10^9 m^3 of storage, more than all the other storage features of the project combined. The tunnel spillways are open channel flow type with two 12.2- by 16.6-m radial gates located at the intake to control releases to each tunnel (figure 1). Each tunnel consists of a 12.5-m-diameter section inclined at 55°, a vertical bend (elbow) and 300-m of near horizontal tunnel followed by a deflector bucket.

After 16 years of filling, the reservoir spilled in July 1980 resulting in minor damage to the tunnel liner. Field observations in the tunnel following the spill indicated cavitation had caused the liner damage. Incidents of cavitation and resultant damage to flow surfaces occur in high velocity flow where the water pressure is reduced locally because of an irregularity in the surface. As the vapor cavities move into a zone of higher pressure, they collapse, sending out high pressure shock waves. If the cavities collapse near a flow boundary, there will be damage.

Analysis of the spillway flow at Glen Canyon Dam conducted after the 1980 spill indicated a high potential for cavitation damage if the spillways operated for any length of time. An aeration slot similar to the successful design used at Yellowtail Dam in the late 1960's was envisioned for Glen Canyon Dam. The slot is designed to entrain air in the flow which significantly reduces the effect of the collapsing vapor bubble. The project office had gathered the necessary field data to begin the aeration slot design when the spillways were required to pass the summer flood of 1983.

Glen Canyon Dam Releases - June-July 1983

In late May 1983, runoff in the upper basin of the Colorado River was steadily increasing due to snowmelt from an extremely large snowpack. Figure 2 shows the inflow and releases for the summer. On June 2 the left tunnel spillway gates were opened to release 280 m^3/s. By June 5 the gates were further opened to release 570 m^3/s. Early in the morning of June 6, loud rumbling noises were heard coming from the left spillway. The spillway gates were lowered to inspect the tunnel with only 150 mm of freeboard on the gates.

Several large holes were found in the tunnel invert at the downstream end of the elbow, figure 3. Although some of the damage was initiated by cavitation forming on small calcite deposits along the tunnel invert, there is also speculation that a subatmospheric core vortex, caused by secondary currents, may have formed in the elbow which on contact with the flow surface caused severe damage in a very short period of time. This might explain the rapid increase in damage over a period of 72 hours.

To prevent overtopping of the radial gates it was necessary to operate both spillways. An analysis of the cavitation potential indicated that if the releases could be held below 170 m^3/s, it would take several months of operation to produce serious damage. The fact that the left spillway was already seriously damaged and continued high inflows into Lake Powell would force higher releases through the spillways prompted a decision: continue to use the left tunnel spillway as needed and maintain the right spillway release at 170 m^3/s or less, for as long as possible. In making the decision, it was recognized that the damage to the invert of the elbow and downstream left tunnel would continue. It was, however, hoped that this larger discharge would prevent the formation of a hydraulic jump in the spillway tunnel. Instead, the high energy jet would be directed downstream along the tunnel centerline producing damage in the horizontal tunnel away from the elbow.

From June 16-23, the left tunnel spillway discharge was increased as needed from 340 to 650 m^3/s to ensure a continued flip from the tunnel deflector bucket thus preventing the formation of a hydraulic jump in the tunnel. This operational plan proved successful and provided an additional 16 days of protection for the right spillway before it became necessary to also increase its release rate past the damage threshold.

To increase storage capacity in Lake Powell and continue controlled releases through the spillways, 2.4-m-high metal flashboards were designed and installed on top of the four spillway gates. The metal flashboards provided an additional 1.6×10^9 m^3 of storage in Lake Powell. The flashboards proved to be very useful after the peak inflow had passed and the spillway gates were closed on July 23 with a reservoir elevation of 1130.1 m, some 2.38 m and 1.5×10^9 m^3 of storage above the top of the gates.

Throughout the period of high flood releases, the four 2440-mm, hollow-jet valves and eight power units operated 24 hours a day releasing a combined discharge of 1250 m^3/s without incident. The excellent performance of these units was crucial to the successful operation of flow releases at Glen Canyon Dam during the summer of 1983.

Tunnel Spillway Damage

Once the spillway gates were closed, the inclined section and elbow of each tunnel were inspected. Major damage had occurred in the elbow of both spillways. Twisted reinforcement steel extended from the damaged tunnel liner in the horizontal section of each spillway.

Engineers later entered the tunnel from the downstream deflector buckets. Upon entering the left tunnel, it was obvious that serious damage had occurred. There was approximately 230 m^3 of concrete, reinforcing steel, and sandstone in the deflector bucket. Once inside the tunnel, the first 60 m were relatively free of debris. A large sandstone boulder, 2.4 by 4.6 by 4.6 m was found in the tunnel invert some 150 m upstream from the bucket. Debris several feet deep had accumulated along the tunnel invert upstream from the large boulder.

Extensive damage had occurred in the tunnel elbow. Immediately downstream from the elbow, a hole 10.7-m deep, 40.8-m long, and 15.2-m wide had been excavated in the sandstone by the high energy spillway flow. Three-fourths of the tunnel liner circumference had been removed in the area of the deep hole, figure 4.

Inspection of the right tunnel spillway revealed less damage. There was very little debris deposited in the tunnel invert. However, a large hole was found in the invert immediately downstream of the elbow. The invert liner was removed for some 53 m and sandstone had been excavated up to 3.6 m deep.

Spillway Aerator Design

Hydraulic model studies were conducted at a 1:43 scale to develop a spillway aerator similar to the design used in 1968 to prevent cavitation damage in the tunnel elbow at Yellowtail Dam. The Glen Canyon aerator design consisted of a short ramp to lift the water over the air supply slot and prevent the slot from filling with water. Research indicates and field tests have verified that the addition of small quantities of air near the boundaries of high velocity passageways can prevent cavitation damage to flow surfaces (1) (2). Small quantities of air (as low as 8 percent) substantially reduce the effect of the high pressure shock waves emitted by the collapsing vapor cavities.

The aerator is located on the 55° incline, approximately 46 m upstream from the start of the elbow, figure 5. A small ramp located immediately upstream of the aeration slot is 178 mm high at the invert but diminishes to zero at the tunnel springline. The slot is 1.2 by 1.2 m in cross section and extends over the lower three quarters of the tunnel circumference. The tunnel is designed for free flow. The ramp creates a low pressure zone under the water jet and air is drawn from the free air flow above the water body into both sides of the slot. An offset away from the original tunnel profile ensures that water does not strike the air slot. The air drawn under the water jet mixes with the water along the lower surface of the jet and then flows through the tunnel elbow.

Tunnel Liner Repair

Repair of the concrete tunnel liner in each spillway tunnel involved a monumental task in a very short time frame (3). Approximately 10 months were available to complete the repairs and aerator construction including mobilization time. Field personnel were assigned to one of two 10-hour, 6-day a week shifts throughout the construction period. Tunnel lining and invert replacement was made to the same line and grade as specified in the original construction.

Knowing that the aerator would prevent cavitation damage, complete restoration of the downstream tunnel lining to a smooth surface in areas of minor damage was unnecessary and economically unjustifiable. Savings of several million dollars were realized by the relaxed surface tolerance criteria. For concrete surfaces downstream from the aerator, the repair criteria was relaxed so that offsets up to 19 mm required no repair. Results of the tunnel spillway tests confirmed the correctness of this decision.

Tunnel Performance Tests

Field performance tests were conducted approximately 1 year after the serious erosion damage had occurred at Glen Canyon Dam. The tests were conducted from August 11 through August 17, 1984, and included only the left tunnel spillway. The purpose for the test was to verify the adequacy of the spillway aerator design and repair criteria and to secure field test data for correlation studies with the 1:43 scale model. Although two other Bureau of Reclamation tunnel spillways had been equipped with aerators, Yellowtail Dam (1968) and Flaming Gorge Dam (1982), neither spillway had instrumentation installed in the invert.

The situation at Glen Canyon Dam in 1984 provided an excellent opportunity for prototype conformity tests. Instrumentation boxes and conduits were installed in the tunnel elbow and air slot during the repair contract at a fraction of the cost of instrumenting an existing tunnel spillway. Due to the high runoff during the summer of 1984, Lake Powell was again in surcharge and could provide the estimated 0.15×10^9 m^3 of water required for the test.

Eleven 380-mm-deep by 150-mm-diameter instrumentation boxes were installed in the aerator and repaired invert of the left tunnel elbow. The boxes, installed flush with the concrete liner surface were connected by 38-mm conduit. A computer-based data acquisition system was developed to collect and store data from various instruments. Three types of data were gathered: air velocity in the aerator (pitot-static probes), dynamic pressure, and static pressure (tunnel invert). The instrumentation plan included 13 measurements in 11 boxes. Although only one-half of the instruments were operational during the tests, due to water damage, sufficient data were acquired to adequately evaluate the performance of the aerator and repaired tunnel liner.

The test program was designed with two phases: a series of short-term tests to collect data at a number of flow conditions up to 1420 m^3/s; and a second, long-term test to determine the adequacy of the slot in preventing cavitation damage to the flow surfaces. Table 1 presents a synopsis of the spillway operation for the two phases of the test program. Tunnel inspections were performed immediately before and after each phase of the test and halfway through the phase 2 test.

Table 1. - Flows and volumes during the tests on the left spillway.

	Flow rate of discharge (m^3/s)	Test duration (hr)	Volume of discharge (1×10^3 m^3)
Phase 1	142	1	500
	283	1	1,000
	566	17.5	36,000
	991	0.5	3,600
	1420	1.0	5,200
Phase 2	283	3.5	3,600
	566	48	100,000
		Total volume =	150,000

There is a significant temperature gradation at Lake Powell. To avoid severe temperature shock to the downstream fishery during the 1420 m^3/s spillway test (figure 6), 470 m^3/s of the warmer surface waters were released through the left spillway all night. This warmer flow mixed with the much colder 1000 m^3/s powerplant discharge so that the downstream water temperature was slowly raised in preparation for the test.

The maximum measured air velocity in the aerator occurred during the 1420 m^3/s test. The air velocity reached 76 m/s. Based on previous experience and theory, the phase 2 duration tests were conducted with an exposure time long enough that minor cavitation damage (holes approximately 150-mm deep) would have resulted without an aeration slot. Although some concrete pop-outs were observed, the frequent tunnel inspections performed throughout the test sequence showed no damage from flow induced cavitation.

Summary

The Glen Canyon Dam tunnel spillways damaged during the summer of 1983 were completely repaired and an aerator was placed in each tunnel spillway to prevent future cavitation damage. Results of the field tests indicate that the spillway aerators are successful in preventing cavitation damage. There was no observed damage caused by cavitation and measurements of air demand and pressures (static and dynamic) support this finding. The spring/summer floods on the Colorado River in 1983 and again in 1984 were two of the largest on record. The tasks of operating the reservoir system, developing a successful design modification to prevent future damage, completing a $31 million repair/modification at a difficult construction site, and conducting field verification tests were all completed between these two major floods.

References

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2. Frizell, K. W., "Glen Canyon Dam Spillway Tests Model-Prototype Comparison," Proceedings of the Conference, Hydraulics and Hydrology in the Small Computer Age," August 12-19, 1985, ASCE.

3. Burgi, P. H., and M. S. Eckley, "Repairs at Glen Canyon Dam," Concrete International: Design and Construction (ACI), March 1987.

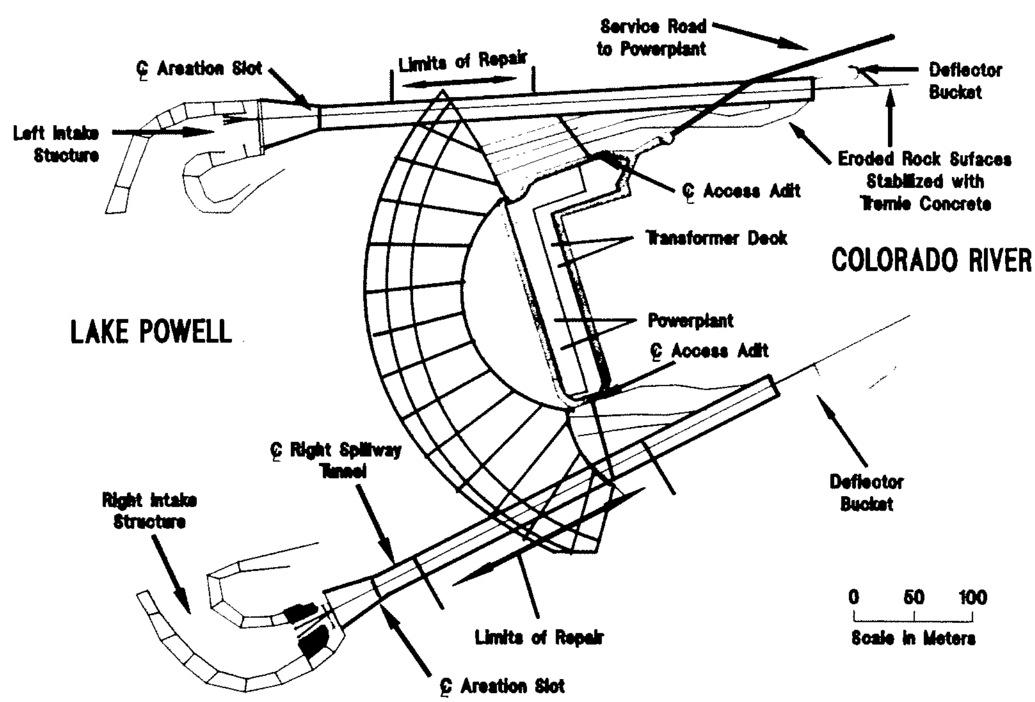

Figure 1. - Plan view of the 216-m-high Glen Canyon Dam.

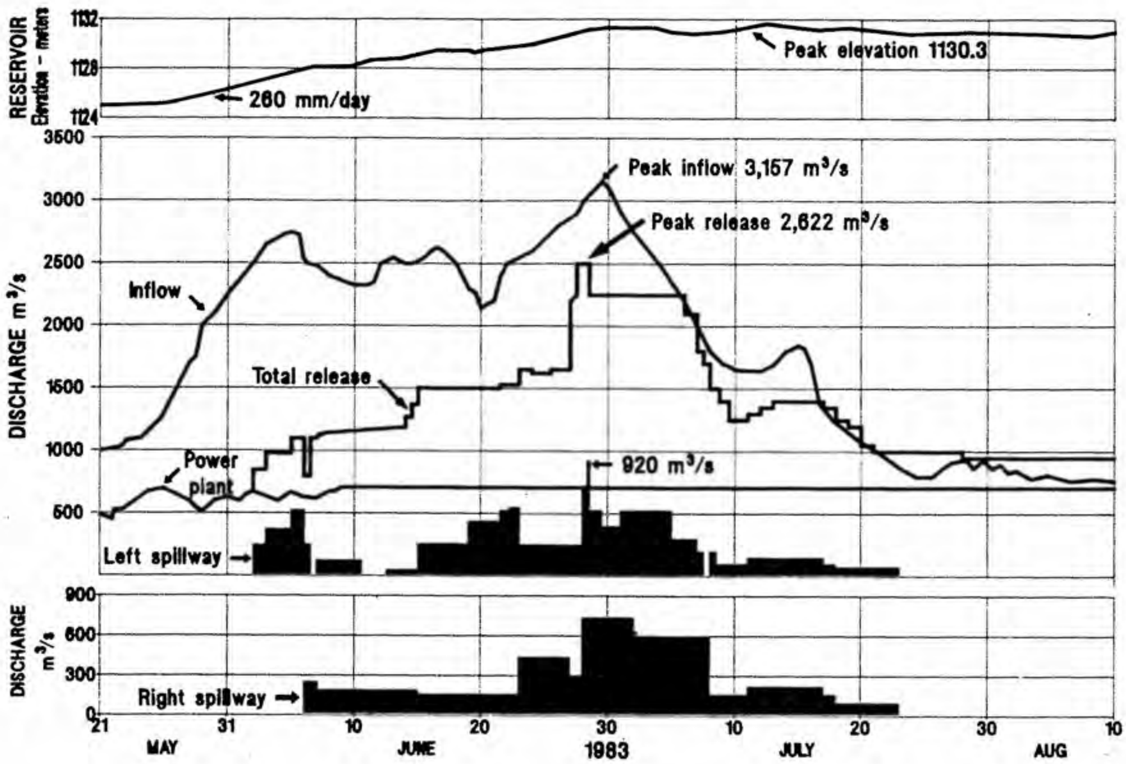

Figure 2. - Operation of waterways at Glen Canyon Dam. May-August 1983.

Figure 3. - Series of large holes found in Glen Canyon Dam left tunnel spillway 3 days after start of spill. June 6, 1983.

Figure 4. View looking downstream across the 10.7-m-deep hole in the invert liner at base of the vertical bend - left tunnel spillway. September 1983.

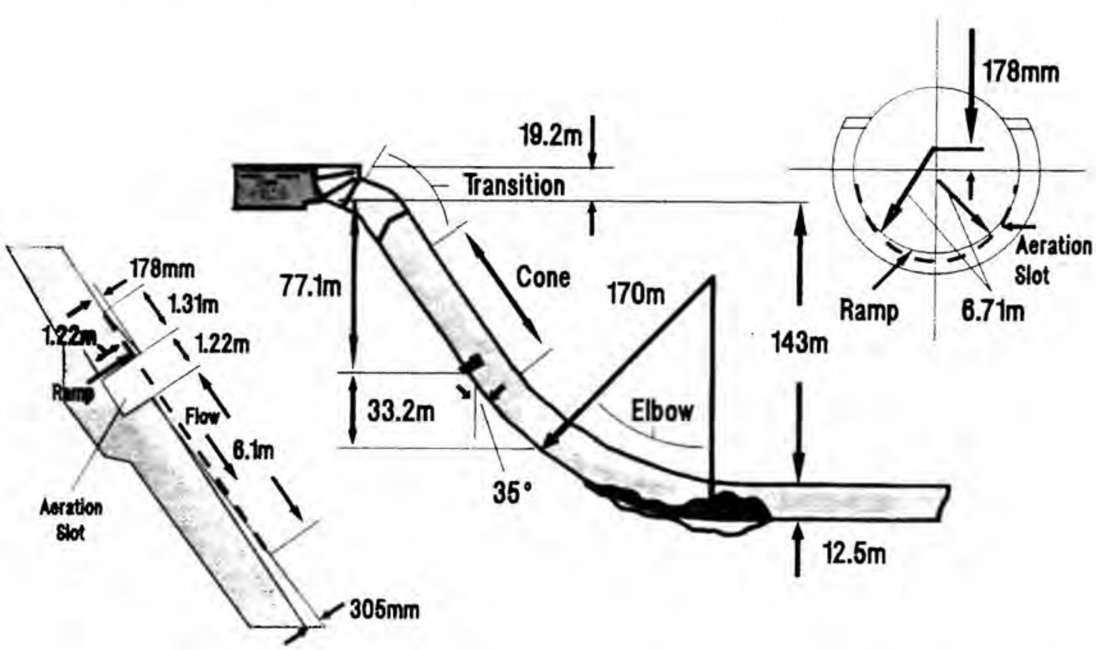

Figure 5. - Spillway aerator design - Glen Canyon Dam.

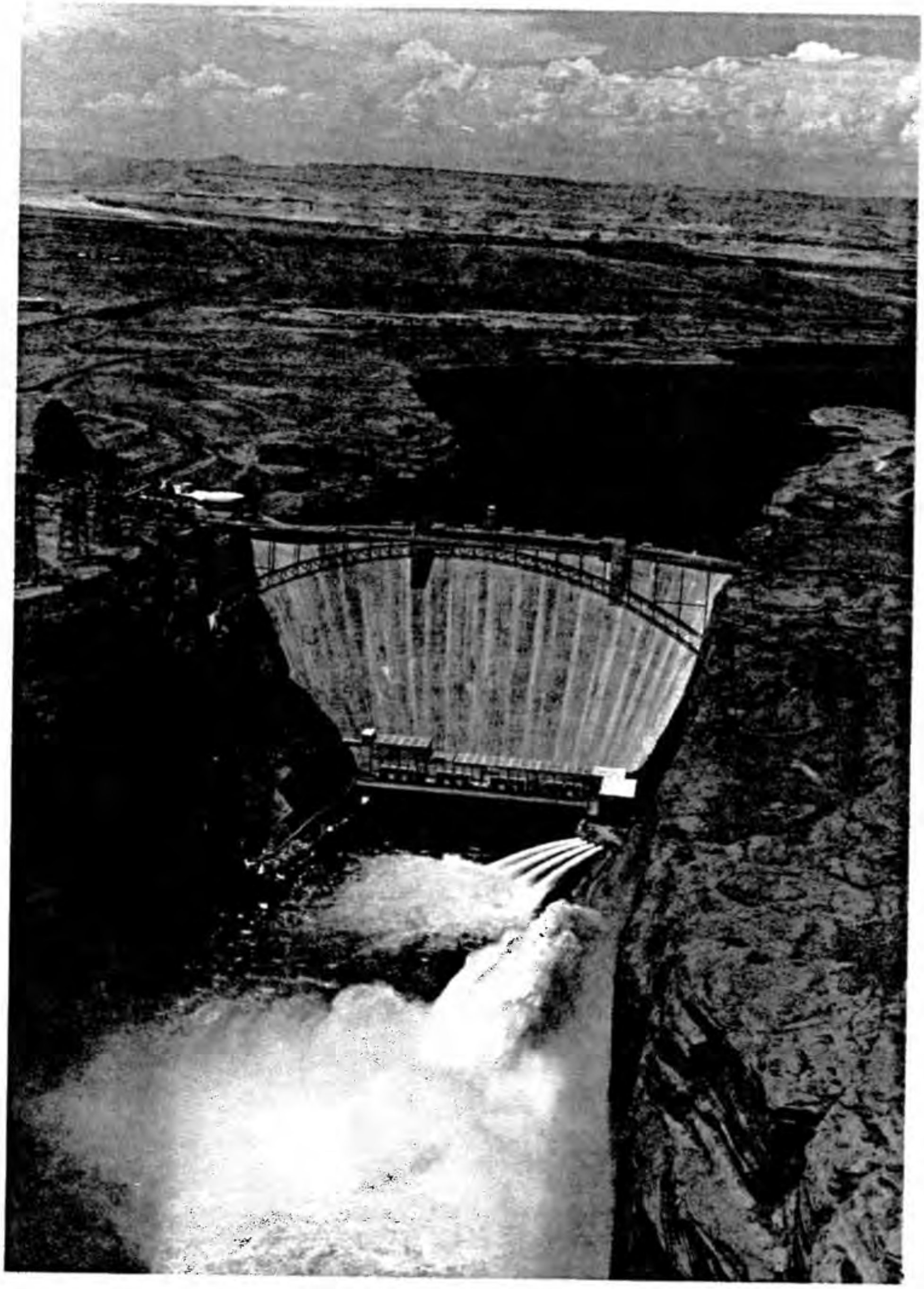

Figure 6. - Glen Canyon Dam spillway test - August 12, 1984.
1420 m^3/s - left spillway.
28 m^3/s - four 2440-mm hollow-jet valves.