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Flaming Gorge Tunnel Spillway Aerator Analysis

by

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MEMORANDUM

To: John Trojanowski, Principal Engineer
Technical Service Center
Waterways and Concrete Dams Group

From: Kathleen H. Frizell, Hydraulic Engineer
Technical Service Center
Water Resources Research Lab Group

Subject: Flaming Gorge Tunnel Spillway Aerator Analysis

Attached is the Aerator Analysis for Flaming Gorge Dam, as requested by your office.

This analysis was peer reviewed by K. Warren Frizell of D-8560. If you have any questions concerning this document, you can contact me at 303-445-2144.

Attachment

cc: Power Office, Salt Lake City UT, Attention: UC-600 (Allen)
Manager, Flaming Gorge Field Division, Dutch John UT, Attention: FG-100 (Blanchard)
Chief, Dam Safety Office, Attention: D-6600 (Rocklin)
Director, Technical Service Center, Attention: D-8470 (Official Files)
(w/attachment to each)

bc: D-8130 (Files)
D-8311 (Trojanowski)
D-8560 (Files/K. Frizell)
(w/attachment to each)

WBR:KFrizell:amv:4-27-01:445-2144
(J:\8560\Documents\FlamingGorge.MKF.wpd)

Flaming Gorge Tunnel Spillway Aerator Analysis

Introduction

Flaming Gorge Dam, completed in 1962, is located on the Green River in northwestern Utah about 40 miles north of Vernal Utah. The dam is a concrete arch dam with a structural height of 502 ft and a crest length of 1285 ft at elevation 6047. As part of the Colorado River Storage Project, the primary purpose of Flaming Gorge Dam is to provide storage for release to the Lower Colorado River Basin and Mexico during subnormal runoff years. The reservoir capacity is 3,788,900 acre-feet. The main features of the dam are a tunnel spillway, a river outlet, and a 36 MW-capacity powerplant. The river outlet can discharge up to 4,000 ft^3/s with two 66-in hollow jet valves. The tunnel spillway is located on the left abutment of the dam with a capacity of 28,800 ft^3/s at reservoir El. 5845. The concrete-lined tunnel is 675-ft-long and reduces in size from 26.5 ft in diameter at the upstream portal to 18 ft in diameter at the downstream portal and flip bucket. The spillway intake structure is controlled by two 16.75- by 34-foot hydraulically operated fixed-wheel gates, figure 1.

Reclamation has several similar type geometry tunnel spillways, including Yellowtail Dam, Glen Canyon Dam, and Hoover Dam. Each has experienced cavitation damage at times during their operation. Each has had an aerator installed in the sloping portion of the tunnel to provide air to the water flowing through the tunnel. Small quantities of air have been shown to significantly

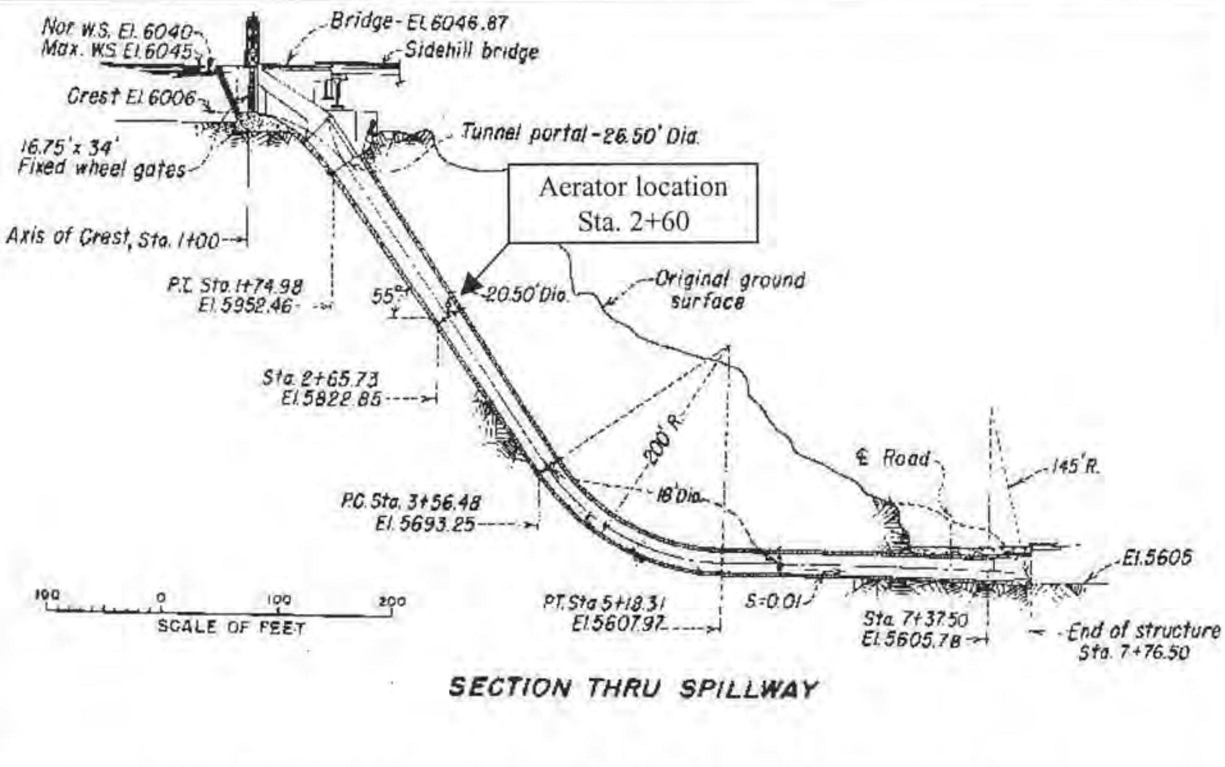


Figure 1. - Flaming Gorge tunnel spillway geometry. Aerator location is noted at Sta. 2+60.

reduce the potential for cavitation damage. The location and design of aerators is based upon the cavitation index of the flow, and the condition of the surface lining of the structure. Analytic techniques are used to determine the flow and aeration characteristics and provide an initial design for an aerator [1]. Hydraulic model studies are usually recommended to verify the performance of the aerator.

In July 1975, the spillway tunnel at Flaming Gorge Dam was operated to determine the potential for cavitation damage. No damage was detected, however, there was concern that higher flow rates might produce cavitation given the poor condition of the concrete in the tunnel lining. An analysis of the cavitation potential completed at that time indicated that cavitation could occur. An aerator was designed in 1981, but the theory was still being developed and no hydraulic model study was performed for the aeration device. The aerator was installed in 1983. Subsequent spillway tests were conducted with flow rates of 4,000 and 5,000 ft^3/s with no damage detected, even where the tunnel lining had not been repaired below the aerator. However, additional limited evaluation lead to the opinion that the aeration device may not be adequate under higher flow rates [2].

Objective

The CFR ROF made 5 Safety of Dams recommendations for Flaming Gorge Dam. Of these, one was a request to investigate the cavitation and damage potential for the tunnel spillway for flow rates exceeding 20,000 ft^3/s. The objective is to perform the necessary hydraulic analysis to determine the cavitation potential and subsequent damage potential for the tunnel spillway at Flaming Gorge Dam. This includes determining the effectiveness of the existing spillway aerator up to the design discharge of 28,800 ft^3/s. This document provides the results of the analysis.

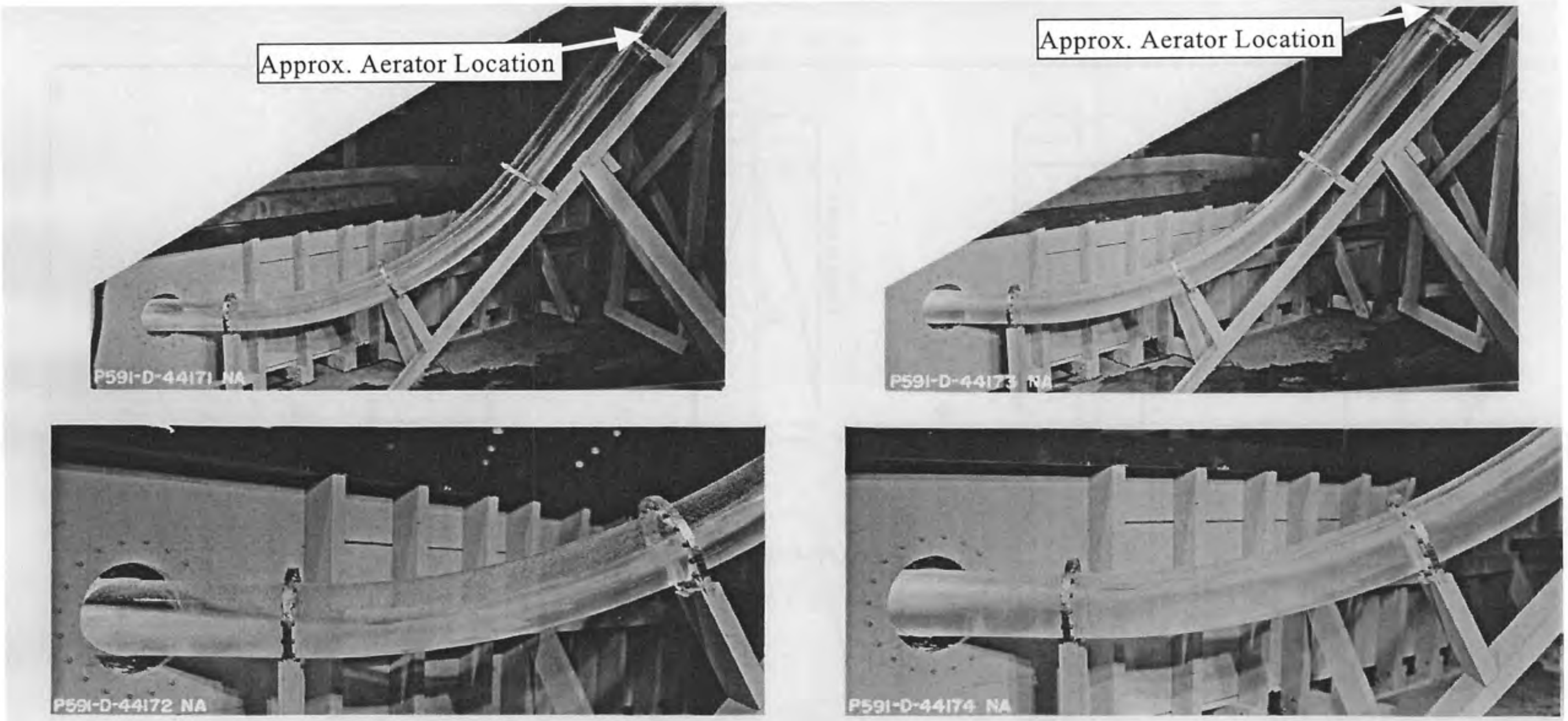
Investigation

The investigation of the aerator includes:

- Reviewing previous studies and correspondence
- Determining the tunnel spillway geometry
- Determining initial discharges, depths, etc. at the tunnel crest
- Inputting geometry into the program WS77.exe from Reclamations' Monograph No. 42
- Modifying tunnel geometry through the vertical bend to allow the program to execute for higher discharges
- Investigating aerator location and geometry
- Inputting aerator geometry into the program TRAJ.exe from Reclamations' Monograph No. 42
- Analyzing the hydraulic and cavitation outputs from the programs
- Making recommendations based upon results of analysis

Previous hydraulic modeling

Hydraulic modeling was performed in 1964 for the original design of the tunnel spillway without the aerator [3]. These studies dealt with the intake geometry, pier and crest geometry and flip bucket design. Photographs were taken of the spillway operation at 15,000 and 28,800 ft^3/s, figure 2. The aeration device location at Sta. 2+60 is approximately indicated on the photographs. Notice the depth of flow in the tunnel at this point and further downstream below the elbow where the report states, "the depth of flow in the horizontal section was about 0.85 of the tunnel diameter, but because of the smooth flow conditions the space above the water surface was considered adequate". Unfortunately, it also appears that the flow depth in the area of the aerator is also quite deep. This information was used with further investigation of the hydraulic and cavitation parameters in the final recommendations



Discharge = 15,000 cfs

Discharge = 28,800 cfs

FLAMING GORGE DAM
1:36 Scale Model

Flow in Sloping Tunnel, Vertical Bend
and Horizontal Tunnel

Figure 2. - Photograph from 1964 hydraulic model study prior to aerator design and installation. Note the depth of flow at the approximate aerator location.

Hydraulic Analysis

The tunnel spillway geometry shown in figure 1 was used to determine the input into the water surface and cavitation potential program, WS77.exe, from Reclamation's Monograph No. 42. The output from that program includes the flow depth, velocities, etc, and the cavitation characteristics for the input geometry, discharge, and reservoir conditions. Flow rates of 4,000, 8,000, 15,000, 20,000 and 28,800 ft^3/s were investigated. The input geometry file is shown in table 1.

Table 1. Flaming Gorge Dam tunnel spillway geometry file.

STA	INVERT ELEV	WIDTH OR R2	SIDE SLOPE	RADIUS	UPPER RADIUS	CL HEIGHT	LOWER RADIUS	WALL OR C2	RAD CURV	RUGOSITY
174.97	5952.46			13.25					.0	.0001
197.66	5920.06			12.50					.0	.0001
220.35	5887.65			11.75					.0	.0001
243.038	5855.25			10.50					.0	.0001
260.00	5831.036			10.438					.0	.0001
265.73	5822.85			10.25					.0	.0001
311.11	5758.05			9.63					.0	.0001
356.48	5693.25			9.00					.0	.0001
383.46	5662.11			9.00					200.0	.0001
410.43	5640.85			9.00					200.0	.0001
437.43	5625.95			9.00					200.0	.0001
464.37	5615.98			9.00					200.0	.0001
491.34	5610.07			9.00					200.0	.0001
518.31	5607.97			9.00					200.0	.0001
568.31	5607.47			9.00					.0	.0001
618.31	5606.97			9.00					.0	.0001
668.31	5606.47			9.00					.0	.0001
718.31	5605.97			9.00					.0	.0001
737.50	5605.78			9.00					.0	.0001
761.50	5605.54	18.00	.00						.0	.0001
769.50	5605.46	18.00	.00						.0	.0001
775.08	5605.40	18.00	.00						.0	.0001

The program would not execute for the discharges of 20,000 and 28,800 ft^3/s because the ratio of the flow depth to radius of curvature through the elbow was too large for the 1-D approximation used by the program. Therefore, to get the program to provide hydraulic and cavitation information through the steep slope to the vertical curve, the radius of curvature was increased from the actual radius of 200 ft to 350 ft and rerun. The hydraulic and cavitation parameters through the aerator location and down the steep slope at the higher flow rates are shown in tables 2 and 3 for the maximum flow rate. (Obviously, the information through and downstream from the elbow is not valid.) This information was used with the TRAJ.exe program [1] to investigate the adequacy of the aerator geometry.

Table 2. - Flow characteristics for Q=28,000 ft^3/s with initial depth=19.38 ft, rugosity=0.0001 ft and N=0.0109 with reservoir elevation 6045.

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	QAIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THINKNESS BOUNDARY LAYER FT
175	5952.46	1.428	19.382	66.624	11.118	6028.737	0	S2	5.993	26.368	0.555
197.7	5920.06	1.4281	17.243	79.758	9.89	6028.736	0	S2	6.114	24.931	0.876
220.4	5887.66	1.4279	16.138	90.701	9.257	6024.694	0	S2	6.25	23.465	1.148
243	5855.25	1.4285	16.252	100.133	9.32	6020.342	0	S2	6.519	20.99	1.394
260	5831.04	1.4275	15.357	106.71	8.811	6016.794	0	S2	6.535	20.866	1.568
265.7	5822.85	1.4286	15.332	108.776	8.792	6015.564	0	S2	6.581	20.492	1.626
311.1	5758.05	1.4279	14.336	123.898	8.224	6004.907	0	S2	6.753	19.246	2.037
356.5	5693.25	1.4283	13.871	136.864	7.956	5992.66	0	S2	6.953	17.998	2.417
373.4	5671.08	1.3066	13.988	135.73	31.437	5989.446	0	S2	7.014	17.986	2.549
393.9	5648.58	1.1029	13.606	139.555	32.73	5984.729	0	S2	7.154	17.985	2.689
445.4	5605.59	0.8334	12.999	146.358	34.79	5974.296	0	S2	7.458	17.983	2.987
476.1	5586.88	0.6095	12.798	148.832	36.215	5968.865	0	S2	7.919	17.982	3.143
543.6	5559.03	0.4127	12.54	152.168	37.51	5958.251	0	S2	8.683	17.98	3.451
640.5	5544.72	0.1477	12.534	152.247	38.373	5945.746	0	S2	11.881	17.979	3.85
690.5	5544.22	0.01	12.268	155.889	12.268	5937.396	0	S3	15.346	17.994	4.05
740.5	5543.72	0.01	12.378	154.353	12.378	5930.075	0	S3	15.346	17.994	4.247
790.5	5543.22	0.01	12.486	152.885	12.485	5922.921	0	S3	15.346	17.994	4.442
840.5	5542.72	0.01	12.595	151.438	12.594	5915.926	0	S3	15.346	17.994	4.636

Table 3. - Cavitation characteristics for Q=28,800 ft^3/s with initial depth=19.38 ft, rugosity=0.0001ft and N=0.0109. Note that the flow sigma is 0.20 at the aerator location and drops to 0.12 at the beginning of the vertical curve in the elbow.

				DAMAGE POTENTIAL						
STATION	FLOW SIGMA	SIGMA OF UNIFORM ROUGHNESS	REQUIRED CHAMFER TO STOP CAVITATION	CIRCULAR ARC			90-DEGREE OFFSET			TURBULENCE INTENSITY
				1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM	1/4-IN 5-MM	1/2-IN 10-MM	1-IN 25-MM	
174.97	0.551	0.029	1 TO 6	7.00E-01	2.67E+00	7.42E+00	2.26E+00	6.81E+00	1.77E+01	0.026
197.66	0.372	0.029	1 TO 10	8.18E+00	2.09E+01	4.92E+01	1.50E+01	3.78E+01	8.98E+01	0.025
220.35	0.283	0.029	1 TO 15	3.27E+01	7.67E+01	1.72E+02	5.02E+01	1.20E+02	2.75E+02	0.024
243.04	0.233	0.029	1 TO 19	8.32E+01	1.88E+02	4.12E+02	1.15E+02	2.68E+02	6.05E+02	0.024
260.00	0.202	0.029	1 TO 23	1.60E+02	3.54E+02	7.67E+02	2.09E+02	4.78E+02	1.07E+03	0.024
265.73	0.195	0.029	1 TO 25	1.91E+02	4.21E+02	9.10E+02	2.45E+02	5.59E+02	1.25E+03	0.024
311.11	0.148	0.03	1 TO 36	6.58E+02	1.42E+03	3.02E+03	7.65E+02	1.71E+03	3.76E+03	0.023
356.48	0.120	0.03	1 TO 48	1.63E+03	3.48E+03	7.33E+03	1.76E+03	3.90E+03	8.50E+03	0.023
373.45	0.205	0.03	1 TO 23	1.66E+02	3.68E+02	7.95E+02	1.77E+02	4.08E+02	9.14E+02	0.023
393.85	0.198	0.03	1 TO 24	1.94E+02	4.29E+02	9.25E+02	2.03E+02	4.65E+02	1.04E+03	0.023
445.43	0.186	0.03	1 TO 26	2.57E+02	5.63E+02	1.21E+03	2.57E+02	5.86E+02	1.31E+03	0.023
476.13	0.184	0.03	1 TO 27	2.69E+02	5.90E+02	1.27E+03	2.64E+02	6.03E+02	1.34E+03	0.023
543.63	0.180	0.03	1 TO 27	2.97E+02	6.49E+02	1.39E+03	2.82E+02	6.43E+02	1.43E+03	0.022
640.48	0.182	0.03	1 TO 27	2.74E+02	6.00E+02	1.29E+03	2.52E+02	5.76E+02	1.28E+03	0.022
690.48	0.105	0.03	1 TO 59	2.89E+03	6.12E+03	1.28E+04	2.62E+03	5.77E+03	1.26E+04	0.022
740.48	0.107	0.03	1 TO 57	2.57E+03	5.47E+03	1.15E+04	2.31E+03	5.10E+03	1.11E+04	0.022
790.48	0.109	0.03	1 TO 55	2.31E+03	4.90E+03	1.03E+04	2.05E+03	4.53E+03	9.87E+03	0.022
840.48	0.112	0.03	1 TO 54	2.07E+03	4.40E+03	9.25E+03	1.82E+03	4.02E+03	8.78E+03	0.022

The aerator for Flaming Gorge is located on the 55-degree slope in the circular transition section where the diameter of the tunnel is 10.44 ft at Sta. 2+60 and El. 5831.04. The general layout is shown in figure 3. The aerator consists of a 0.33 ft-high by 3 ft-long ramp, a 2 ft-square air slot, and a 0.33 ft offset away from the invert that returns back to the invert in 9 ft. The 3-ft by 2-ft air vent opening is located about 15 ft above the invert.

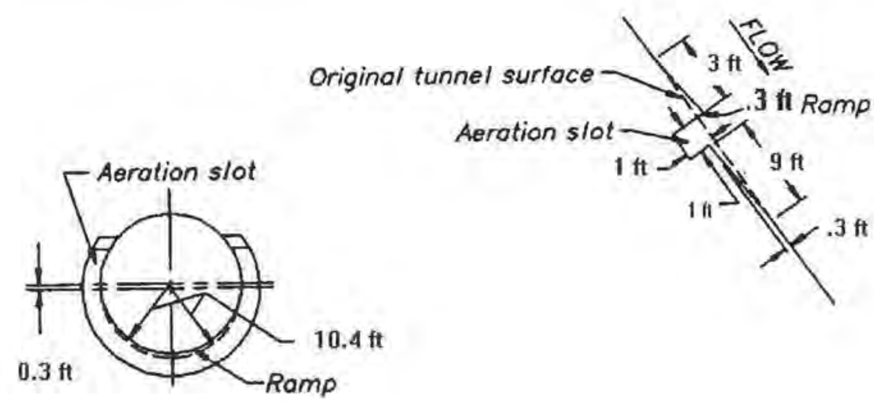


Figure 3. - Flaming Gorge aerator design located at Sta. 2+60. The air slot is 1-ft by 1-ft with a 0.3 ft-high upstream ramp and downstream transition. The air slot opening is about 15 ft above the invert.

The trajectory of the jet from the aerator and the velocity of the air in the air slot were computed by the program using the aerator geometry and output from the water surface program. The objective is to size the ramp height and angle so that the jet impinges at or upstream from the area of cavitation concern. The function of the air slot is to provide adequate air flow underneath the jet. For tunnel spillways the air slot is designed to have an opening above the water surface along the tunnel crown where adequate venting may occur. If the air slot is undersized, the pressure drop across the slot becomes too large and sonic velocity will occur in the duct. If sonic velocity occurs, the air flow is choked and the air discharge will not increase as the water flow rate increases. Jet instability and inadequate aeration could be a problem.

The results from the program indicate that for all flow rates the jet for the Flaming Gorge aerator will impact upstream from the tunnel elbow and should disperse air appropriately. However, the air velocity reaches sonic velocity at a water discharge of 8,000 ft^3/s. Adequate air volumes to prevent cavitation have been determined to be about 7.5 percent [4]. Choking of the air slot still provides enough air for protection from cavitation; however, the jet may become unstable and this is not a desirable condition.

Additional analysis was performed to determine if enlarging the air slot area would allow adequate ventilation of the jet. This analysis was performed with the existing ramp height first and then with a higher ramp. The results indicated that the combination of a higher ramp and larger air slot area would prevent choking of the air volume. The analysis did not determine whether or not the air vent area would be submerged.

Cavitation potential

The cavitation index, σ, is the ratio of the pressure differential between a reference pressure and vapor pressure and the flow velocity given by:

$$\sigma = \frac{(P_o - P_v)}{\rho V_o^2 / 2}$$

where P_o= atmospheric pressure
P_v= vapor pressure of water
V_o= velocity of water

From past experience, cavitation in hydraulic structures has occurred when the velocity increases or pressure decreases such that the cavitation index drops below 0.20.

At the design discharge of 28,800 ft^3/s, the cavitation index at the location of the aeration device is 0.202 and decreases throughout the remainder of the sloping section, table 3. Field tests have shown that the aerator will protect the tunnel for discharges up to 5,000 ft^3/s. The air slot chokes at a discharge of about 8,000 ft^3/s and the jet may become unstable, but air should still be supplied, perhaps through a discharge of 20,000 ft^3/s.

The flow depth in the tunnel is about 15.3 ft at the aerator location for a discharge of 28,800 ft^3/s, table 2. This depth will partially, if not fully, block off the air slot entrance portal. The air slot can be assumed to submerge at about 22,000 to 24,000 ft^3/s. With the air slot submerged, the aeration device will actually become a trigger for cavitation. Once the air slot is submerged the device will act as a large offset and produce significant cavitation damage, including possible loss of the tunnel lining. It should be assumed that the tunnel lining would be destroyed if operated under the design discharge for any substantial length of time.

Results

- Discharges below 20,000 ft^3/s will be protected from cavitation damage by the operation of the presently installed aeration device at Flaming Gorge Dam.

- The aeration device is inadequately designed for discharges of 20,000 ft^3/s and above, including the design discharge of 28,800 ft^3/s. Cavitation damage would be expected to occur for these higher flow rates. The damage is projected to be loss of the tunnel lining.

Recommendations

To ensure proper operation of the aeration device at Flaming Gorge Dam the existing aerator should be modified. A suggested modification would be to increase the air slot size and make a fully concentric ring that will allow air to enter the slot above the maximum flow depth. In addition, the ramp angle may need to be increased to assist with reducing the pressure drop therefore increasing the air flow rate through the slot. The aerator would most likely be similar to the Hoover design that was model studied to ensure the proper geometry [5]. If it is determined that the aeration device should be modified, it is recommended that a hydraulic model study be performed to ensure the appropriate geometry is determined for the device.

References

[1] Falvey, Henry T., "Cavitation in Chutes and Spillways", U.S. Bureau of Reclamation, Engineering Monograph No. 42, Denver, Colorado 80225, April 1990.

[2] Falvey, Henry T., "Flow Surface Specifications at Flaming Gorge Dam", Internal Memorandum, November 15, 1985.

[3] Rhone, T.J., "Hydraulic Model Studies of Flaming Gorge Dam Spillway and Outlet Works Colorado River Storage Project, Utah", U.S. Bureau of Reclamation, HYD-531, Denver, Colorado, May 28, 1964.

[4] Peterka, A. J., "The Effect of Entrained Air on Cavitation Pitting," Proceedings of the Joint Meeting of the International Association for Hydraulic Research, American Society of Civil Engineers, Minneapolis, MN August 1953.

[5] Houston, K.L., Quint, R.J., Rhone, T.J., "An Overview of Hoover Dam Tunnel Spillway Damage", Proceedings of the ASCE Waterpower '85 International Conference on Hydropower, Las Vegas, Nevada, September 25-27, 1985, pp. 1421-1430.