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Hydraulic Model Study of Buckhorn RCC Replacement Dam
(H&S Project No. 3820)

by

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Introduction

The city of Wilson, North Carolina, has commissioned Hazen and Sawyer (H&S) to provide the design for a new roller-compacted concrete (RCC) dam to expand the water supply for the city. The new Buckhorn replacement dam will be 44 ft high and about 2500 ft long and will be constructed directly downstream from the existing earthfill dam. The stepped spillway section will be 30 ft high with a crest length of 420 ft and a probable maximum precipitation (PMP) discharge of 68,901 ft^3/s. The tailwater is very high at this site with submergence of the spillway crest expected at the PMP.

The low height of the stepped spillway, wide range of operating conditions, and high unit discharge and tailwater make it difficult to estimate the ability of the steps to dissipate energy. As a result, determining the required protection and/or stilling basin design downstream from the spillway would also be difficult. Reclamation's Water Resources Research Laboratory (WRRL) was contracted by the city to perform a sectional model of the proposed RCC stepped spillway for Buckhorn Dam.

Sectional Model

A 2-ft-wide sectional model, representing a 20-ft section of the 420-ft-long Buckhorn Dam spillway, was designed with a Froude scale of 1:10. The model included the upstream vertical face of the dam, the spillway crest (el. 148), 0.90:1 stepped downstream spillway slope and training walls, and a downstream horizontal apron (el. 118). The crest shape included a 1:1 upstream inclined face with transitional steps to the tangent point with the 0.90:1 downstream face [1]. The steps are 2 ft high for the remainder of the slope. The model included provisions to modify the upstream slope of the crest and the step height, and to add appurtenances to assist with stilling action [2] in the horizontal downstream toe. Tailwater was controlled by a downstream flap gate based upon data provided by H&S.

Purpose

The major objective of the model study was to ensure that the crest design would pass the PMP under the required maximum head of 12.5 ft. Additional modifications to the crest shape would be investigated to simplify field construction of the spillway crest. The stilling basin wall heights and performance were investigated to ensure design adequacy under the PMP. Also, the performance of the steps near the top of the crest under low flow conditions was studied.

Test Plan

The model was operated to determine the hydraulic performance of the spillway under the expected range of hydraulic conditions. H&S provided a spillway rating curve, flood frequency data, and routing results. A wide range of flows from the 2-year event to the PMP, with corresponding unit discharges of 3.5 and 164 $ft^3/s/ft$, were investigated and documented.

Model tests were performed to investigate:

- Discharge ratings for the initial and modified crest designs.
- Hydraulic performance of the spillway crest, stepped chute, and hydraulic jump characteristics for the initial and modified designs.
- Recommendations to improve the performance of the spillway design.

The discharge and tailwater ranges (in prototype values) investigated are shown in table 1.

Table 1. - Flood routing information and tailwater rating for the Buckhorn Dam spillway.

Flood Frequency	Peak Flow (ft^3/s) Outflow	Tailwater (ft)
0.00	0.00	0.00
2.00	1465.00	128.41
5.00	3475.00	131.62
10.00	4853.00	132.82
25.00	6324.00	134.64
50.00	8014.00	134.76
100.00	9719.00	135.56
500.00	12751.00	136.91
½ PMP	29805.00	141.78
3/4 PMP	48892.00	145.75
PMP	68901.00	149.05
1 1/4 PMP	86844.00	151.56

Results

1. The initial crest shape was based upon a design head, H_o, of 10 ft, associated with the 3/4 PMP flow rate. This crest design will pass the PMP under the required reservoir elevation with a 1:1 or 3:1 upstream sloping face, requiring 11.78 ft and 12.49 ft of head, respectively. The discharge coefficient at the PMP for the 1:1 sloping upstream face is 4.06. The 3:1 sloping approach reduces the crest efficiency as demonstrated by a reduced discharge coefficient of 3.72. Flow over the crest, at lower discharges including the 2- and 5-year events, springs off the top step of the crest. Therefore, the crest shape was redesigned to minimize the range of flows for which this occurs (figure 1a).

2. The final crest shape (figure 2) was based upon a design head, H_o, of 4 ft with a 2:1 upstream sloping face. This is about one-third of the head of the PMP (68,901 ft^3/s) and provides a much steeper flow profile. The final design will pass the PMP with a discharge coefficient of 4.0 and a head of about 11.89 ft which meets the required reservoir elevation. The flow follows the steps for the lower flows down to the 2-year event (Q = 1465 ft^3/s) (figure 1b). As the flow is decreased to 1000 ft^3/s, the jet again springs free of the steps.

3. The steep crest profile will produce a tendency for higher flow rates to spring free from the crest. Although the nappe stays attached at the PMP under the final crest design, it is recommended that the end piers be rounded. Rounded end piers will reduce end contraction that could introduce air to the crest and increase the tendency of the nappe to spring free from the crest at flows near the PMP.

4. The initially designed horizontal apron at the downstream toe of the dam does not produce adequate energy dissipation above the 500-year event. The hydraulic jump is submerged and a high velocity jet exits along the floor of the basin.

5. A 5-ft-high sill located 20 ft downstream from the dam toe is recommended to improve the flow velocities leaving the basin. This configuration performed well at the one-half PMP discharge with the formation of a well defined hydraulic jump (figure 3). Under the full PMP (figure 4), the sill location, which is further from the toe of the dam then the other arrangements investigated, changed flow conditions considerably. Under the PMP, the upstream velocities behind the sill were lower (about 4 ft/s or less) and the downstream surface waves were higher than lower flow rates investigated. The velocity seemed to diffuse better than the other designs that were investigated although the jet returns to the invert about 70 ft downstream from the toe of the dam with velocities ranging from about 4 ft/s to 6 ft/s.

6. The spillway wall height should follow the water surface profile of the PMP on the crest and down the slope until intersecting with the horizontal stilling basin wall at the height of the 100-year tailwater or 17.6 ft. Freeboard should be added as deemed necessary.

7. A sensitivity study was performed to determine the effect of submergence of the crest by the tailwater. Table 2 shows that at 1-1/4 PMP, increasing the tailwater depth by about 10 percent from 151.55 ft to 155 ft increases the upstream head to more than 14 ft and causes overtopping of the dam. An increase in tailwater depth of about 6 percent to 153.5 ft causes the required head to increase by less than 1 percent. Decreasing the tailwater depth by 10 percent to 148 ft decreases the required head by about 3 percent.

Table 2. Head required to pass the 1-1/4 PMP for varied tailwater conditions.

Discharge (ft^3/s)	Tailwater Elevation (ft)	Head above Crest (ft)
86841.5	148	13.655
86841.5	151.55	13.695
86841.5	153.5	13.815
86841.5	155	>14.00 (overtops dam)

Investigations

The following sections provide discussion of the hydraulic performance of the initial designs and subsequent modifications.

Stepped Crest Profile

Several modifications to the initially provided crest design were investigated. Each is discussed in the following sections.

Initial Design

The initial crest was designed to match the nappe profile for a design head of 10 ft with a 1:1 sloping upstream face [1]. The steps were designed to have the tips of the steps match the nappe profile. The step heights varied in the area of the nappe shape between the smooth apex of the crest and the tangent point with the 0.9:1 slope of the dam. The steps began 1.69 ft below the crest with two 1/2-ft-high steps, then two 1-ft-high steps followed by two 1.5-ft-high steps to transition down to the tangent point with the 0.9:1 slope 7.69 ft below the crest. The steps on the constant slope were 2 ft high.

For the initial crest shape with a 1:1 sloping upstream face, a discharge of 68,901 ft^3/s (PMP) was passed under a reservoir head of 11.78 ft with a discharge coefficient of 4.06. The discharge rating and coefficient curves are shown in figures 5 and 6 for the initial crest design. The downstream tailwater elevation exceeded the level of the crest by 1.07 ft. A decrease in the discharge coefficient was expected due to the crest submergence, but the flow depth over the crest was so large that the downstream water level did not influence the crest coefficient. The crest shape was more efficient than needed, therefore, it was assumed that modifications could be made to aid construction that could potentially reduce the crest efficiency.

The upstream slope of the crest was modified to a 3:1 sloping upstream by adding a new portion over the 1:1 sloping face without changing the downstream nappe profile. This produced a lower crest coefficient for the higher flow rates, but the crest structure still passed the required discharge at the PMP with a head of 12.49 ft and a discharge coefficient of 3.72 (figures 5 and 6). Both crest geometries passed the PMP under the maximum reservoir head requirement of 12.5 ft.

Observations of flow conditions over the steps revealed that the flow impinged upon the upper step and sprang free of the stepped surface under low flow conditions, including the 2-year (1465 ft^3/s) and 5-year (3475 ft^3/s) events (figure 1a). At higher flows, the jet thickness and head values more closely corresponding to the design head overrode the tendency for the jet to impinge and spring free. Poor flow conditions under low flow conditions has been a common problem for stepped spillways, but the client wanted to attempt to improve the flow conditions under this more common flow range. Impingement and springing free at low flows is generally solved by adding some intermediate smaller steps near the top of the crest. Intermediate steps were added along the nappe profile without success. The jet simply impinged and sprung free from the next downstream step each time. Another attempt to solve the impingement problem during low flows was to carry the smooth portion of the crest further downstream before beginning the steps. The upper steps were covered over, not exposing the first step until 7.7 ft below the crest. This also was unsuccessful.

Final Design

The profile shape for low flow rates and heads is much steeper than that associated with the PMP. It was determined that the only effective way to improve low flow conditions was to redesign and steepen the crest profile. Recent research has shown that crests may be designed for an "effective" head to design head ratio of three [3]. In this case, the effective head is approximately 12 ft (estimated head required to pass the PMP for the final design) and the design head would be 4 ft. Crest efficiency increases but the area of subatmospheric pressures and the tendency of the nappe to spring free from the crest limits the design head ratio.

The nappe profile computed using a design head of 4 ft corresponds to a low flow event. Plotting this profile over the initial crest profile revealed, as expected, a considerably steeper profile. The model was modified to the new crest profile with a 2:1 sloping upstream face. This moved the crest 3.2 ft downstream of the initial crest centerline with the 2:1 sloping approach intersecting the upstream vertical dam face at the same location as before to maintain desired stability.

Figures 7 and 8 show the discharge rating curve and discharge coefficient for the final crest shape. The rating curve for the final shape is similar to the curve developed for the initial crest shape with the 1:1 upstream face. This occurs as a result of combining the more efficient crest profile with the less efficient approach of the 2:1 upstream face. The head required to pass the PMP is 11.90 ft which meets the required criteria. The corresponding discharge coefficient is 4.0.

Observations of flow conditions with the final crest shape indicate that flow conditions are greatly improved for the lower flows down to the 2-year event ($Q = 1465$ ft^3/s). At this flow, the top surface of the jet does spray outward somewhat but the under side of the jet stays attached to the stepped profile (figure 1b). As flow is decreased to 1000 ft^3/s, the jet again springs free of the steps.

At the PMP the nappe stays attached, although the profile or thickness of the jet spreads out immediately downstream of the crest. To test the possibility of the nappe springing free at higher heads, a 2 by 4 piece of wood was placed vertically into the flow at the top of the crest. This test allowed air to be drawn underneath the flow nappe causing the jet to lift off the crest. This phenomenon could occur near square end piers on the spillway but should be limited in extent given the length of the crest. To help prevent this phenomena from occurring, it is recommended that the end piers are rounded or curved. The jet remained attached during tests at the one-half PMP flow rate.

In addition, the head required to pass the 1-1/4 PMP was investigated with tailwater elevations ranging from 148 ft to 155 ft (table 2) or no crest submergence to 7 ft of submergence. This sensitivity test showed minimal effect on the discharge rating with a decrease in crest submergence, but a reduction in the crest efficiency producing dam overtopping at a downstream tailwater elevation of 155 ft.

Energy Dissipation - Steps and Stilling Basin

The stepped spillway is only 30 ft high with a 0.9:1 downstream slope and 2-ft-high steps. The tailwater level submerges the crest and was suspected to cause problems with energy dissipation on the steps and in the stilling basin. The initial stilling basin design consisted of a 40-ft-long horizontal apron with no end sill. Two sill heights and locations were tested in addition to the initial design.

Initial Design

High tailwater affects the performance of the stepped spillway and the formation of the hydraulic jump throughout the range of flows. The initial design simply provided for a flat concrete-lined floor at the toe of the spillway slope with a proposed length of about 40 ft. No additional means of dissipating energy was expected to be necessary at the toe of the stepped spillway.

For relatively low flows, less than the 100-year, 9719 ft^3/s, event, the toe of the jump is located on the slope of the spillway above the floor of the basin. The hydraulic jump was well-formed with no high velocity jet impingement on the floor or exiting the basin. The hydraulic jump formed on the spillway slope and extended downstream for about 20 ft. For the 500-year event, the jump was contained within 30 ft from the toe of the dam. Energy dissipation continued to be excellent and the stepped spillway performed adequately. Between the 500- and one-half PMP events, at a discharge of about 20,000 ft^3/s, the hydraulic jump is submerged by the high tailwater levels. At the one-half, three-fourths, and full PMP flows, the high velocity jet dives down through the tailwater along the face of the spillway and sweeps out the end of the basin. The velocity for the concentrated jet exiting along the floor of the basin is 19 ft/s and 23 ft/s for the one-half and full PMP, respectively. A result of this is a return flow along the surface back into the stilling basin with an unstable oscillating flow along the surface. The stepped spillway loses efficiency under the high tailwater.

Stilling Basin Modifications

Adequate stilling action with an acceptable apron length were not achieved with the stepped spillway and downstream horizontal apron for flow rates exceeding the 500-year event. Therefore, various sill heights and locations were investigated to assist with energy dissipation.

Observation of flow rates above the 500-year event indicated that something was needed to force the jump. The high tailwater was causing poor stilling action in the basin and was likely to negatively influence any modification. Sill location and height was investigated beginning with a sill the same height and location downstream from the dam toe as the jet was thick at the PMP.

The sill configurations tested were:

- a 10-ft-high sill located 10 ft downstream from the dam toe
- a 5-ft-high sill located 10 ft downstream from the dam toe
- a 5-ft-high sill located 20 ft downstream from the dam toe

Comparisons of flow conditions with those of the horizontal apron alone showed basically no difference in basin performance with any of the sill options up until the hydraulic jump was entirely drowned by the tailwater for the discharge (20,000 ft^3/s) about halfway between the 500-year and one-half PMP events. Therefore, only the one-half and full PMP events were investigated and compared for each modification.

Ten-ft-high sill located 10 ft downstream from the dam toe - This configuration forced a good hydraulic jump for both the one-half and full PMP; however, the behavior was similar to that of a submerged roller bucket energy dissipater. The jet formed a boil on the surface, but dove back down to the riverbed about 100 ft downstream. The entire jet was initially diverted from the invert, but there were high upstream invert velocities behind the sill and a fairly intact surface jet downstream. The size of this sill is also somewhat unreasonable considering the size of the spillway and additional modifications were investigated.

Five-ft-high sill located 10 ft downstream from the dam toe - This configuration forced a good hydraulic jump for the one-half PMP where the jet thickness was about equal to the sill height and behaved quite similar to the 10-ft sill at this flow, but less turbulent on the surface with waves less than 2 ft in height. Under the PMP, the jet thickness exceeded the sill height and a significant portion of the jet returned to the invert about 40 ft below the dam toe. Upstream velocities occurred behind the sill, but the jet returned to the invert close enough to the dam that other options were investigated.

Five-ft-high sill located 20 ft downstream from the dam toe - This sill again performed well for the one-half PMP forming a hydraulic jump more similar to the 10-ft-high sill (figure 3). Under the full PMP, the location further from the toe of the dam changed the flow conditions considerably (figure 4). Compared to the 10-ft-high sill, the boil was reduced and less dissipation appeared to be taking place. Compared to the closer 5-ft-high sill, the jet returned to the invert farther downstream and with less strength. The downstream flow seemed more turbulent with less jet continuity than the previous sill arrangements. As a result, the upstream velocities behind the sill were lower (4 ft/s and less), the downstream surface waves were higher, but there was not a definitive return location in the riverbed. With the 5 ft sill located 20 ft downstream, the velocity seemed to diffuse more with depth. In addition, there is an economical advantage to this design over the 10 ft sill; therefore, it is the recommended design (figure 9).

Training Wall Height

Traditionally, stilling basin wall heights have contained the flow and tailwater elevations of the PMP. The high tailwater levels at this site would require stilling basin wall heights that exceed the height of the crest of the spillway. The client was interested in minimizing the height of the stilling basin training walls, as this would be a considerable cost savings. Therefore, the agreed upon objective was to contain the high velocity jet along the face of the spillway and reduce the horizontal wall height through the stilling basin to an acceptable value.

The model was used to determine the jet thickness down the face of the stepped spillway and the required wall heights along the spillway face by recording the water surface profiles for several flow rates. The flow depth associated with the PMP must be contained in the spillway. The coordinates defining the PMP profile are given in table 3.

Table 3. Final modified crest PMP water surface profile with coordinates referenced from the upstream face of the dam.

X (ft)	Y(ft)
0.00	159.89
6.00	157.90
8.00	157.40
10.00	156.80
12.00	156.10
14.00	155.20
16.00	154.10
18.00	152.80
20.00	151.30
21.40	149.80
33.68	140.55
39.18	135.55
41.18	133.95
45.88	130.55

The stilling basin wall height was reduced to elevation 135.6 ft or a height of 17.6 ft. This corresponded to the height of the tailwater for the 100-year event. Flow conditions were observed with the aid of ribbons attached to the top of the wall. The extremely high tailwater drowns out the hydraulic jump, therefore reducing the boiling and turbulence normally expected in the basin. Only minor surface waves overtop the walls for events greater than the 100-year event.

Observations at the PMP and one-half PMP indicate that there are no high velocities impacting the training walls, therefore the wall heights along the spillway and containing the stilling basin given in table 4 and shown in figures 4 and 9 should be adequate and are recommended for the final design. The wall heights do not include freeboard and a suitable safety factor should be added.

Table 4. Top of dam and training wall profile coordinates referenced from the upstream face of the dam.

X (ft)	Y (ft)
0.00	162.00
16.00	162.00
16.00	155.24
22.14	149.8
40.98	135.6
80.52	135.6

References

[1] *Design of Small Dams*, Third Edition, U.S. Department of the Interior, Bureau of Reclamation, Third Edition, Denver CO, 1987.

[2] Peterka, J., *Hydraulic Design of Stilling Basins and Energy Dissipators*, Engineering Monograph No. 25, U.S. Department of the Interior, Bureau of Reclamation, Denver CO, 1978.

[3] Vermeyen, T. B., *Hydraulic Model Study of Ritschard Dam Spillways*, Reclamation Report, R-91-08, U.S. Department of the Interior, Bureau of Reclamation, Denver CO, October 1991.

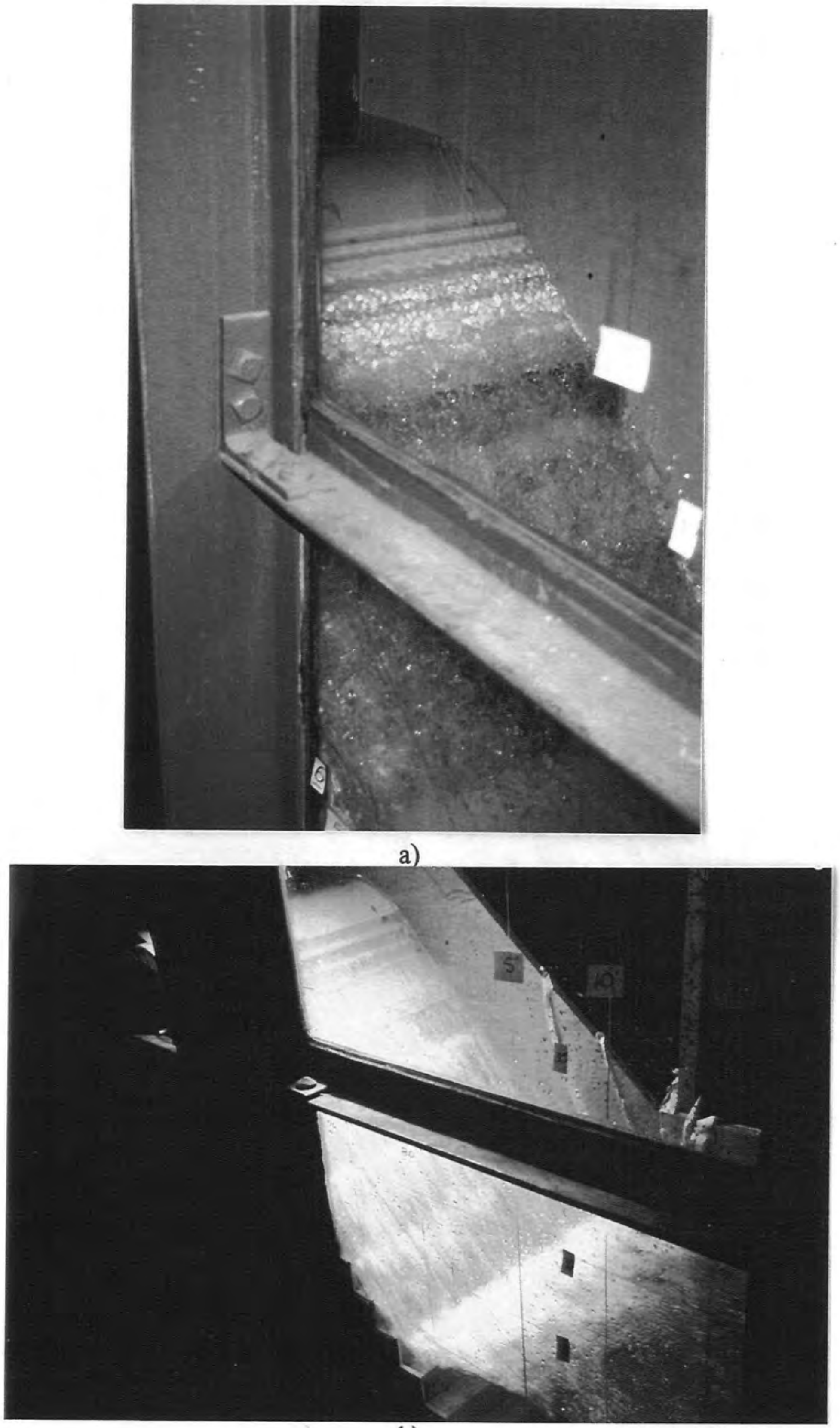

Figure 1. Flow over the crest during the 2-year event, Q=1465 ft^3/s for a) the initial crest shape with 3:1 sloping upstream face with the jet springing free from the stepped surface, and b) the final crest design with splashing, but not leaving the surface.

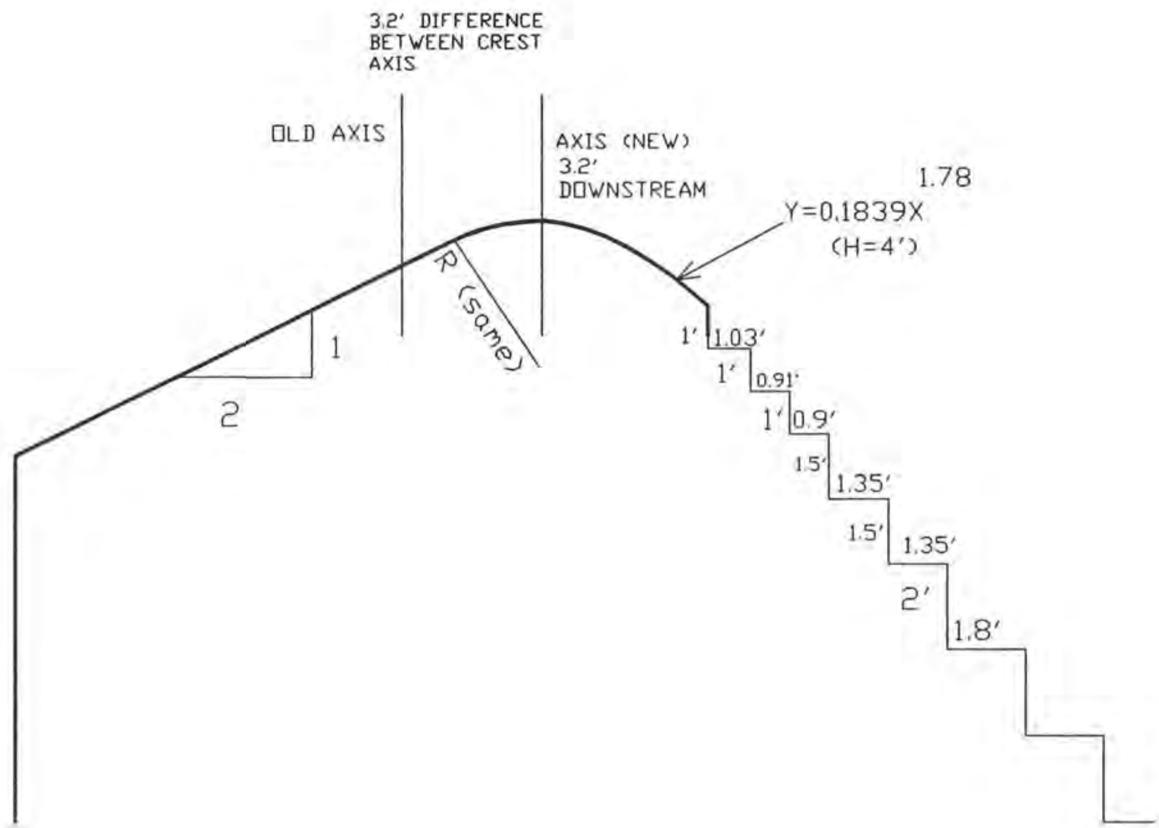

Figure 2. Buckhorn Dam crest and spillway final design.

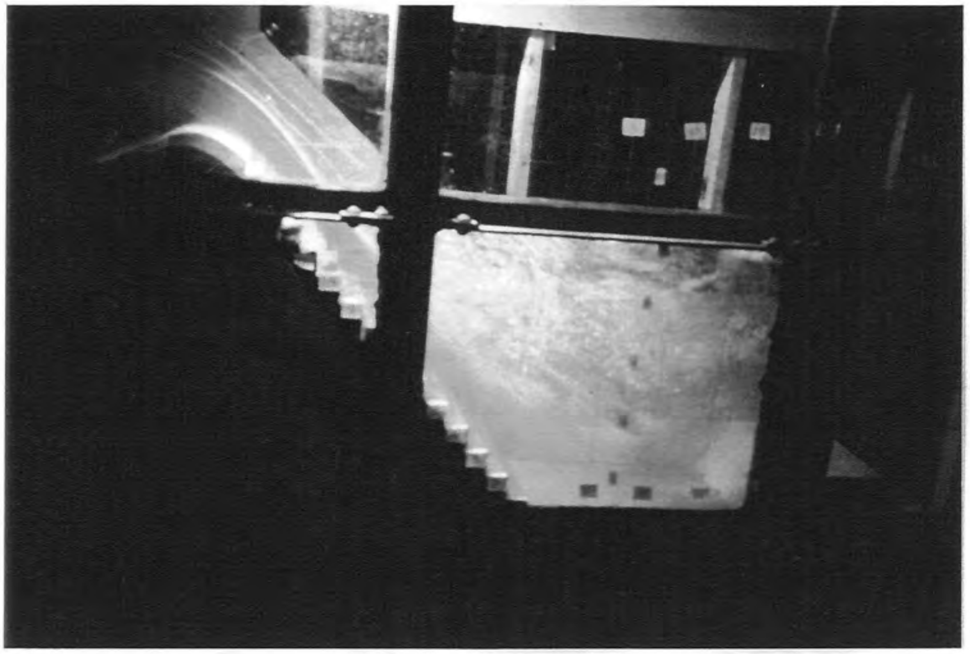

Figure 3. Flow conditions at the one-half PMP, Q=29,805 ft^3/s, for the final spillway and basin design.

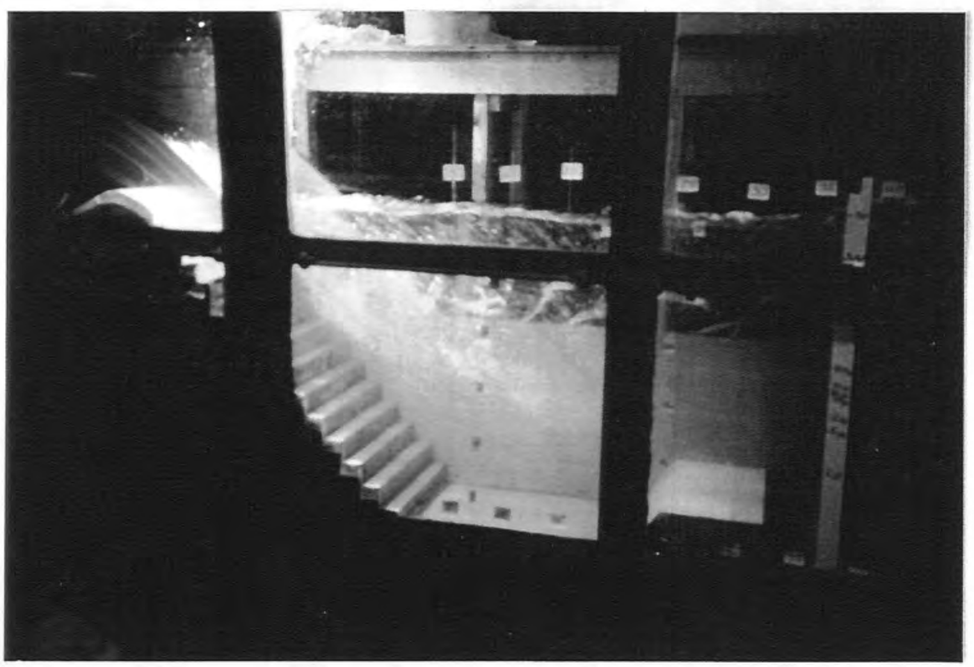

Figure 4. Flow conditions at the PMP, Q=68,901 ft^3/s, for the final spillway and basin design.

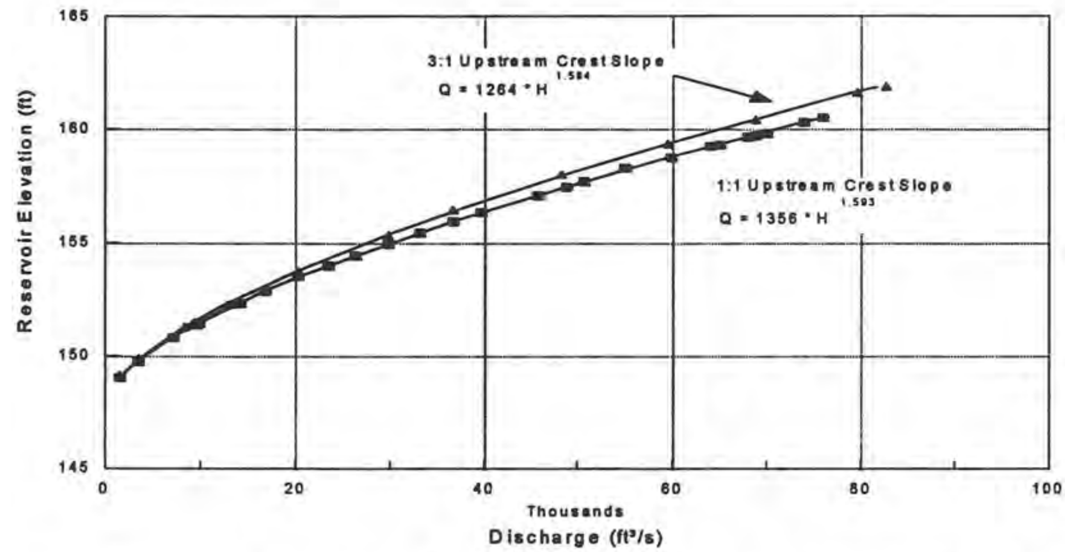

Figure 5. Discharge rating curves for the initial crest shape with 1:1 and 3:1 sloping upstream face.

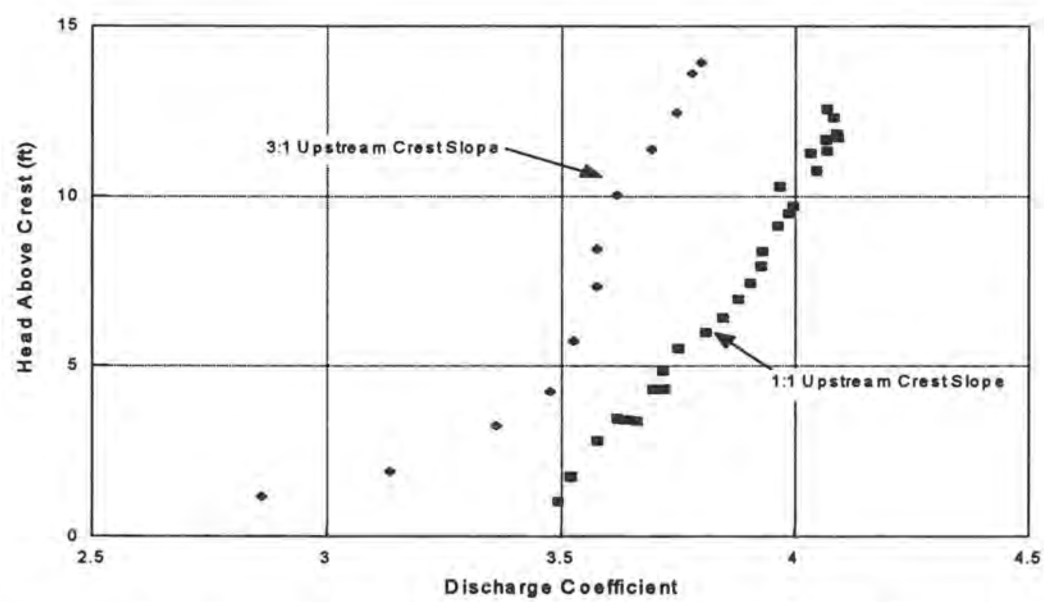

Figure 6. Discharge coefficients for the initial crest shape with 1:1 and 3:1 sloping upstream face.

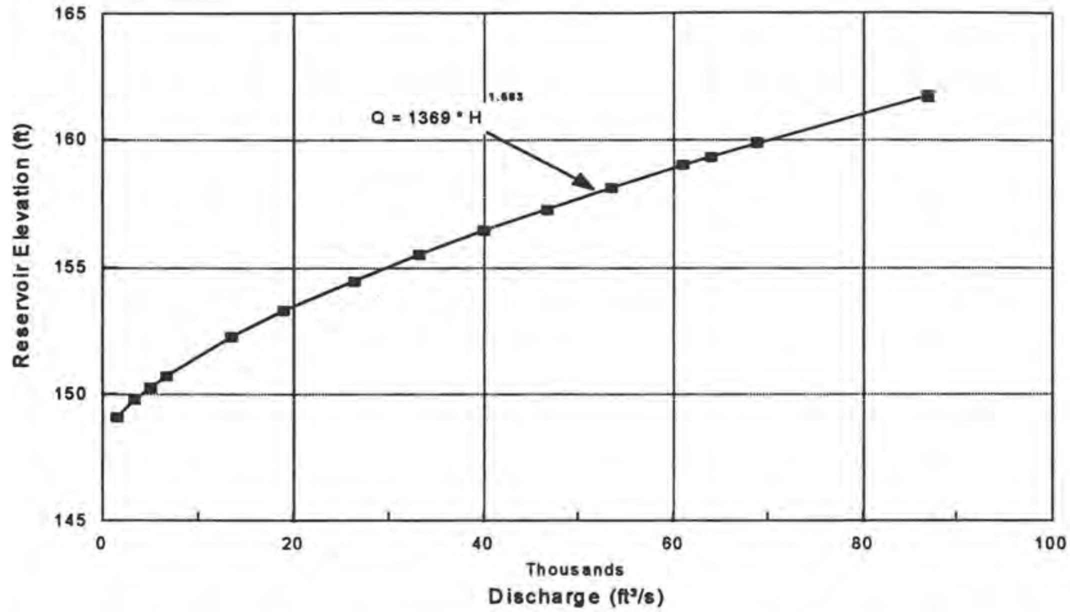

Figure 7. Discharge rating curve for the final crest design with 2:1 sloping upstream face.

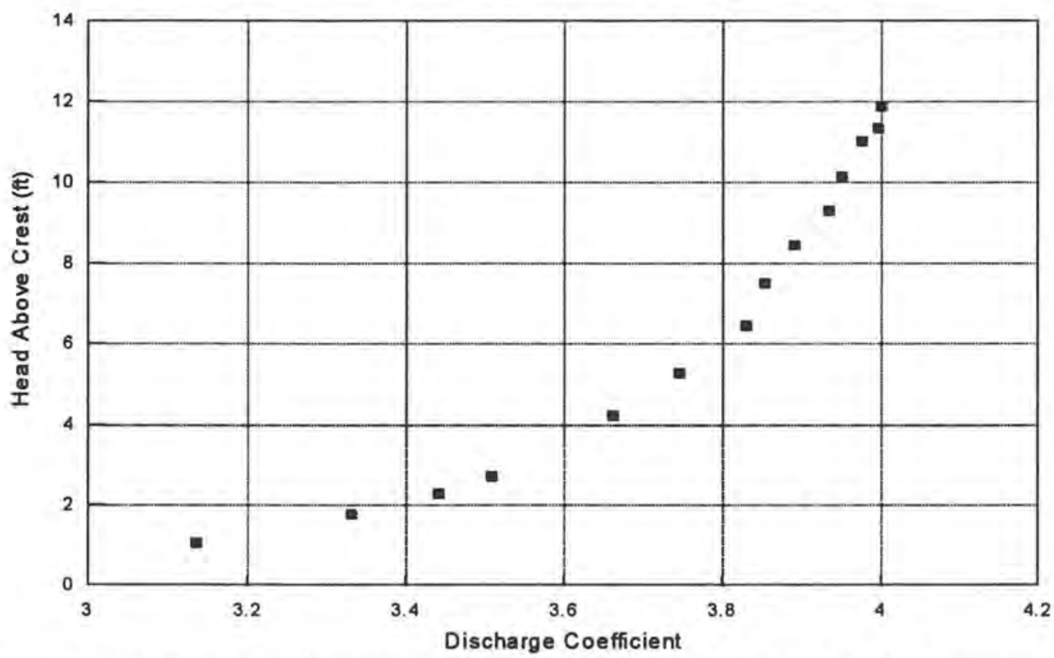

Figure 8. Discharge coefficients for the final crest design with 2:1 sloping upstream face.

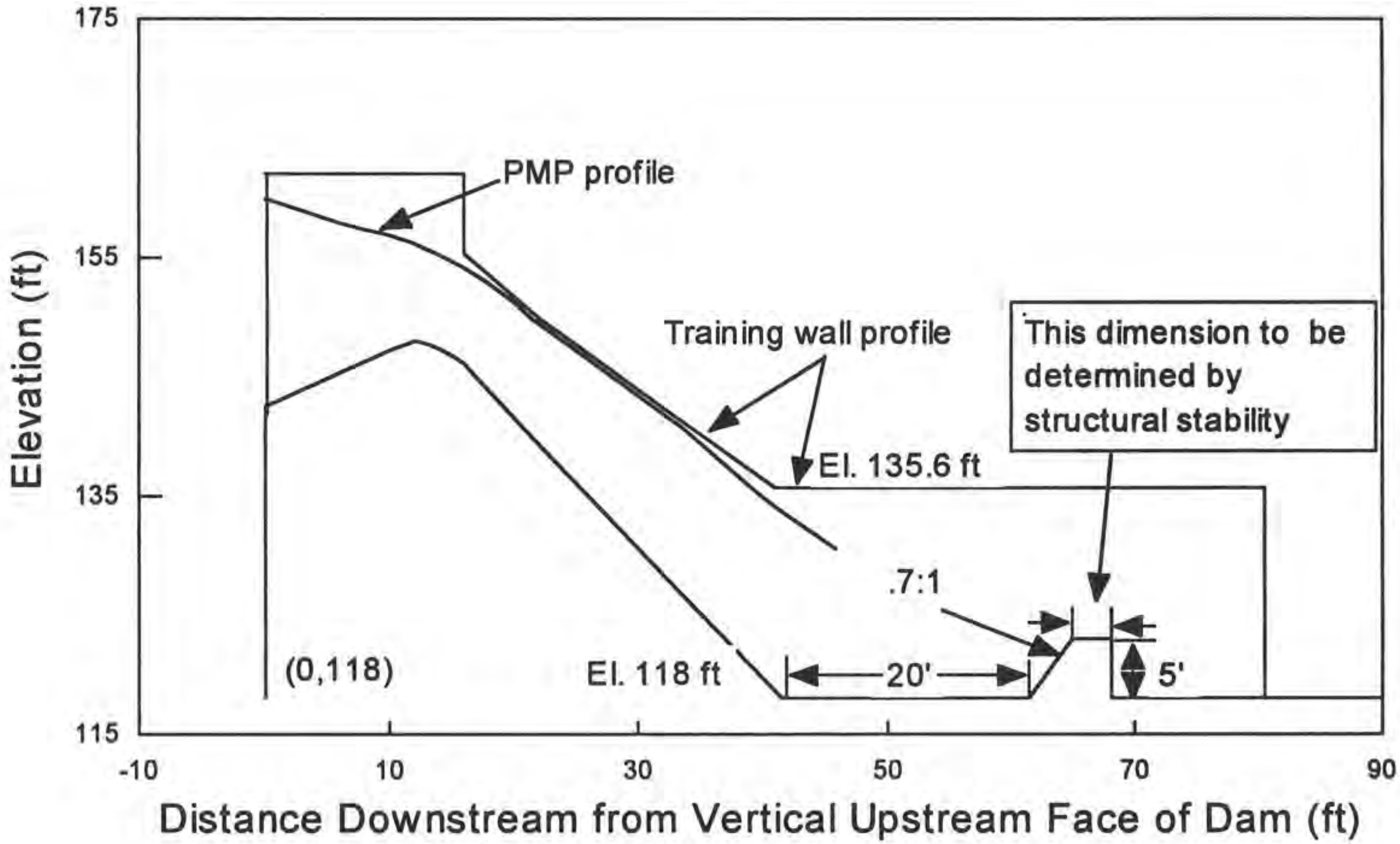

Figure 9. PMP profile and training wall final design without added freeboard, and end sill final design.