The Role of Hoover Dam in the Development of Spillway Aerators

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INTRODUCTION

Hoover Dam (originally Boulder Dam) is one of the most iconic American infrastructure projects, and a facility that both demonstrated and produced hydraulic engineering advancements. In particular, the 50-ft diameter spillway tunnels at Hoover Dam were record-breaking hydraulic structures when construction was completed in 1936. Hydraulic model studies performed to develop the designs of the drum-gate-controlled, bathtub-type, side channel inlets and ogee crest profiles have been cited for decades afterward, partly due to their documentation in the famous multi-volume *Boulder Canyon Project Final Reports*. In fact, the tunnel spillway concepts developed for Hoover were also eventually used for many more dams worldwide and several constructed by Reclamation during the next 30 years, including Kortes (1946-51), Flaming Gorge (1959-62), Glen Canyon (1957-64), Yellowtail (1963-66), and Blue Mesa (1962-66).

Although the tunnel spillway designs proved successful in most respects, as structures advancing the state of the art they were not without problems. In particular, the Arizona spillway at Hoover Dam operated for the first time during a four-month period from August to the start of December 1941, with the reservoir having filled quickly after dam closure due to relatively small water storage capacity in the upper Colorado River basin. During most of this time the flows through the Arizona spillway were modest, averaging about 13,550 ft^3/s, except for a short period of a few hours when the flow rate tripled to about 38,000 ft^3/s due to an unexpected malfunction and lowering of one of the spillway's drum gates. The Nevada tunnel during the same period carried more modest flows of about 8,000 ft^3/s for only a few days. On December 12—just 5 days after the attack on Pearl Harbor that brought the U.S. into World War II—a routine inspection of the spillway tunnels revealed serious damage on the Arizona side, the result of cavitation that enabled simple water vapor bubbles to initiate erosion that scoured a hole in the tunnel floor that was 115 ft long and 35 ft deep. Whether the short period of high discharge was a strong contributing factor has never been firmly established, but it almost certainly contributed to the extensiveness of the damage.

Cavitation had been known as a source of erosion damage in and around high-head outlet works facilities (pressurized pipe outlets) since about 1910, but Hoover provided one of the first examples of serious damage to an open-channel spillway. The source of the problem was quickly identified as a misalignment of the tunnel invert that created a low-pressure zone along the tunnel lining. This initiated formation of water vapor bubbles in the flow that damaged the flow surfaces when those bubbles collapsed (imploded) upon their transition back to liquid state. The misalignment at Hoover was a gradual hump in the floor profile, not the more common abrupt offset that has initiated cavitation damage in other structures. Still, the hump was enough that it produced low pressure conditions along the spillway surface at high discharge, and this initiated the damage process. Once the surface was roughened, the severity of cavitation likely increased, and led at some point to mass erosion. The combination of processes allowed the extent of the damage to grow rapidly.

With an understanding of the physics driving the cavitation damage process, emergency repairs were initiated to reconstruct the tunnel and correct the alignment problem. To ensure the best chance of good performance going forward, special attention was paid to joints and the surface finish, even utilizing highly skilled stone masons in the concrete finishing process. In parallel, Reclamation's chief design engineer, John L. Savage, set the hydraulics laboratory to work developing methods for mixing air into the flow, with the yet-unproven thought that a bubbly, compressible, two-phase flow might disrupt the cavitation damage cycle. The mechanism being sought was somewhat unknown, but speculation was that the slightly compressible nature of air-entrained flow might provide a cushioning effect that would dampen pressure spikes associated with cavitation bubble collapse, and additionally, air added to the flow might reduce the degree of negative pressures experienced at the spillway surface, thereby retarding the formation of vapor bubbles in the flow.

The first studies were challenging, requiring the development of new instrumentation and test methods, and unfortunately, they were not immediately successful, but Reclamation's engineers were persistent. This paper describes those initial unsuccessful studies, the work a decade later that showed the idea had merit, the studies a quarter-century later that proved it could be practically implemented, and finally almost a half-century later how the idea would come full circle back to Hoover and its upstream neighbors, Glen Canyon, Flaming Gorge, and Blue Mesa Dams.

INITIAL AERATOR STUDIES

Bradley (1945) conducted the initial studies aimed at finding a means of entraining some quantity of air into the tunnel spillway flow. Significant unknowns that made this study challenging were the quantity of air needed, the location at which it was required, no prior experience pointing to an effective method for inducing air entrainment, and limited knowledge of scale effects related to modeling of air-water flows. Although damage had occurred well downstream in the tunnel, the study considered air-entraining appurtenances at stations that were much further upstream.

The studies were conducted at a scale of 1:60 which may have been too small to achieve scalable quantitative modeling of air flow rates but was still sufficient to evaluate the relative performance of different air-entraining devices. Early tests focused on aerator devices—sills, deflector ramps, and individual dentates—located on the bottom of the tunnel's transition section, at locations either 100 ft or 140 ft downstream from the spillway crest. These devices were intended to create a low pressure that would draw air naturally under the jet without using compressors. Air flow was provided to these devices via orifice openings through the tunnel wall that enabled estimation of air flow rates but were impractical for actually supplying air to the aerator devices in a prototype installation. Subsequent testing combined the most effective sill designs with a wall ramp on the sides of the transition designed to provide a route for air to get under the spillway flow at the downstream sides of the aerators. This design achieved an estimated volumetric air flow rate ranging from 11.5% at a water discharge of 40,000 ft^3/s down to 4.0% at 100,000 ft^3/s. This was deemed insufficient, but with hindsight and the benefit of subsequent research findings, this was a potentially useful air flow rate, especially considering the small scale of the model which likely reduced the air flow rates relative to prototype scale. The deficiency that probably still affected this design was the rapid deaeration of the flow that would have occurred this far upstream in the tunnel. To some degree this was observed in the model and may have been exacerbated again by the model scale, since surface tension would have dominated bubble behavior in the model leading to an air mixture with relatively large bubbles that quickly moved to the surface.

A missed opportunity in this study was the fact that only relatively large deflectors and sills were considered. Attempts to move the aerators further downstream caused the spillway flow to launch free from the tunnel invert for its full length. This was recognized as an undesirable operating condition with violent impingement of the flow when it returned to the tunnel floor. Subsequent research in later decades would show that much smaller ramps located further downstream could achieve greater air entrainment and better retention of that air in the water column, while avoiding the excessive launching of the jet.

The problem of deaeration before air reached the locations of observed cavitation damage was addressed in the model study by measuring the quantity of air in the flow near the boundary within the downstream vertical bend or elbow. This was accomplished with devices that skimmed a small quantity of water and air from the 1/16-inch thick layer of fluid nearest the boundary and conveyed it to an ingenious system that measured the volumes of air and water collected during a 10-minute time period. These measurements showed that deaeration through the elbow was dramatic, with almost no air measurable near the boundary at the exit of the elbow. The results were deemed to be negative overall. The potential for significant scale effects was understood and the potential inaccuracy of the primitive measurements was recognized, but it was still believed that model air flow rates needed to be many times higher for aeration to offer a feasible solution.

DEMONSTRATING THE EFFECT OF ENTRAINED AIR

Despite the disappointing results from the Hoover spillway model, Reclamation continued to pursue research to link entrained air to the elimination of cavitation damage. Peterka (1953) reported on two laboratory devices designed to produce intense, controlled cavitation in environments that facilitated the study of aeration effects. The first apparatus made use of a magnetostrictive oscillator consisting of a nickel tube exposed to an alternating electromagnetic field. As a magnetostrictive material, nickel experiences a strain when exposed to a magnetic field; with sufficient power, an oscillating alternating current can drive the magnetostrictive oscillator to vibrate strongly enough that vapor bubbles alternately form and collapse at a frequency of 7.8 kHz. This enables laboratory study of the damage created by cavitation. Simple tests demonstrated that a thin jet of air injected against the face of a submerged sample attached to the magnetostrictive oscillator caused significant reduction of cavitation damage. The tests did not quantify the amounts of air needed to produce an effect, but comparative tests established that the protective effect increased as the air flow was increased.

The second device was a so-called “cavitation machine” consisting of a two-dimensional venturi supplied with water from a high-head pump capable of producing flow velocities in the venturi throat over 100 ft/s. Samples of concrete or other materials could be installed downstream from the throat of the device to expose them to an intense cloud of collapsing cavitation vapor bubbles. Peterka reported tests of material loss rates from concrete samples that demonstrated that the erosion rate decreased proportionally as the mean air concentration increased from 0 to about 2 percent, and continued to decrease slowly for air concentrations above 2 percent, until cavitation damage ceased at about 7.5 percent air by volume. The tests also showed that the cavitation index of the flow, $\sigma = (P_0 - P_v)/(\rho V^2/2)$, increased linearly in proportion with the increasing air flow rate. The cavitation index expresses the relative difference between the mean pressure of the flow field (P_0) and the vapor pressure of water (P_v), normalized by the dynamic pressure of the flow (with r = fluid density and V = velocity). Incidentally, a successor cavitation machine is still in use at Reclamation and is presently being used to study how damage rates are affected by the additional factors of concrete strength and/or protective coatings.

The Peterka (1953) study established a target for the design of aerator devices: air flow concentration rates of at least 2 and preferably as high as 7 to 8 percent. Importantly, without instrumentation to measure air concentrations at precise locations in the flow, Peterka's work led only to a gross recommendation of a mean air flow rate for the entire flow. Subsequent quantitative research linking air flow rates and damage rates found similar or smaller effective air flow rates (Rasmussen 1956; Russell & Sheehan 1973). Today, instrumentation that enables careful measurement of air concentration at the flow boundary is leading researchers to believe that concentrations as low as 1% at the boundary can be highly effective.

AIR-SLOT DESIGN DEVELOPMENT

Yellowtail Dam. Construction of this 525-ft high dam on the Bighorn River in south central Montana was completed in late 1965, with a single 32-ft diameter tunnel spillway. Heavy rains in the spring of 1967 led to the spillway's first operation. After about 18 days at flow rates varying from 12,000 to 18,000 ft^3/s, the supercritical flow and flipping action at the tunnel exit was lost and a hydraulic jump moved upstream into the tunnel. After a month in service, inspection revealed major damage in the exit of the lower elbow extending into the horizontal portion of the tunnel. The most serious damage was initiated by cavitation triggered by local failures of epoxy mortar patches. The worst erosion holes were up to 7 ft deep (Colgate 1971). In addition to the severely damaged areas, there were many instances of less advanced damage within the elbow section (vertical curve). These were initiated by minor surface irregularities such as calcium carbonate deposits, failures of mortar and epoxy repairs, and loss of aggregate in areas that had been heavily ground to eliminate high spots in the concrete surface. Damage was initiated at surface imperfections that intruded into the flow as little as one-eighth inch.

In addition to planning an intensive repair effort, recent success with aeration slots in the river outlets of Grand Coulee Dam (Colgate & Elder 1961) encouraged Reclamation to pursue an aerator design that could be incorporated into the repairs. The 1:49.5 scale model was used to study different aerator locations and to perfect the geometry of the aerator slot. Work quickly focused on a downstream aerator location set just above the start of the lower vertical curve, and at least three different slot geometries were tested before an acceptable design was reached. Although this scale may not have been sufficient to accurately model actual air entrainment rates, it was adequate to study the most important implementation details—the interaction of the deflected jet with the geometry of the air slot and tunnel boundaries. Simple offset slots of various widths tended to fill with water at high discharges due to the near-surface flow striking the edges of the offset and running down under gravitational action to fill the invert of the slot. A conical nozzle with a small eccentricity proved more successful and its shape was tuned to minimize the tendency for fins generated at the downstream impingement point of the jet to wrap around the tunnel to a degree that could seal off the air flow passage (since air supply to the aerator needed to come from downstream). Many trials were needed to develop a design that would function properly over the full design discharge range. Visual observations of the model (there were no quantitative measurements of air concentration) indicated that significant air remained in the flow through the bend, but uncertainty about the rate of deaeration and the relation between entrained air in the model and prototype led designers to pursue a second air slot to be located about two-thirds of the way through the bend. However, this location was more challenging due to the large centrifugal forces in the bend, and there were significant issues again with flooding of the slot and control of fins in the flow. Ultimately, designs that were feasible to construct only performed well for narrow ranges of discharge. It was concluded that a design that would succeed over the required flow range would require tunnel modifications that were too extensive to include in the repair program, so as a result, the second aerator concept was dropped.

Following completion of the repairs and aerator construction at Yellowtail, a sequence of field tests and followup inspections was used to verify that aeration provided sufficient cavitation protection. Test flows up to 15,000 ft^3/s caused some failures of small surface repairs, but no cavitation damage, despite the known presence of remaining surface irregularities in the downstream portion of the bend that were similar in size, shape, and location to those that caused extensive cavitation damage in 1967.

POST-YELLOWTAIL INSTALLATIONS

Table 1 summarizes the properties of the five Reclamation facilities with aerator-equipped tunnel spillways. A narrative of the experiences at these facilities follows.

Flaming Gorge Dam. The experience at Hoover and Yellowtail indicated there would be serious cavitation damage in the Flaming Gorge spillway. Field tests were conducted in 1975 at 5,000 ft^3/s. No damage attributable to cavitation was seen, but with a need to repair some poor concrete surfaces in the tunnel the decision was made to proceed with installation of a tunnel aerator. The aerator design was similar to that developed for Yellowtail but was located further upstream in the 55-degree inclined section of the tunnel. No model studies were conducted; the aerator location was chosen based on the cavitation index values corresponding to the damaged locations at other facilities. Construction was completed just prior to the major flooding of 1983 and the spillway operated for 30 days at flows up to about 17% of design discharge. No cavitation damage was observed, even in areas downstream from the aerator that were hastily evacuated by the contractor and left in rough condition with stairway bolts protruding from the surface. Subsequent experience at other facilities suggests that the design may not entrain enough air for flow rates above two-thirds of maximum design discharge.

Glen Canyon Dam. The dual tunnel spillways operated in 1980 and after a field inspection showing some cavitation damage, plans were made to install aerators in both tunnel spillways in 1984. However, the 1983 flood precluded those plans and proved just how destructive damage by cavitation and resulting abrasion can be when exposure extends over a long period of time

(Burgi et al. 1984; Falvey 1990). Damage to the left tunnel was the most severe, reaching a depth comparable to the tunnel diameter (41 ft) and extending a distance of almost 300 ft. 8-ft high flashboards were added to the spillway gates to temporarily increase maximum reservoir storage so that spillway releases could be limited to safe levels and eventually taken out of service for repairs. Even as both spillways were still operating during the summer of 1983 to pass the flood releases, the design, physical model studies, and plans for the repairs and construction of aerators proceeded on a fast track so that the spillways could be back in operation for the spring runoff in 1984. The 1984 flood runoff exceeded even that of 1983. In August 1984 the left spillway was tested up to 50,000 ft^3/s, far greater than the maximum flow of 32,000 ft^3/s that had caused damage in 1983 (Frizell 1985). No damage associated with cavitation was found after the tests even though there were some imperfections left unrepaired before the tests. These extensive field tests proved that the repair criteria used in high head tunnel spillways could be relaxed somewhat if the tunnel has an aerator.

Table 1. — Reclamation tunnel spillways equipped with aerators to prevent cavitation damage.

Tunnel Spillway	Dam Built/ Aerator Added Spillway Capacity	Elbow Radius	Tunnel Diameter	Distance from Elbow PT to Aerator	Distance from Aerator to Crest	Distance from Max Water to Tunnel DS Invert	Notes
Yellowtail Dam	1965/1968 92,000 ft^3/s	290 ft	32 ft	23 ft	271 ft	485 ft	Spillway cavitation damage occurred in 1967. Aerator installed in 1968 no damage when tested in 1969 and 1970
Flaming Gorge Dam	1962/1983 28,800 ft^3/s	200 ft	18 ft	137 ft	175 ft	432 ft	Aerator installed in1982-83. No cavitation damage after 1983 spill
Glen Canyon Dam (2)	1964/1983 208,000 ft^3/s	351 ft	41 ft	109 ft	253 ft	574 ft	Aerators were installed after severe cavitation damage in 1983 spill. Left spillway tested in 1984. No cavitation damage
Blue Mesa Dam	1964/1985 34,000 ft^3/s	168 ft	21 ft	83 ft	147 ft	332 ft	Cavitation damage was noted in 1970 inspection. Did not spill in 1983. Aerator added in 1985.
Hoover Dam (2)	1935/1987 400,000 ft^3/s	226 ft	50 ft	256 ft	258 ft	559 ft	Cavitation damage in 1943 and 1983. Aerators were installed in 1985. Approach flow from side channel spillway caused unstable flow resulting in the need for aerator model studies.

Blue Mesa Dam. The Blue Mesa spillway operated up to 3,500 ft^3/s for several days in June 1970, with resulting cavitation damage. Although no spillway releases were made at Blue Mesa in 1983, analysis indicated extensive cavitation damage would occur if an aerator was not installed. Laboratory model studies were performed by Reclamation in 1983 along with the Glen Canyon studies and an aerator was constructed in 1985. After the aerator's installation, the spillway was tested up to 2,000 ft^3/s with no damage observed.

Hoover Dam. At Hoover Dam, the repairs made in 1945 were untested for nearly 40 years. A combination of dry conditions in the early 1950s and gradually increasing water storage resources in the upper Colorado River basin had prevented the reservoir from filling again. Over time it became evident from the operating experience at other tunnel spillways that even the finely finished concrete in Hoover's Arizona tunnel would be susceptible to cavitation damage under high discharge conditions. This prospect was fulfilled with the high releases needed to pass the 1983 runoff. Post-operation inspections revealed light damage in the Arizona tunnel and severe damage on the Nevada side initiated by a small popout in the concrete surface. The decision was made to retrofit both tunnels with aerators. A site-specific model study was performed in Reclamation's Denver laboratory at a scale of about 1:52 (Houston 1984). This scale was still too small to enable accurate modeling of air flow rates and deaeration tendencies, but these were now well understood from the decades of research conducted since the 1940s and the recent experiences at the other tunnel spillways. This model's purpose was to ensure good air supply to the aerator and good flow conditions downstream from the necessary tunnel modifications. The model was also used to study some long-needed modifications to the flip bucket structures at the downstream ends of the spillway tunnels. Aerator construction and tunnel repairs were finally completed in June 1987, 51 years after the original completion of Boulder Dam.

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