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Cavitation in Bureau of Reclamation Tunnel Spillways

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SUMMARY: Cavitation damage has been a problem in tunnel spillways since 1941 when massive erosional damage was discovered at Hoover Dam. Five Bureau of Reclamation dams with tunnel spillways have been equipped with aeration devices since then. This paper describes the history and the sequence of studies done by the Bureau since that time.

Introduction

Cavitation damage has been experienced in Bureau of Reclamation outlet works structures as far back as 1910 [Warnock, 1945]. However, it was not until the 1940's that cavitation problems were experienced in open channel flow when the tunnel spillways at Boulder Dam (now Hoover Dam) were first placed in operation. During the first 4 months of operation the average flow was 382 m^3/s, except for a few hours on October 28 when one of the drum gates was inadvertently dropped and the flow increased to 1076 m^3/s in the Arizona spillway.

During an inspection on December 12, 1941, a massive eroded area was discovered in the lower portion of the Arizona tunnel. The hole was approximately 35 meters long, 9 meters wide with a maximum depth of 14 meters. The source of this damage was cavitation caused by a misalignment of the tunnel invert a few feet upstream of the eroded area. Studies were conducted to determine the most appropriate repair and to investigate alternatives to prevent damage in the future. The consensus at that time was to make the tunnel lining as smooth as possible. Another approach suggested was to introduce air between the high velocity water jet and the tunnel lining [Bradley, 1945]. Extensive experiments were made in an attempt to accomplish this objective.

Hoover Model Studies. - A 1 to 60 scale model of the Arizona spillway was constructed to accomplish the studies. The objective was to force aeration of the spillway by natural means, air compressors were out of the question.

Sills and other devices were installed on the floor of the tunnel transition to cause the jet to spring free of the floor creating a subatmospheric pressure below the jet to draw the air into the space created. A number of devices were tried; however, the amount of air drawn into the model was small. The studies were finally discontinued since a successful method was not developed to entrain a significant amount of air in the flow near the vertical bend. The misalignment was corrected when the damage was repaired. The surface was finished with a terrazzo machine and bushing and grinding to make the concrete as smooth as possible.

Yellowtail Studies. - In 1967, prototype operation of the tunnel spillway at Yellowtail Dam in Montana caused severe damage to the tunnel near the vertical bend [Colgate, 1971]. Model studies were conducted to develop an aeration device to be installed during tunnel repairs on the premise that entrained air would help prevent cavitation damage in the future.

Aeration slots around the periphery of the tunnel were tried at three different locations: (1) high in the inclined portion of the tunnel; (2) near the start of the vertical bend; and (3) near the end of the vertical bend. Preliminary designs of the aeration device filled with water thus preventing air from entering the jet. Aerators in the vertical bend were not successful due to the centrifugal force of the water.

A conical nozzle (ramp) was installed at the upstream face of the aeration slot just above the vertical bend. This cone was successful in entraining air in the flow; however, a large fin formed on both sides of the tunnel where the contracted jet impinged on the sidewalls. The recommended design corrected this problem by using a 0.9-meter by 0.9-meter slot with a 76-mm ramp in the invert to lift the jet over the slot. The ramp offset varied from 76 mm at the invert to 0 just above the springline. This configuration minimized the effect of side fins especially at higher flows where the upper portion of the jet is not contracted. The location just above the vertical bend was chosen since it was the most effective in aerating the flow through the vertical bend at all spillway discharges.

This configuration was installed in the prototype structure. The damaged area was repaired with backfill concrete, epoxy-bonded concrete, and epoxy-bonded epoxy mortar. The epoxy mortar was used as a veneer over practically the entire invert surface from Station 7+70 to Station 10+50 to correct the surface texture such as aggregate popout and cavitation damage caused by calcium buildup [Borden, et al., 1971].

Prototype tests were conducted during June 18-23, 1969, to verify the adequacy of the aeration and the repair methods. The spillway was operated for 5 days at a flow of 142 m^3/s. No cavitation damage was observed in the tunnel. On June 27, 1969, the tunnel was operated at 425 m^3/s for 24 hours without damage. It was concluded that the aeration slot was supplying air to the invert surfaces in sufficient volume to mitigate cavitation damage. During July 1970, additional tests were conducted with flows from 340 to 453 m^3/s. No evidence of cavitation damage was found anywhere in the tunnel.

Flaming Gorge. - Previous experience at Hoover and Yellowtail indicated that cavitation would also be a problem at other Bureau of Reclamation structures with high-head tunnel spillways. In July 1975, tests were conducted at Flaming Gorge to determine if a cavitation problem existed [Falvey, 1989]. During the limited tests at a flow of 142 m^3/s, no apparent cavitation damage occurred in the tunnel. However, the concrete in the tunnel was very poor and needed repair. A decision was made to install an aeration device during the repairs. The aerator was patterned after the Yellowtail device. However, the slot was located further upstream where the minimum cavitation index is 0.181. Model studies were not conducted.

In 1983, the aerator had been installed; however, repairs on the concrete surface downstream from the slot were not complete. The tunnel was required to pass flows from 113 to 142 m^3/s for 30 days. There was no cavitation damage observed in the construction zone where the jet impinged, attesting to the effectiveness of the aeration in preventing cavitation damage.

Glen Canyon. - Plans were underway to build aeration devices and design data had been collected at Glen Canyon Dam when the tunnel spillways were required to pass the Colorado River flood of 1983. Lake Powell had been slowly filling since the dam was completed in 1964. The spillways had only been used for short tests in 1980. In early June 1983, the left spillway was operated at 425 m^3/s for 42 hours and 566 m^3/s for an additional 22 hours. After a rumbling noise was heard the gates were closed for an inspection. Cavitation damage had occurred in the vertical bend [Burgi et al., 1984]. During the next month both spillways were used as well as the hollow-jet valve outlet works and the powerplant. The maximum flow through the left spillway was 906 m^3/s. The peak inflow was 3158 m^3/s and the peak release from the reservoir was 2622 m^3/s.

During the flood, 2.4-m-high flashboards were added to the 15.9-m-high radial gates controlling flow into the tunnel spillways. This allowed the spillways to be shut down much sooner than would have otherwise been possible. Massive erosional damage had been sustained in both the left and right tunnels. In the left tunnel, a series of holes had been created in the now familiar "Christmas tree" pattern. The largest hole, near the end of the vertical bend, was 11 meters deep, 41 meters long and 15 meters wide. Most of the tunnel liner had been removed in this area. A smaller but similar hole was found in the right spillway.

Emergency repairs were begun immediately. At the same time model studies were initiated to develop aeration devices [Pugh, 1984]. The initial aerators were located and designed using the technology and experience developed up to that time. The aerators were located in the conical reducing section of the tunnel about one-half of the way down the tunnel between the intake and the vertical bend. Different ramp heights and offsets away from the flow on the downstream side of the slot were tried. A successful design was developed and installed in both tunnels during the winter and spring of 1983 and 1984. A schematic diagram of the Glen Canyon aerator is shown in figure 1. During the spring of 1984 a major flood again occurred in the Colorado River basin. Even though the reservoir had been drawn down during the winter, the lake level rose onto the flashboards before the construction was complete.

During July 1984 a series of tests were conducted in the left spillway to verify the adequacy of the aerator. Flows up to 1416 m^3/s were passed through the spillway. A sustained test for several days at 566 m^3/s was also conducted. No cavitation damage could be detected in the tunnel.

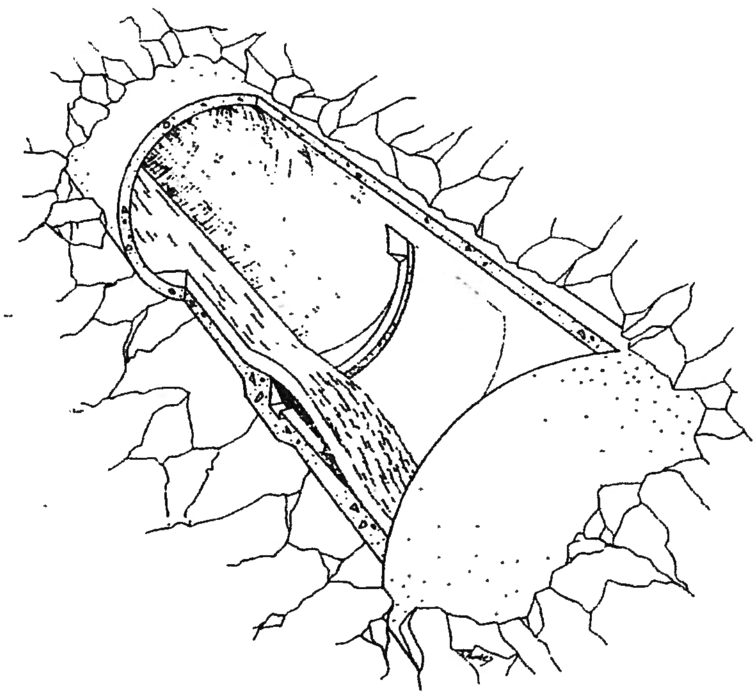

Figure 1. - Schematic diagram of Glen Canyon spillway aerator.

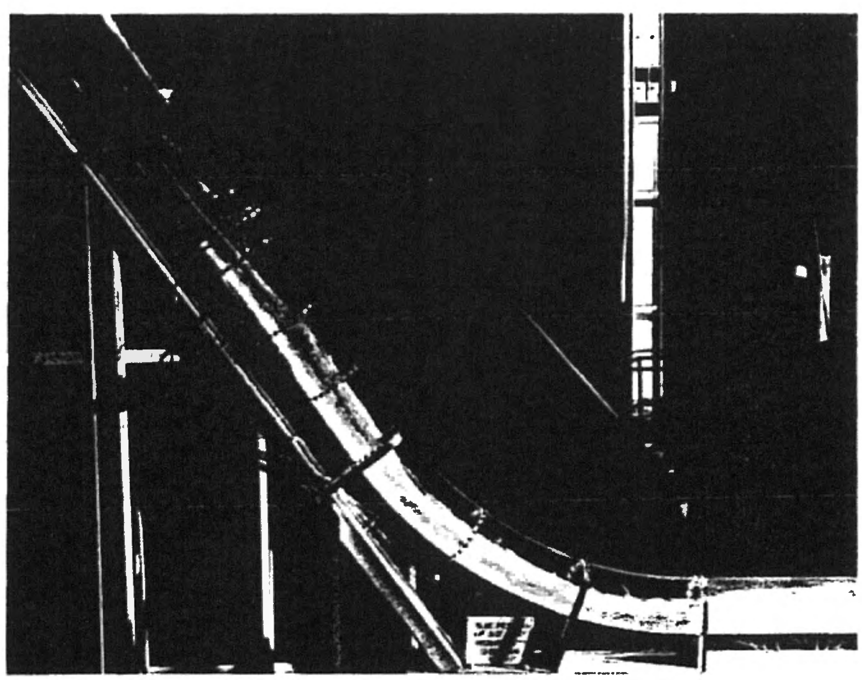

Figure 2. - Blue Mesa model operating with aerator at a simulated 566 m^3/s.

Blue Mesa. - Model studies were conducted for the Blue Mesa tunnel spillway at the same time as Glen Canyon. By this time, impending cavitation damage in high-head tunnel spillways could be predicted, even with little operational experience. The Blue Mesa spillway was not required to pass flood flows during 1983 and 1984 since maximum releases were sustained through the outlet works and powerplant. The Blue Mesa aerator was completed in 1985 after which the tunnel was operated at flows up to 57 m^3/s for several days with no reports of resulting damage. Figure 2 shows the 1:22 scale Blue Mesa model (with aerator) operating at a simulated 566 m^3/s.

Hoover. - During the 1983 flood, flows of less than 283 m^3/s were passed through both spillways at Hoover. Minor cavitation damage occurred as a result. Aeration devices for Hoover were studied in a model of the Arizona tunnel in 1984. Unstable flow from the side channel inlet structure and pressure flow in the downstream tunnel at high discharges caused by the flip bucket geometry prompted changes to the previous aeration device designs [Houston, et al., 1985]. Aerators determined from the model studies were installed at Hoover during 1985 and 1986.

Future field tests are planned for Hoover and Blue Mesa to compare to model measurements and to further refine current design procedures.

The following figures illustrate the aerators installed at Yellowtail, Flaming Gorge, Glen Canyon, Blue Mesa, and Hoover. In other Bureau of Reclamation tunnel spillways with lower cavitation potential such as Kortes and Seminoe, aerators have not been deemed necessary. However, influences of secondary flows in the vertical bend are not known at this time. Additional research is needed to determine if some tunnel geometries may cause a tendency toward rotation in the core of the jet, suspected cause of cavitation damage in some structures. [Pine Flat (Corps of Engineers) and some Bureau gates.]

Current Bureau Practice in Spillway Cavitation Mitigation

The following steps should be taken when assessing cavitation potential. Details of these methods are given in a monograph entitled "Cavitation in Hydraulic Structures" [Falvey, 1989].

1. Determine cavitation potential for preliminary design by computer analysis of the flow and cavitation parameters for the spillway.

2. Consider redesign of spillway geometry shape to lower cavitation potential, if necessary.

3. If needed, locate aerator according to spillway geometry and cavitation index. (Cavitation index about 0.20).

4. Determine ramp offset and angle according to required trajectory and depth of water at design flow.

5. Design air duct according to calculated air demand, limit air velocity to about 60 to 90 m/s.

6. Consider model studies for verification, especially if unusual flow conditions exist.

Conclusions

Aeration has been shown to be effective in mitigating cavitation damage. The design process to admit air to the flow in sufficient amounts and in the proper location has gradually evolved. The effectiveness of aeration has been thoroughly demonstrated; however, the aeration scheme must be well designed to assure that it is effective through the entire range of operations.

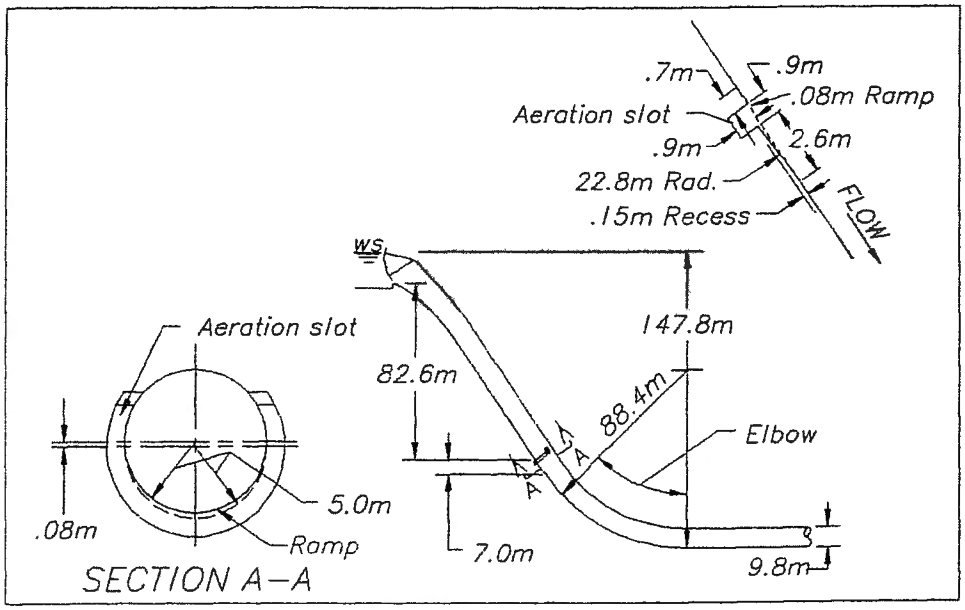

Figure 3. - Aerator details - Yellowtail Dam.

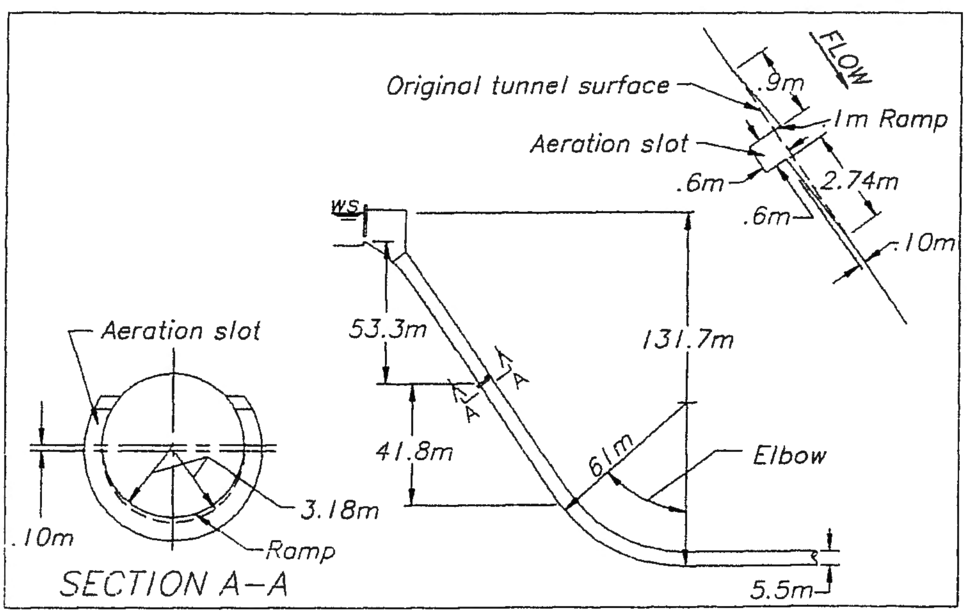

Figure 4. - Aerator details - Flaming Gorge Dam.

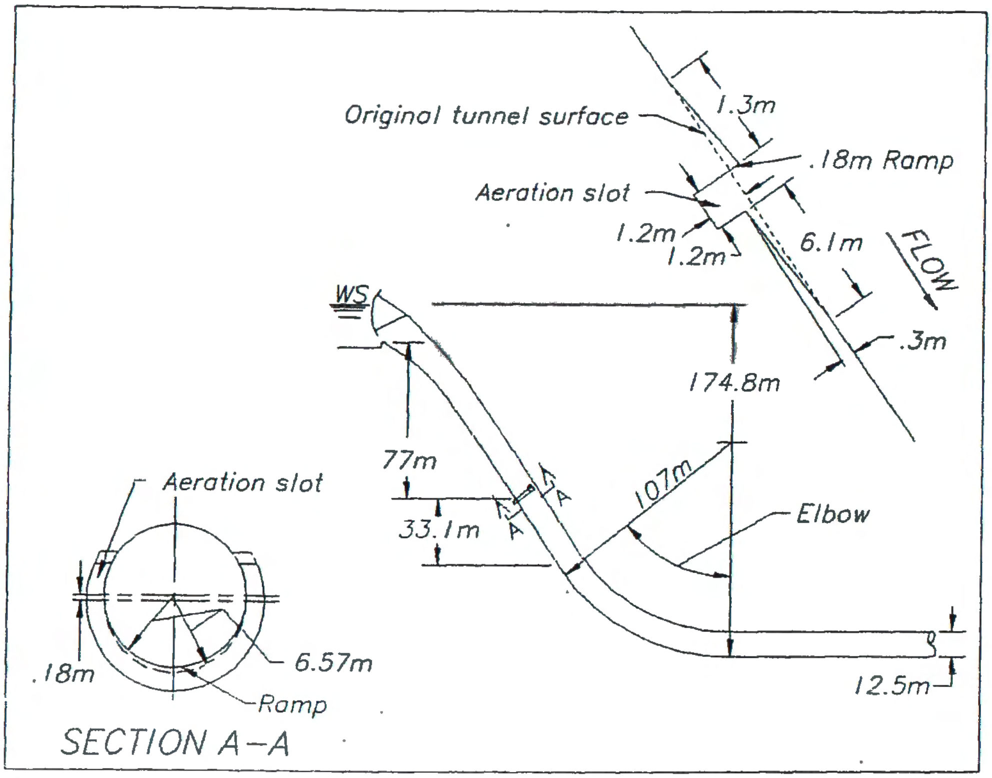

Figure 5. - Aerator details - Glen Canyon Dam.

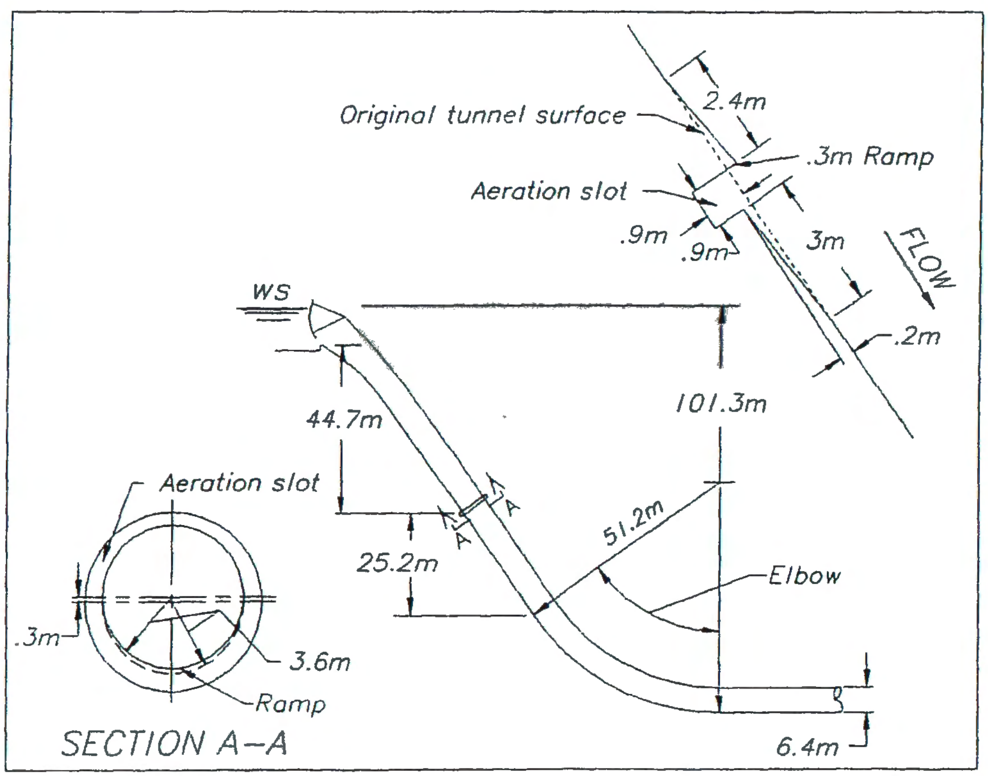

Figure 6. - Aerator details - Blue Mesa Dam.

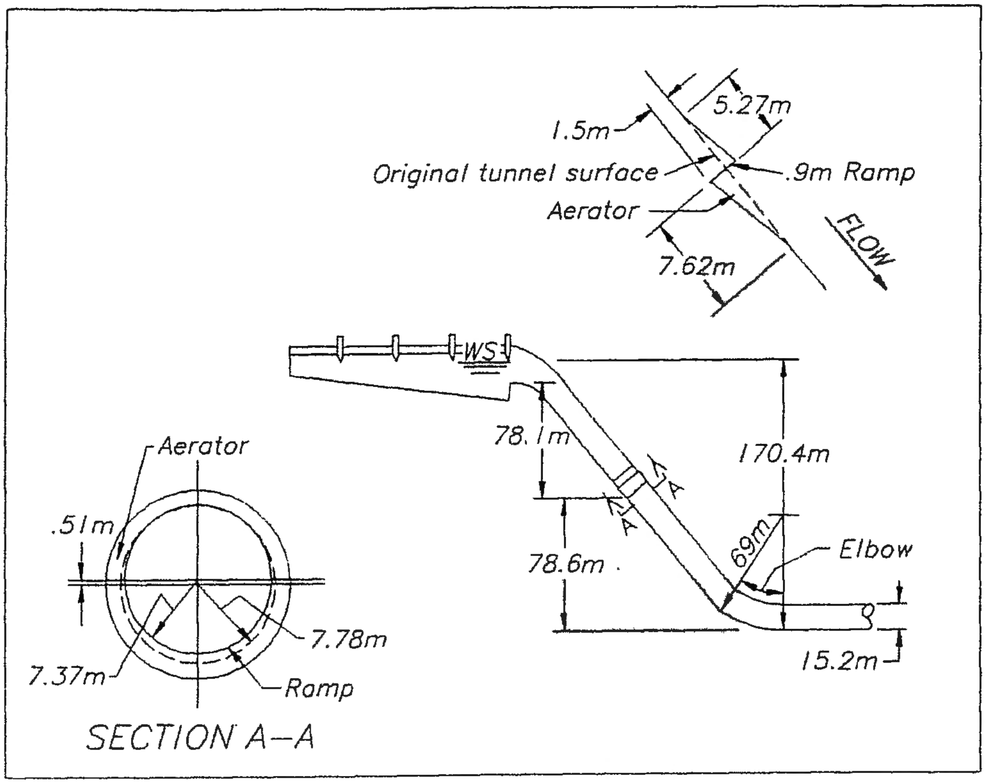

Figure 7. - Aerator details - Hoover Dam.

Bibliography

1. Borden, R. C., D. Colgate, J. Legas, C. E. Selander, "Documentation of Operation, Damage, Repair, and Testing at Yellowtail Dam Spillway," Report REC-ERC-71-23, May 1971, USBR.

2. Bradley, J. N., "Study of Air Injection into the Flow in the Hoover Dam Spillway Tunnels," Report HYD-186, October 24, 1945, USBR.

3. Burgi, P. H., B. M. Moyes, T. W. Gamble, "Operation of Glen Canyon Dam Spillways - Summer 1983," ASCE Proceedings, "Water for Resource Development," 1984.

4. Colgate, D., "Hydraulic Model Studies of Aeration Devices for Yellowtail Dam Spillway Tunnel," REC-ERC-71-48, December 1971, USBR.

5. Falvey, H. T., "Cavitation in Hydraulic Structures," Engineering Monograph No. 42 (1989) USBR.

6. Houston, K. L., R. J. Quint, T. J. Rhone, "An Overview of Hoover Dam Tunnel Spillway Damage," ASCE Proceedings, Water Power '85, September 1985.

7. Pugh, C. A., "Modeling Aeration Devices for Glen Canyon Dam," ASCE Proceedings, Water for Resource Development, Coeur d'Alene, Idaho, August 1984.