PAP-459

BLUE MESA AERATION SLOT

DESIGN SUMMARY

BY

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PAP-459

D-1531

PAP-459

Memorandum

Denver, Colorado
February 16, 1984

D-220 (Muller)

ACTING Head, Hydraulic Structures Section

Blue Mesa Aeration Slot - Design Summary
(In response to your telephone call of February 1, 1984)

PURPOSE

Bureau of Reclamation experience of structures with tunnel spillways indicates that there is potential for major damage to the tunnels as a result of cavitation. Hoover, Yellowtail, and Glen Canyon Dams have experienced major damage. As the water velocity increases, the potential for damage increases. However, the potential for damage is very sensitive to increases in velocity. For instance, a 10-percent increase in velocity could double the potential for damage.

Small amounts of air dispersed through high velocity water are known to significantly decrease cavitation damage. At Yellowtail Dam, an aeration groove has been successful in eliminating damage in the tunnel spillway. Because of the success of this slot, there has been a worldwide trend to install aeration devices in high velocity chutes and spillways.

Some of these devices have filled with water and actually caused cavitation damage. Model studies ensure that the slot will not fill with water and the flow downstream from the slot will not cause the tunnel to seal at high flows due to waves and fins.

DESIGN OF AERATION SLOTS

The design of aeration devices is still evolving; questions remain about how much air is entrained by the slot, how long the air stays near the boundary, what air distribution is needed to protect the surface, and what are the effects of bends and flow turbulence.

The cavitation potential is dependent on the cavitation index

$$K = (p_o - p_v)/(\rho V^2/2) \qquad (1)$$

(a ratio of pressure forces to inertia forces).

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Major damage has occurred in 24 hours for flows with $K < 0.12$. Minor damage of concrete surfaces has been noted after 2 days operation for $K = 0.15$. Experience at Bureau structures has shown that major damage does not occur in flows for which $K > 0.20$.

The location and configuration of the aeration device is dependent on the individual application. Aeration slots should not be located in a vertical bend because the centrifugal force in the flow may prevent the air from being drawn in as intended. The aeration slot should be located far enough upstream from the vertical bend to ensure an adequate jet length to entrain air along the exposed flow surface. In addition, the aeration groove should be located upstream from the point where the cavitation index drops below 0.20 to prevent the ramp from being damaged.

A ramp is needed to lift the water over the slot which prevents the slot from filling with water and which provides a free surface under the nappe to entrain air in the flow. If the water is not deep relative to the height of the ramp, the trajectory of the jet is given by the following:

$$y = x\tan\phi + \frac{gx^2}{2V^2\cos^2\phi} \tag{2}$$

The ramp angle can be chosen to cause the jet to impact at any desired location. It would be desirable to have the jet impact past the point where the cavitation index is the lowest. However, the jet should not impact the flow surface within the vertical bend because this will cause extremely poor flow conditions in the downstream tunnel. Therefore, the jet is designed to impact upstream from the start of the vertical bend.

A convenient relationship for determining the impact point is given by

$$\cos^2\phi\,(S_o - \tan\phi) = \frac{gx}{2V^2} \tag{3}$$

This equation can be solved by iterations to determine the ramp angle when the distance to the impact point is given.

The ramp height (Δ) should be large enough to deflect the deep flows downstream. Data published by Shi-bo [3] indicate that the ramp height should be at least $0.2y_o$ (y_o = the water depth). If the ramp height is less, the jet throw distance will be reduced. For closed tunnel spillways, a ramp height ($0.2y_0$) for the design flow could cause the tunnel to seal and flow full. Therefore, a smaller ramp height must be used. Because there is no set criteria for selecting the ramp height, a hydraulic model is almost a necessity in designing the ramp.

In circular conduits the ramp height should be varied from a maximum value at the invert to zero at the springline. If the ramp is continued all the way around the tunnel, a fin forms where the jet strikes the conduit walls. As the flow is increased, this fin becomes larger. At large enough flow rates, the fin can fold over and choke the tunnel. In the configuration with the ramp height decreasing to zero at the springline, the fin actually decreases for flow depths above the springline. One disadvantage of this design is that the flow will impact close to the air slot above the springline. To alleviate this situation and ensure that the slot does not fill with water, an offset away from the original tunnel profile is provided downstream of the slot. This offset continues all the way around the downstream edge of the slot to ensure that water does not enter the air slot for any flow condition. This offset should be about one-fourth of the slot depth. A straight line transition back to the original tunnel surface at a 1:15 to 1:20 chamfer is adequate.

Air Vent Size

The air vent size should be large enough to prevent large negative pressures from forming under the jet. In general, large negative pressures can be avoided by limiting air velocities to 300 ft/s. In areas where the air vent intake is exposed to the public, air velocities should be restricted to 100 to 150 ft/s to prevent high noise levels.

The air demand is dependent on the flow velocity and angle of the ramp leading to the aerator. The following equation gives an estimate of the airflow for a chute.

$$Q_a = \frac{BV^3 \cos^3 \phi \, (S_o - \tan \phi)^2}{4g} \qquad (4)$$

For a circular conduit, the above equation can be used to get a rough estimate of air demand by using the wetted perimeter of the flow in place of B. Model tests have shown that the maximum amount of air (Q_a/Q) is entrained when the flow in the circular tunnel reaches the springline (where the ramp feathers out).

Aerator Design - Blue Mesa Dam

A computer program is used to determine the cavitation potential. Figure 1 shows the results of the program for flows of 2,000, 3,500, 5,000, 7,500, 10,000, and 33,700 ft^3/s. The dotted line is the tunnel profile. The other lines give the cavitation coefficients for the various flows. The damage potential is shown on figure 2. This coefficient is computed by using the cavitation index and flow velocity at that point. The amount of damage can then be estimated from the damage index which is computed by multiplying the damage potential by log (time in hours). If the damage index exceeds 150 x 10^3, damage can be expected to occur. Figure 3 compares the cavitation index to past damage. Appendix 1 lists the computer program results.

The cavitation index drops to about 0.14 at the beginning and end of the vertical bend, the damage potential is usually greatest at the end of the vertical bend. The centrifugal force in the bend increases the cavitation coefficient thus decreasing the damage potential.

The air slot was located at station 13+65 to be above the point where K drops below 0.20. This is about 100 feet above the start of the vertical bend (x = 57.8 ft). Equation 3 was used to estimate the ramp angle, for Q = 5,000 ft^3/s (a normal operating condition).

y_o = 4.44, V = 88 ft/s, S_o = 1.428 = tan 55°

$$\cos^2\phi\,(S_o - \tan\phi) = \frac{gx}{2V^2}$$

By iterative solution, ϕ = 49°. So the ramp angle = 55° - 49° = 6°.

The ramp height (Δ) was set at 10 inches (about 0.2 y_o, at Q = 5,000 ft^3/s). For Δ = 10 inches, and the ramp angle = 6°, the ramp length = 8 feet. This height feathers out to zero at the springline to prevent fins in the vertical bend during the high flows.

The air vent size can be calculated from equation (4). When the tunnel is one-half full, Q = 20,000 ft^3/s the velocity is 93 ft/s, WP = B = 34 feet, Q = 49°, S_o = 1.428 Q_a = 4,621 ft^3/s.

ϕ

For an air velocity of 300 ft/s, the air slot would be 2.8 x 2.8 ft. Therefore, a 3- by 3-ft slot was recommended. The downstream edge of the slot was offset 8 inches from the original tunnel line to prevent the slot from filling with water. A 1:15 chamfer was used downstream from the slot to bring the profile back to the original line. Figure 4 is a sketch of the air slot designed for Blue Mesa.

The design of the air slot is based on developments made over the past few years by Henry Falvey (1530A) and from model studies of Yellowtail and Glen Canyon air slots.

The air slot design described above was tested in the hydraulic model. Before the air slot was installed, the model was tested without an air slot. Flow profiles and pressures were measured for a range of flows through the tunnel. Flow converging through the radial gates caused a large fin down the center of the tunnel for low flows. When the air slot was installed, the size of the fin was reduced and downstream flow conditions improved. Figure 5 is an example of a pressure profile through the tunnel before and after the air slot was installed.

Air demand was measured in the model by measuring the maximum air velocity in the slot (at the water surface) and multiplying by the area of the slot. Figure 6 shows the air demand. This air demand is not as high as predicted by equation (4). This may be because the ramp tapers to nothing at the springline. The exact air velocity is not critical when the air vent does not restrict the airflow. It is reasonable to make the vent size conservative until a better method is available to predict air demand.

Air was completely entrained in the flow surfaces downstream from the slot in the model. The air stayed in the flow through the vertical bend. The maximum measured amount of air drawn in (Q_a/Q) was 10 percent. However, the air was concentrated along the surface of the nappe making the air concentration much higher close to the tunnel surface.

One concern in installing air slots is that the additional air will cause bulking that could reduce the flow capacity of the tunnel. However, it was determined during the model study that the bulking was essentially the same before and after the air slot was installed. The relatively large model (scale 1:21.913) should give a fairly accurate representation of friction and air entrainment. Computer simulations before the model was built indicated that the smooth acrylic pipe should accurately scale prototype friction at this scale without reducing the pipe length.

Before the air slot was installed, air started entraining from the flow surface downstream from the vertical bend. At the tunnel flip bucket, the flow was essentially fully aerated. After the air slot was installed, the flow appeared aerated downstream from the air slot. The depth of the air-water mixture was essentially the same at the flip bucket as it was before the air slot was installed.

The original model study of Blue Mesa [4] (1964) predicted that the tunnel would be 80 percent full at the portal ($Q = 33{,}700\ ft^3/s$). However, this study did not include the downstream tunnel and did not simulate bulking because it was assumed that the relative friction in the model would be too high.

The present model study indicates that the tunnel will flow 95 to 98 percent full at the portal, with or without the air slot installed ($Q = 33{,}400\ ft^3/s$).

CONCLUSION

The study of cavitation and prevention of cavitation damage is progressing rapidly. As more information becomes available and new procedures are introduced, the procedures used in this memorandum will be updated.

REFERENCES

1. Falvey, H. T., "Prevention of Cavitation on Chutes and Spillways," Proccedings of the Conference on Frontiers in Hydraulic Engineering, ASCE, Cambridge, Mass. August 9-12, 1983.

2. Falvey, H. T., "Cavitation in Spillways, Part Two - Aeration Groove Design for Cavitation Protection," unpublished, 1984.

3. Shi-bo, Pan, "Self-Aeration Capacity of a Water Jet Over an Aeration Ramp," Water Conservancy and Hydroelectric Power Research Institute, USBR Translation No. 1868, translated from the Peoples Republic of China Journal of Hydraulic Engineering.

4. Beichley, G. L., "Hydraulic Model Studies of Blue Mesa Dam Spillway," Report No. Hyd-515, July 1964.

NOTATIONS

B - width of chute
y_o - water depth (normal to flow surface)
K - cavitation index
p_o - pressure
p_v - vapor pressure
V - velocity
S_o - slope of chute or tunnel
g - gravitational constant
X - horizontal distance
y - vertical distance
Q_a - air discharge
Q - water discharge

Δ - ramp height
ρ - water density
ϕ - vertical angle between the ramp and horizontal.

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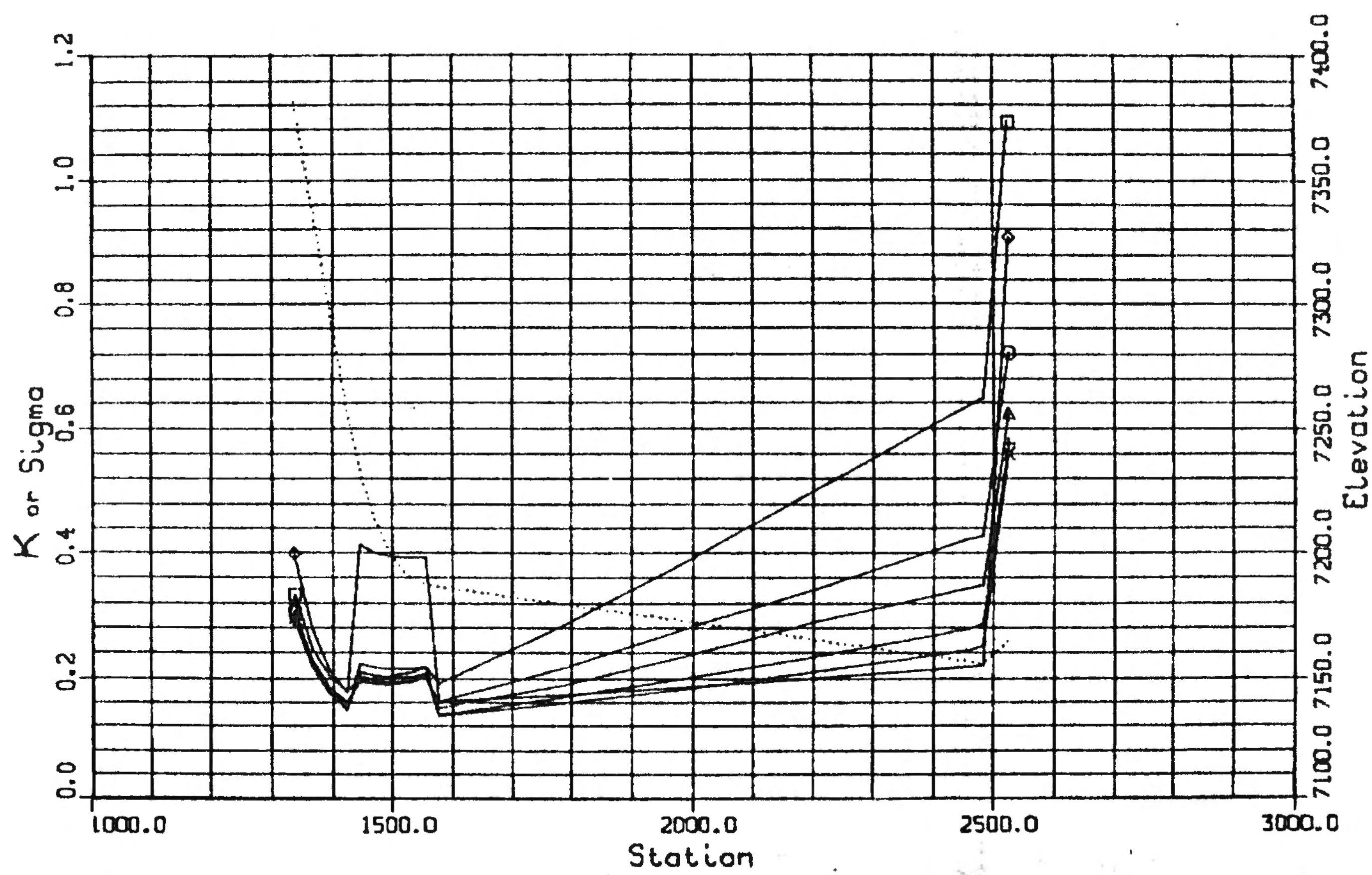
Attachments

Copy to: D-1530
✓D-1531
D-1532
D-1530A

BLUE MESA DAM SPILLWAY



Figure

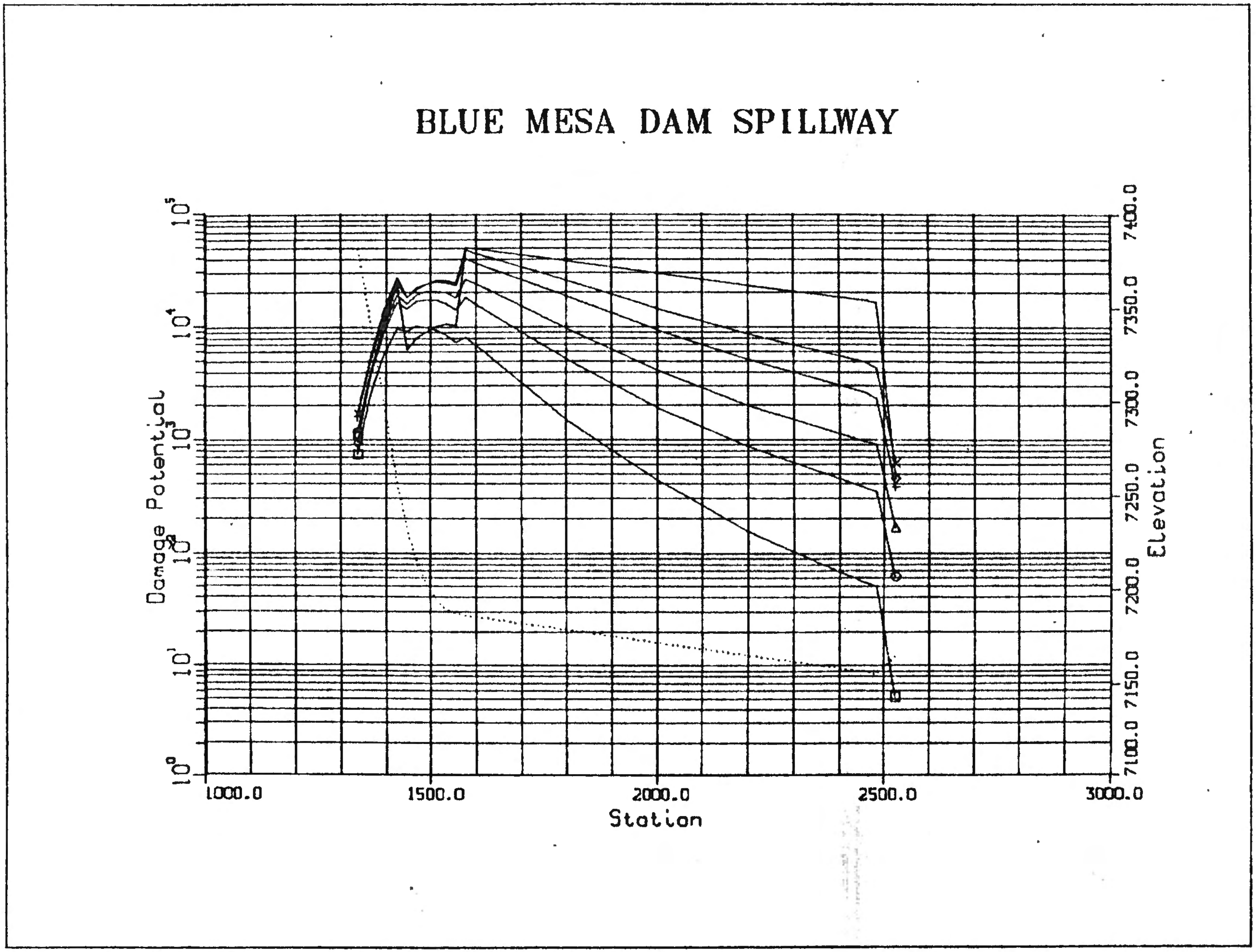

BLUE MESA DAM SPILLWAY
Damage Potential
Elevation
Station
1000.0
1500.0
2000.0
2500.0
3000.0
7100.0
7150.0
7200.0
7250.0
7300.0
7350.0
7400.0

Figure 2

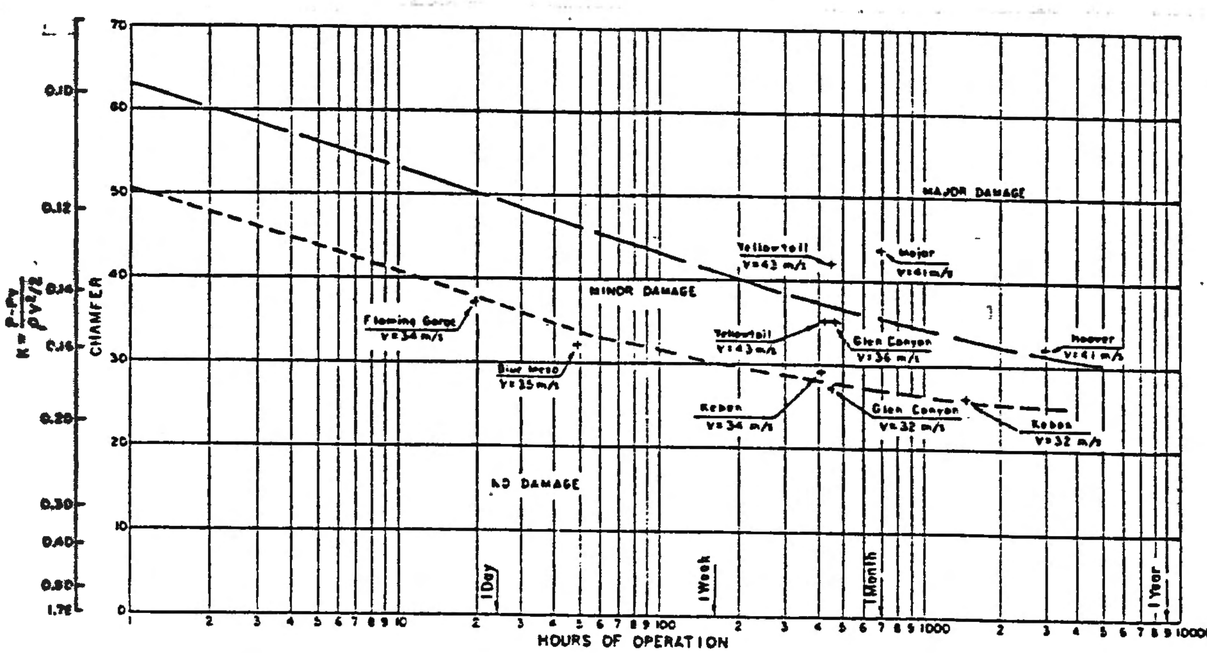
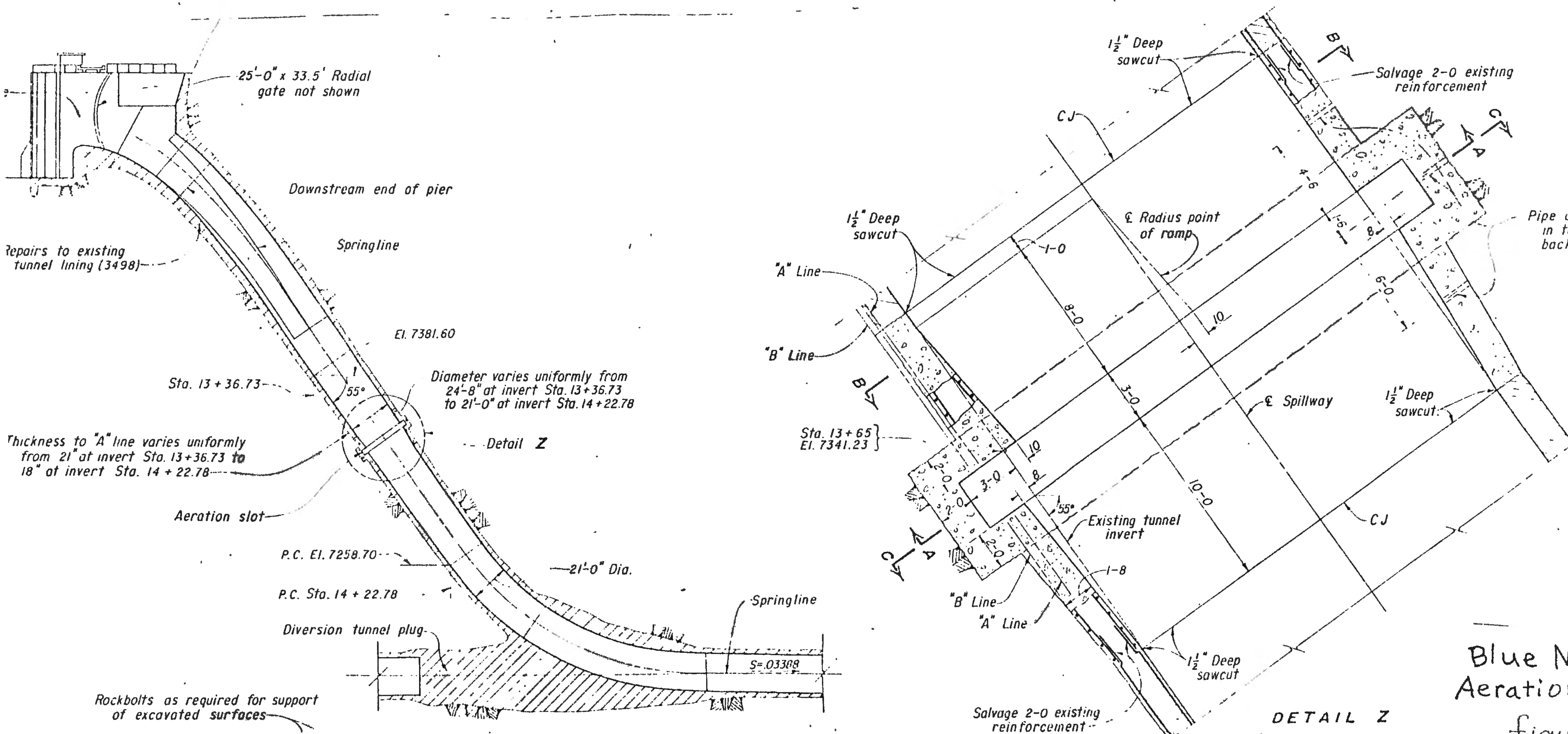
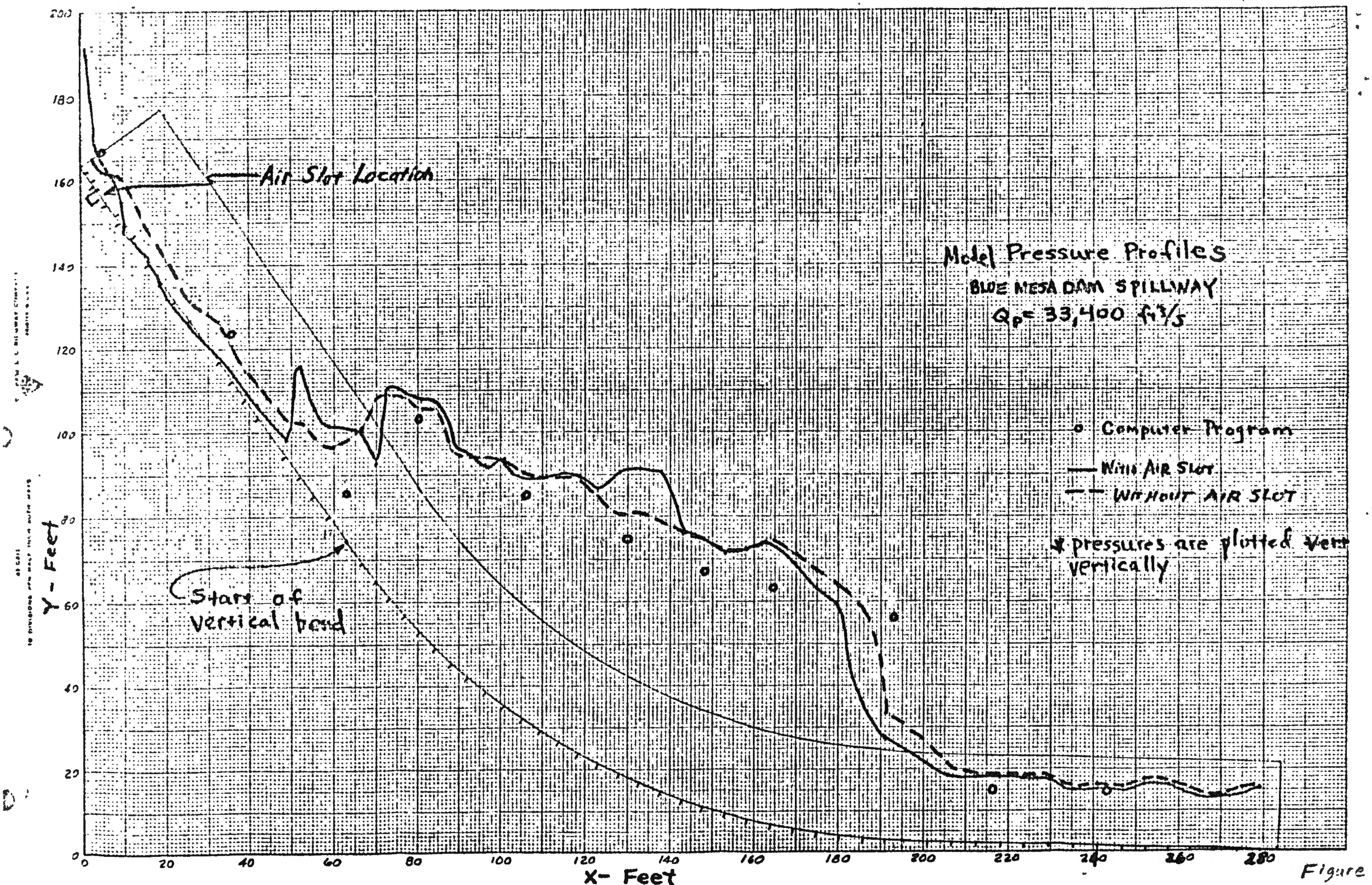


Figure 3. Cavitation Damage in Spillways and Chutes



Blue Mesa
Aeration Slo
figure 4



Air Slot Location
Model Pressure Profiles
BLUE MESA DAM SPILLWAY
Q_p = 33,400 ft³/s
o Computer Program
With Air Slot
Without Air Slot
* pressures are plotted vertically
Start of vertical bend
Y - Feet
X - Feet

Figure 5

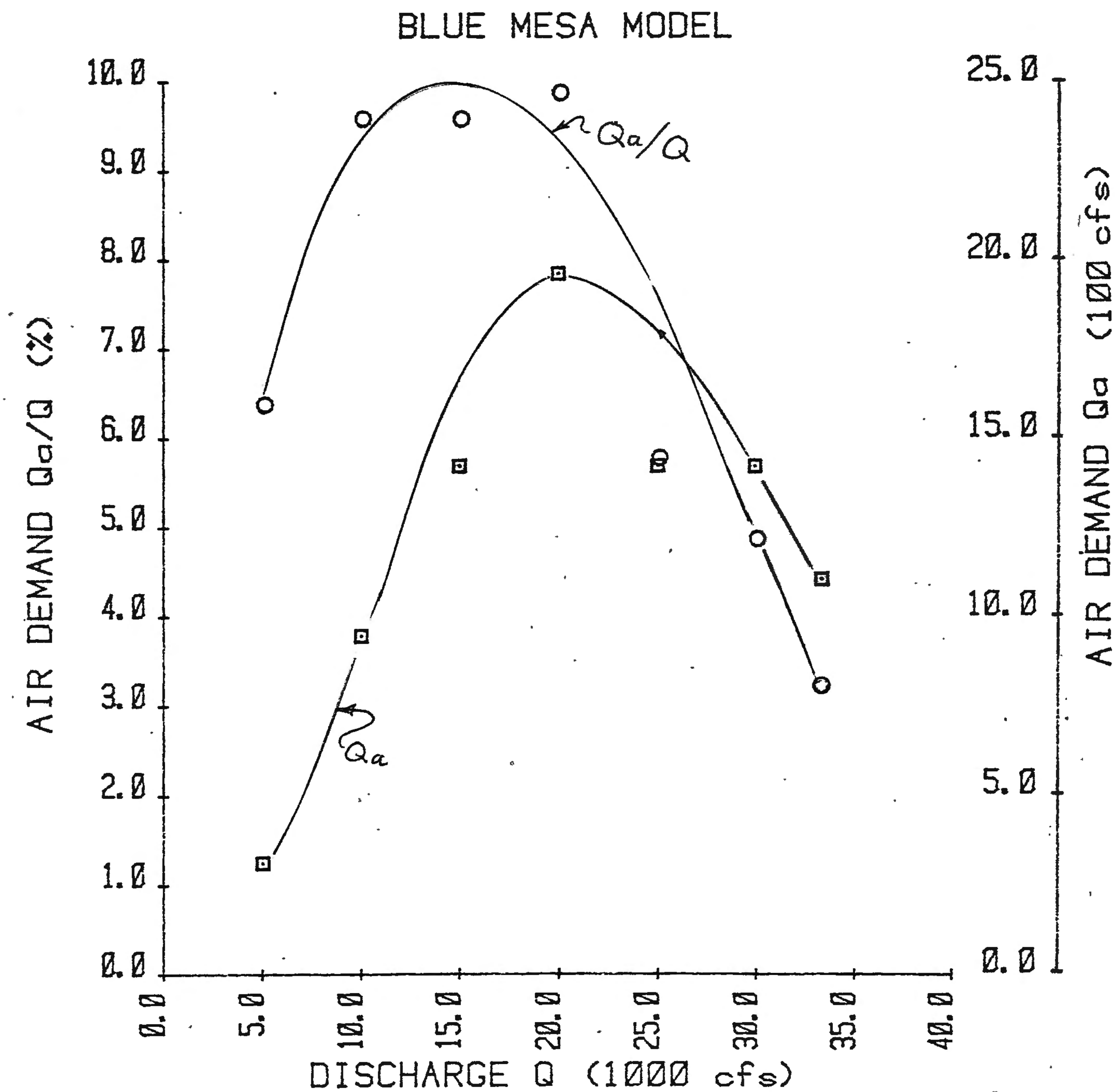

BLUE MESA MODEL
AIR DEMAND Qa/Q (%)
AIR DEMAND Qa (100 cfs)
DISCHARGE Q (1000 cfs)
Qa/Q
Qa
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0

figure 6

BLUE MESA DAM SPILLWAY

Q = 2000.0 CFS   INITIAL DEPTH = 2.66 FT   RUGOSITY = .001000 FT   N = .0118

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1336.7	7381.60	1.4282	2.660	72.003	1.526	7464.248	0.000	S2	1.789	9.897	.737
FLOW SIGMA = .334 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .021 IN 1 TO 12 CHAMFERS REQUIRED DAMAGE POTENTIAL = .741E+03											
AIR SLOT 1365											
1365.4	7340.64	1.4282	2.448	83.572	1.404	7451.329	0.000	S2	1.814	10.051	1.121
FLOW SIGMA = .247 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .010 IN 1 TO 18 CHAMFERS REQUIRED DAMAGE POTENTIAL = .258E+04											
1394.1	7299.67	1.4280	2.338	91.961	1.341	7435.082	0.000	S2	1.840	10.218	1.448
FLOW SIGMA = .204 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN 1 TO 23 CHAMFERS REQUIRED DAMAGE POTENTIAL = .569E+04											
1422.8	7258.70	1.4285	2.280	98.368	1.307	7416.025	0.000	S2	1.868	10.398	1.746
FLOW SIGMA = .178 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .005 IN 1 TO 28 CHAMFERS REQUIRED DAMAGE POTENTIAL = .987E+04											
1444.0	7233.92	1.1678	2.256	99.897	5.873	7403.847	0.000	S2	1.903	10.252	1.933
FLOW SIGMA = .203 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 23 CHAMFERS REQUIRED DAMAGE POTENTIAL = .936E+04											
1467.0	7215.42	.8043	2.236	101.194	6.286	7392.388	0.000	S2	1.994	9.771	2.096
FLOW SIGMA = .200 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 24 CHAMFERS REQUIRED DAMAGE POTENTIAL = .102E+05											
1488.0	7203.46	.5695	2.237	101.153	6.546	7382.844	0.000	S2	2.113	9.493	2.227
FLOW SIGMA = .202 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 23 CHAMFERS REQUIRED DAMAGE POTENTIAL = .101E+05											
1510.0	7194.80	.3936	2.248	100.421	6.697	7373.604	0.000	S3	2.275	9.320	2.248
FLOW SIGMA = .206 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 23 CHAMFERS REQUIRED DAMAGE POTENTIAL = .944E+04											
1532.0	7189.48	.2418	2.264	99.394	6.747	7364.972	0.000	S3	2.538	9.214	2.264
FLOW SIGMA = .211 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 22 CHAMFERS REQUIRED DAMAGE POTENTIAL = .864E+04											

APPENDIX 1

BLUE MESA DAM SPILLWAY

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1554.7	7187.16	.1022	2.292	97.604	6.720	7356.600	0.000	S3	3.126	9.158	2.292
FLOW SIGMA = .218 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .009 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .744E+04											
1577.0	7186.40	.0341	2.305	96.789	2.304	7348.720	.315	S3	4.117	8.992	2.305
FLOW SIGMA = .192 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN 1 TO 25 CHAMFERS REQUIRED DAMAGE POTENTIAL = .820E+04											
1600.0	7185.63	.0335	2.341	94.631	2.339	7340.926	.275	S3	4.136	8.992	2.341
FLOW SIGMA = .201 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 24 CHAMFERS REQUIRED DAMAGE POTENTIAL = .680E+04											
1800.0	7178.85	.0339	2.648	79.030	2.646	7288.179	.001	S3	4.123	8.993	2.648
FLOW SIGMA = .291 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .024 IN 1 TO 14 CHAMFERS REQUIRED DAMAGE POTENTIAL = .150E+04											
2000.0	7172.07	.0339	2.924	68.396	2.922	7254.897	0.000	S3	4.123	8.993	2.924
FLOW SIGMA = .393 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .063 IN 1 TO 9 CHAMFERS REQUIRED DAMAGE POTENTIAL = .434E+03											
2200.0	7165.30	.0339	3.167	60.912	3.165	7231.839	0.000	S3	4.125	8.992	3.167
FLOW SIGMA = .499 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .136 IN 1 TO 7 CHAMFERS REQUIRED DAMAGE POTENTIAL = .157E+03											
2460.0	7156.49	.0339	3.433	54.196	3.431	7210.090	0.000	S3	4.124	8.993	3.433
FLOW SIGMA = .637 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .295 IN 1 TO 5 CHAMFERS REQUIRED DAMAGE POTENTIAL = .543E+02											
2484.2	7155.67	.0339	3.454	53.719	3.452	7208.412	0.000	S3	4.122	8.993	3.454
FLOW SIGMA = .649 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .313 IN 1 TO 5 CHAMFERS REQUIRED DAMAGE POTENTIAL = .500E+02											
2525.0	7164.71	-.2214	3.979	43.826	6.993	7204.510	0.000	A3	-1000.000	9.358	3.645
FLOW SIGMA = 1.093 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN 1.520 IN 1 TO 3 CHAMFERS REQUIRED DAMAGE POTENTIAL = .526E+01											

BLUE MESA DAM SPILLWAY

Q = 3500.0 CFS INITIAL DEPTH = 3.76 FT RUGOSITY = .001000 FT N = .0120

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1336.7	7381.60	1.4282	3.760	76.083	2.157	7473.981	0.000	S2	2.350	13.262	.729
	FLOW SIGMA = .306 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .016 IN 1 TO 13 CHAMFERS REQUIRED DAMAGE POTENTIAL = .115E+04										
1365.4	7340.64	1.4282	3.467	87.999	1.989	7463.326	0.000	S2	2.383	13.471	1.109
	FLOW SIGMA = .228 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 20 CHAMFERS REQUIRED DAMAGE POTENTIAL = .387E+04										
1394.1	7299.67	1.4280	3.301	97.320	1.893	7450.136	0.000	S2	2.419	13.690	1.433
	FLOW SIGMA = .186 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .005 IN 1 TO 26 CHAMFERS REQUIRED DAMAGE POTENTIAL = .888E+04										
1422.8	7258.70	1.4285	3.202	104.898	1.836	7434.618	0.000	S2	2.458	13.923	1.727
	FLOW SIGMA = .160 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .003 IN 1 TO 32 CHAMFERS REQUIRED DAMAGE POTENTIAL = .164E+05										
1444.0	7233.92	1.1678	3.163	106.806	8.921	7425.127	0.000	S2	2.504	13.788	1.911
	FLOW SIGMA = .195 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN 1 TO 25 CHAMFERS REQUIRED DAMAGE POTENTIAL = .146E+05										
1467.0	7215.42	.8043	3.119	108.974	9.528	7416.076	0.000	S2	2.626	13.147	2.071
	FLOW SIGMA = .190 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN 1 TO 25 CHAMFERS REQUIRED DAMAGE POTENTIAL = .169E+05										
1488.0	7203.46	.5695	3.105	109.677	9.908	7408.392	0.000	S2	2.784	12.776	2.200
	FLOW SIGMA = .190 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN 1 TO 25 CHAMFERS REQUIRED DAMAGE POTENTIAL = .176E+05										
1510.0	7194.80	.3936	3.107	109.598	10.136	7400.815	0.000	S2	3.000	12.547	2.324
	FLOW SIGMA = .191 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN 1 TO 25 CHAMFERS REQUIRED DAMAGE POTENTIAL = .173E+05										
1532.0	7189.48	.2418	3.124	108.751	10.247	7393.645	0.000	S3	3.352	12.403	2.440
	FLOW SIGMA = .195 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 24 CHAMFERS REQUIRED DAMAGE POTENTIAL = .162E+05										

BLUE MESA DAM SPILLWAY

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1554.7	7187.16	.1022	3.155	107.169	10.247	7386.633	0.000	S3	4.143	12.328	2.556
FLOW SIGMA = .201 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 24 CHAMFERS REQUIRED DAMAGE POTENTIAL = .143E+05											
1577.0	7186.40	.0341	3.154	107.258	3.152	7379.914	.007	S3	5.492	12.051	2.668
FLOW SIGMA = .161 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .004 IN 1 TO 32 CHAMFERS REQUIRED DAMAGE POTENTIAL = .185E+05											
1600.0	7185.63	.0335	3.195	105.251	3.193	7373.148	0.000	S3	5.519	12.051	2.782
FLOW SIGMA = .167 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .005 IN 1 TO 30 CHAMFERS REQUIRED DAMAGE POTENTIAL = .158E+05											
1800.0	7178.85	.0339	3.499	92.270	3.497	7324.572	0.000	S3	5.501	12.051	3.499
FLOW SIGMA = .220 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .012 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .526E+04											
2000.0	7172.07	.0339	3.803	81.853	3.800	7290.310	0.000	S3	5.501	12.052	3.803
FLOW SIGMA = .283 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .026 IN 1 TO 15 CHAMFERS REQUIRED DAMAGE POTENTIAL = .191E+04											
2200.0	7165.30	.0339	4.050	74.756	4.048	7264.804	0.000	S3	5.503	12.050	4.050
FLOW SIGMA = .342 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .048 IN 1 TO 11 CHAMFERS REQUIRED DAMAGE POTENTIAL = .881E+03											
2460.0	7156.49	.0339	4.339	67.736	4.337	7239.195	0.000	S3	5.502	12.051	4.339
FLOW SIGMA = .420 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .092 IN 1 TO 9 CHAMFERS REQUIRED DAMAGE POTENTIAL = .374E+03											
2484.2	7155.67	.0339	4.364	67.197	4.361	7237.157	0.000	S3	5.499	12.052	4.364
FLOW SIGMA = .428 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .097 IN 1 TO 8 CHAMFERS REQUIRED DAMAGE POTENTIAL = .349E+03											
2525.0	7164.71	-.2214	4.877	57.357	11.288	7232.189	0.000	A3	-1000.000	12.715	4.545
FLOW SIGMA = .722 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .461 IN 1 TO 4 CHAMFERS REQUIRED DAMAGE POTENTIAL = .622E+02											

BLUE MESA DAM SPILLWAY

Q = 5000.0 CFS INITIAL DEPTH = 4.80 FT RUGOSITY = .001000 FT N = .0122

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1336.7	7381.60	1.4282	4.800	76.440	2.753	7475.293	0.000	S2	2.800	15.974	.728
	FLOW SIGMA = .310	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .016 IN	1 TO 13 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .116E+04							
1365.4	7340.64	1.4282	4.408	88.891	2.528	7466.147	0.000	S2	2.841	16.205	1.107
	FLOW SIGMA = .228	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN	1 TO 20 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .412E+04							
1394.1	7299.67	1.4280	4.179	98.901	2.397	7454.912	0.000	S2	2.885	16.428	1.430
	FLOW SIGMA = .183	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .005 IN	1 TO 27 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .993E+04							
1422.8	7258.70	1.4285	4.039	107.238	2.316	7441.680	0.000	S2	2.932	16.619	1.723
	FLOW SIGMA = .156	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .003 IN	1 TO 34 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .192E+05							
1444.0	7233.92	1.1678	3.988	109.193	11.544	7433.974	0.000	S2	2.988	16.485	1.906
	FLOW SIGMA = .200	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN	1 TO 24 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .162E+05							
1467.0	7215.42	.8043	3.921	111.886	12.337	7426.583	0.000	S2	3.135	15.787	2.066
	FLOW SIGMA = .195	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN	1 TO 25 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .193E+05							
1488.0	7203.46	.5695	3.893	113.045	12.835	7420.239	0.000	S2	3.326	15.368	2.194
	FLOW SIGMA = .194	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN	1 TO 25 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .206E+05							
1510.0	7194.80	.3936	3.885	113.387	13.141	7413.918	0.000	S2	3.587	15.106	2.317
	FLOW SIGMA = .194	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN	1 TO 25 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .209E+05							
1532.0	7189.48	.2418	3.896	112.937	13.298	7407.875	0.000	S3	4.012	14.941	2.432
	FLOW SIGMA = .196	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .006 IN	1 TO 24 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .202E+05							

BLUE MESA DAM SPILLWAY

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1554.7	7187.16	.1022	3.925	111.737	13.316	7401.902	0.000	S3	4.974	14.853	2.547
	FLOW SIGMA = .201 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 24 CHAMFERS REQUIRED DAMAGE POTENTIAL = .184E+05										
1577.0	7186.40	.0341	3.900	112.768	3.897	7396.077	0.000	S3	6.635	14.497	2.658
	FLOW SIGMA = .149 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .003 IN 1 TO 36 CHAMFERS REQUIRED DAMAGE POTENTIAL = .270E+05										
1600.0	7185.63	.0335	3.941	111.094	3.938	7390.114	0.000	S3	6.667	14.497	2.771
	FLOW SIGMA = .154 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .004 IN 1 TO 34 CHAMFERS REQUIRED DAMAGE POTENTIAL = .239E+05										
1800.0	7178.85	.0339	4.244	99.907	4.241	7345.744	0.000	S3	6.645	14.498	3.687
	FLOW SIGMA = .192 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 25 CHAMFERS REQUIRED DAMAGE POTENTIAL = .986E+04										
2000.0	7172.07	.0339	4.559	90.177	4.557	7312.432	0.000	S3	6.645	14.498	4.559
	FLOW SIGMA = .239 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .017 IN 1 TO 18 CHAMFERS REQUIRED DAMAGE POTENTIAL = .417E+04										
2200.0	7165.30	.0339	4.848	82.643	4.845	7286.805	0.000	S3	6.648	14.498	4.848
	FLOW SIGMA = .287 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .030 IN 1 TO 14 CHAMFERS REQUIRED DAMAGE POTENTIAL = .199E+04										
2460.0	7156.49	.0339	5.141	76.051	5.138	7260.420	0.000	S3	6.646	14.498	5.141
	FLOW SIGMA = .342 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .053 IN 1 TO 11 CHAMFERS REQUIRED DAMAGE POTENTIAL = .973E+03										
2484.2	7155.67	.0339	5.167	75.526	5.164	7258.265	0.000	S3	6.643	14.498	5.167
	FLOW SIGMA = .347 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .055 IN 1 TO 11 CHAMFERS REQUIRED DAMAGE POTENTIAL = .917E+03										
2525.0	7164.71	-.2214	5.740	65.136	15.509	7252.687	0.000	A3	-1000.000	15.653	5.343
	FLOW SIGMA = .624 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .309 IN 1 TO 5 CHAMFERS REQUIRED DAMAGE POTENTIAL = .169E+03										

BLUE MESA DAM SPILLWAY

Q = 7500.0 CFS   INITIAL DEPTH = 6.20 FT   RUGOSITY = .001000 FT   N = .0124

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1336.7	7381.60	1.4282	6.200	79.684	3.556	7483.885	0.000	S2	3.423	19.547	.722
	FLOW SIGMA = .294	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .014 IN	1 TO 14 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .159E+04							
1365.4	7340.64	1.4282	5.717	92.058	3.279	7475.693	0.000	S2	3.474	19.662	1.098
	FLOW SIGMA = .218	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN	1 TO 21 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .534E+04							
1394.1	7299.67	1.4280	5.425	102.287	3.112	7465.846	0.000	S2	3.530	19.640	1.419
	FLOW SIGMA = .176	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .004 IN	1 TO 28 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .127E+05							
1422.8	7258.70	1.4285	5.242	111.012	3.006	7454.376	0.000	S2	3.592	19.399	1.710
	FLOW SIGMA = .149	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .003 IN	1 TO 36 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .249E+05							
1444.0	7233.92	1.1678	5.193	112.485	15.653	7448.136	0.000	S2	3.661	19.217	1.892
	FLOW SIGMA = .210	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN	1 TO 22 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .184E+05							
1467.0	7215.42	.8043	5.095	115.540	16.711	7442.172	0.000	S2	3.843	18.717	2.051
	FLOW SIGMA = .204	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN	1 TO 23 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .222E+05							
1488.0	7203.46	.5695	5.049	117.047	17.380	7437.020	0.000	S2	4.080	18.378	2.178
	FLOW SIGMA = .202	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN	1 TO 23 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .242E+05							
1510.0	7194.80	.3936	5.028	117.735	17.801	7431.849	0.000	S2	4.406	18.149	2.300
	FLOW SIGMA = .202	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN	1 TO 23 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .251E+05							
1532.0	7189.48	.2418	5.031	117.631	18.028	7426.865	0.000	S2	4.938	17.999	2.414
	FLOW SIGMA = .203	CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN	1 TO 23 CHAMFERS REQUIRED	DAMAGE POTENTIAL = .248E+05							

BLUE MESA DAM SPILLWAY

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1554.7	7187.16	.1022	5.057	116.785	18.073	7421.893	0.000	S3	6.151	17.918	2.529
FLOW SIGMA = .206 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 23 CHAMFERS REQUIRED DAMAGE POTENTIAL = .233E+05											
1577.0	7186.40	.0341	4.989	119.047	4.986	7416.954	0.000	S3	8.287	17.592	2.638
FLOW SIGMA = .139 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .003 IN 1 TO 39 CHAMFERS REQUIRED DAMAGE POTENTIAL = .405E+05											
1600.0	7185.63	.0335	5.029	117.705	5.026	7411.804	0.000	S3	8.329	17.592	2.750
FLOW SIGMA = .142 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .003 IN 1 TO 38 CHAMFERS REQUIRED DAMAGE POTENTIAL = .369E+05											
1800.0	7178.85	.0339	5.330	108.414	5.327	7372.141	0.000	S3	8.300	17.592	3.651
FLOW SIGMA = .169 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .005 IN 1 TO 30 CHAMFERS REQUIRED DAMAGE POTENTIAL = .186E+05											
2000.0	7172.07	.0339	5.645	100.028	5.641	7340.366	0.000	S3	8.300	17.595	4.513
FLOW SIGMA = .201 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .010 IN 1 TO 23 CHAMFERS REQUIRED DAMAGE POTENTIAL = .945E+04											
2200.0	7165.30	.0339	5.940	93.138	5.937	7314.546	0.000	S3	8.304	17.596	5.346
FLOW SIGMA = .234 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .017 IN 1 TO 19 CHAMFERS REQUIRED DAMAGE POTENTIAL = .517E+04											
2460.0	7156.49	.0339	6.287	86.074	6.283	7287.132	0.000	S3	8.302	17.595	6.287
FLOW SIGMA = .277 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .030 IN 1 TO 15 CHAMFERS REQUIRED DAMAGE POTENTIAL = .264E+04											
2484.2	7155.67	.0339	6.354	84.818	6.350	7284.900	0.000	S3	8.298	17.599	6.354
FLOW SIGMA = .286 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .033 IN 1 TO 14 CHAMFERS REQUIRED DAMAGE POTENTIAL = .233E+04											
2525.0	7164.71	-.2214	7.069	73.222	22.315	7278.603	0.000	A3	-1000.000	20.061	6.526
FLOW SIGMA = .576 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .254 IN 1 TO 6 CHAMFERS REQUIRED DAMAGE POTENTIAL = .386E+03											

BLUE MESA DAM SPILLWAY

Q = 10000.0 CFS   INITIAL DEPTH = 7.55 FT   RUGOSITY = .001000 FT   N = .0126

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1336.7	7381.60	1.4282	7.550	80.675	4.330	7487.085	0.000	S2	3.952	22.003	.721
FLOW SIGMA = .294 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .014 IN 1 TO 14 CHAMFERS REQUIRED DAMAGE POTENTIAL = .171E+04											
1365.4	7340.64	1.4282	6.959	93.185	3.991	7479.590	0.000	S2	4.013	21.726	1.096
FLOW SIGMA = .218 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .574E+04											
1394.1	7299.67	1.4280	6.599	103.653	3.785	7470.701	0.000	S2	4.081	21.198	1.416
FLOW SIGMA = .175 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .004 IN 1 TO 28 CHAMFERS REQUIRED DAMAGE POTENTIAL = .138E+05											
1422.8	7258.70	1.4285	6.370	112.681	3.653	7460.420	0.000	S2	4.155	20.432	1.706
FLOW SIGMA = .148 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .003 IN 1 TO 36 CHAMFERS REQUIRED DAMAGE POTENTIAL = .274E+05											
1444.0	7233.92	1.1678	6.332	113.623	19.339	7455.165	0.000	S2	4.235	20.249	1.887
FLOW SIGMA = .224 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 20 CHAMFERS REQUIRED DAMAGE POTENTIAL = .181E+05											
1467.0	7215.42	.8043	6.204	116.905	20.646	7450.166	0.000	S2	4.448	20.010	2.046
FLOW SIGMA = .218 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .221E+05											
1488.0	7203.46	.5695	6.139	118.627	21.477	7445.829	0.000	S2	4.727	19.831	2.173
FLOW SIGMA = .215 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .244E+05											
1510.0	7194.80	.3936	6.105	119.534	22.008	7441.457	0.000	S2	5.109	19.703	2.294
FLOW SIGMA = .214 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .257E+05											
1532.0	7189.48	.2418	6.101	119.651	22.303	7437.223	0.000	S2	5.737	19.617	2.408
FLOW SIGMA = .215 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .008 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .257E+05											

BLUE MESA DAM SPILLWAY

STATION FT	INVERT ELEV FT	SLOPE	DEPTH FT	VELOCITY FT/SEC	PIEZ FT	ENERGY GRADE LINE FT	Q AIR/Q WATER	PROFILE	DEPTH NORMAL FT	DEPTH CRITICAL FT	THICKNESS BOUNDARY LAYER FT
1554.7	7187.16	.1022	16.349	116.477	57.357	7455.645	0.000	S2	15.251	20.925	2.534
	FLOW SIGMA = .394 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .045 IN 1 TO 9 CHAMFERS REQUIRED DAMAGE POTENTIAL = .106E+05										
1577.0	7186.40	.0341	15.006	127.262	14.997	7453.486	0.000	M3	1000.000	20.986	2.642
	FLOW SIGMA = .161 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .004 IN 1 TO 32 CHAMFERS REQUIRED DAMAGE POTENTIAL = .513E+05										
1600.0	7185.63	.0335	15.058	126.783	15.050	7451.049	0.000	M3	1000.000	20.986	2.752
	FLOW SIGMA = .163 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .004 IN 1 TO 32 CHAMFERS REQUIRED DAMAGE POTENTIAL = .497E+05										
1800.0	7178.85	.0339	15.477	123.158	15.468	7430.629	0.000	M3	1000.000	20.986	3.631
	FLOW SIGMA = .174 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .005 IN 1 TO 29 CHAMFERS REQUIRED DAMAGE POTENTIAL = .387E+05										
2000.0	7172.07	.0339	15.916	119.651	15.907	7411.504	0.000	M3	1000.000	20.986	4.462
	FLOW SIGMA = .187 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .007 IN 1 TO 26 CHAMFERS REQUIRED DAMAGE POTENTIAL = .301E+05										
2200.0	7165.30	.0339	16.366	116.357	16.357	7393.541	0.000	M3	1000.000	20.986	5.259
	FLOW SIGMA = .200 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .010 IN 1 TO 24 CHAMFERS REQUIRED DAMAGE POTENTIAL = .236E+05										
2460.0	7156.49	.0339	16.965	112.410	16.955	7371.682	0.000	M3	1000.000	20.986	6.253
	FLOW SIGMA = .217 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .013 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .174E+05										
2484.2	7155.67	.0339	17.050	111.885	17.040	7369.732	0.000	M3	1000.000	20.986	6.345
	FLOW SIGMA = .219 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .014 IN 1 TO 21 CHAMFERS REQUIRED DAMAGE POTENTIAL = .167E+05										
2525.0	7164.71	-.2214	20.942	85.868	78.326	7359.112	0.000	A3	-1000.000	55.635	6.512
	FLOW SIGMA = .908 CAVITATION WILL OCCUR FOR OFFSETS GREATER THAN .822 IN 1 TO 3 CHAMFERS REQUIRED DAMAGE POTENTIAL = .458E+03										

STATION GEOMETRY FOR WATER SURFACE PROFILE PROGRAM
BLUE MESA DAM SPILLWAY

STA	INVERT ELEV	WIDTH OR R2	SIDE SLOPE	RADIUS	UPPER RADIUS	CL HEIGHT	LOWER RADIUS	WALL OR C2	RAD CURV
1336.73	7381.60			12.33					0.0
1365.41	7340.64			11.72					0.0
1394.10	7299.67			11.11					0.0
1422.78	7258.70			10.50					0.0
1444.00	7233.92			10.50					168.0
1467.00	7215.42			10.50					168.0
1488.00	7203.46			10.50					168.0
1510.00	7194.80			10.50					168.0
1532.00	7189.48			10.50					168.0
1554.71	7187.16			10.50					168.0
1577.00	7186.40			10.50					0.0
1600.00	7185.63			10.50					0.0
1800.00	7178.85			10.50					0.0
2000.00	7172.07			10.50					0.0
2200.00	7165.30			10.50					0.0
2460.00	7156.49			10.50					0.0
2484.16	7155.67			10.50					0.0
2525.00	7164.71	21.00			0.00	-1.00	10.50	0.00	84.0