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HYDRAULIC MODEL STUDY OF THE SPILLWAY FOR RIDGWAY DAM, COLORADO

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16. ABSTRACT

A physical model having a scale of 30.46:1 was used to develop and verify the hydraulic design of a morning-glory spillway for Ridgway Dam, Colorado. This dam will have a height above the streambed of 227 feet (69.2 m), and the maximum discharge for its spillway will be 9,028 ft^3/s (256 m^3/s). Crest flow conditions were studied to ensure vortex-free operation, to develop a discharge rating curve, and to verify the establishment of satisfactory entrance flow conditions to the conduit. Numerous flow-improving devices were studied, including antivortex piers, antivortex conduit guide vanes, artivortex rock berms, tunnel deflectors, and raised crest sections. A crest treatment that included two piers and a raised crest section was found to most effectively control vortex formation, while establishing adequate conduit entrance conditions and maintaining a satisfactory coefficient of discharge. Air demand at the conduit crown air vent located below the deflector at the crest throat was found to be small, indicating that an air vent was not necessary. Pressures on the flow surfaces of the morning-glory crest, inclined shaft, and upper and lower vertical curves were found to be within safe limits. Flow conditions in both the conduit and stilling basin were satisfactory. Wave heights and bottom scour velocities in the channel downstream of the stilling basin were evaluated as a function of discharge. A maximum trough-to-crest wave height of 4.8 feet (1.5 m) and a maximum bottom scour velocity of 13.0 ft/s (4.0 m/s) occurred at the maximum design discharge.

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PURPOSE

These studies were made to verify and refine the hydraulic features of the design of a morning-glory spillway for Ridgway Dam, Colorado.

CONCLUSIONS

1. The preliminary spillway design (figs. 5 and 6) exhibited undesirable operating characteristics, including a potential for strong vortex formation (fig. 12), oscillating or rocking and cross-over flows in the conduit (fig. 16), and unsymmetrical stilling action with a potential to draw debris into the stilling basin (fig. 19).

2. Through the use of two piers and a raised segment of the crest (figs. 7 and 8), stable control of vortex formation for all discharges was obtained (fig. 14). This crest treatment also yielded acceptable entrance flow conditions at all discharges, which resulted in acceptable conduit flow conditions. The maximum design flood was passed at a reservoir elevation of 6879.35 feet (2096.83 m) (see fig. 15 for crest rating curve), which is below the original design maximum water surface elevation of 6879.9 (2097.0 m). Therefore, the modified crest has a higher coefficient of discharge than had been assumed and considered acceptable in the original crest design.

3. Air demand was minimal at the air vent in the upper vertical curve of the conduit (fig. 10) immediately below the deflector. This was true for all discharges, including the maximum design release, and for a wide range of air vent sizes and configurations (fig. 18). It was found that sufficient venting was occurring both from the crest above and from the spillway conduit below with air flowing upstream above the free water surface. Air demand and air pressures within the conduit indicated that no air vent was required. If it is considered desirable to include an air vent in the final design, an air vent diameter less than the originally proposed 2 feet would be adequate.

4. With the recommended crest treatment (figs. 7 and 8), satisfactory conduit flow conditions were obtained for all discharges, and no cross-over flows (those that pass over the conduit crown) were observed. Similarly, side-to-side rocking action in the flow as it passed down the conduit was minimized. The flow leaving the conduit and entering the stilling basin was evenly distributed and yielded uniform stilling action in the basin.

5. Pressures on the morning-glory crest and in the inclined conduit and in the upper and lower vertical curves of the conduit were found to be within safe limits of operation (fig. 17). Maximum

average subatmospheric pressures of –4 to –5 feet (−1.2 to −1.5 m) of water were observed on the crest between elevations 6869.0 and 6861.0 feet (2093.7 and 2091.2 m). With the maximum reservoir water surface at 6879.3 feet (2096.8 m) for the design discharge of 9,028 ft^3/s (256 m^3/s), the maximum available head on the flow at these locations is less than 20 feet (6.1 m) of water. There is insufficient energy in the flow to yield cavitation development. Average pressures that were slightly subatmospheric (although generally not more negative than −1 foot (−0.3 m) of water were observed down to elevation 6838.0 feet (2084.2 m), which is the beginning of the upper vertical curve. Approximately 41 feet (12.5 m) of total head is available in the flow at elevation 6838.0 feet (2084.2 m). This represents a total energy level that is marginal with respect to potential cavitation development. The pressures observed lower in the conduit were all substantially positive.

6. For typical morning-glory spillways, substantial turbulence and air entrainment occur in the flow as it drops through the vertical intake and as it is deflected by the upper vertical curve. Air entrained into the flow reduces both cavitation development and the potential damage that could result. However, with the design recommended, the piers and raised crest segment reduce the turbulence and air entrainment. Therefore, this design may have less protection against cavitation damage than the typical morning-glory spillway design. Conversely, the computer program analysis HFWS indicates that the potential for cavitation damage at Ridgway Dam spillway is minimal even with no air entrainment.

7. For the recommended crest configuration, the stilling action within the stilling basin was satisfactory for all discharges. Substantial wave action and higher velocity bottom flow occurred downstream of the stilling basin structure at the higher discharges (fig. 20). A maximum trough-to-crest wave height of 4.8 feet (1.5 m) and maximum instantaneous bottom flow velocity of 13.0 ft/s (4.0 m/s) were noted at the maximum design discharge of 9,028 ft^3/s (256 m^3/s). Observed wave heights and bottom velocities as a function of discharge are shown on figures 21 and 22, respectively.

APPLICATION

Application of the specific results of these studies is limited to structures similar to those studied. The vortex suppression, crest rating, air demand, conduit flow conditions, flow surface pressures, and stilling basin action determined are functions of the approach flow, the structural configuration, the discharge, and the tailwater. Unless all of these factors are quite similar to those studied, it would be difficult to apply the results exactly to another structure. However, the design features and operation characteristics developed may provide initial direction for studies of all structures with similar problems.

INTRODUCTION

Ridgway Dam (fig. 1), the principal feature of the Dallas Creek Project in west-central Colorado, will be located on the Uncompahgre River, about 6 miles (9.7 km) north of Ridgway, Colorado (fig. 2). The dam will be constructed to increase usable water supplies for irrigation, for municipal and industrial purposes, and to provide flood control. Ridgway Dam will be a rolled earthfill structure with a height of 227 feet (69.2 m) above streambed. The dam crest, at elevation 6886.0 feet (2098.8 m), will be 2,430 feet (740.6 m) long. The reservoir will have a capacity of 80,000 acre-feet (9.9×10^7 m^3) and will extend 4.6 miles (7.4 km) up the Uncompahgre River.

The principal hydraulic features of the dam are a spillway and a river outlet works. The outlet works consists of a cut-and-cover conduit with a vertical shaft intake. Maximum discharge capacity of the outlet works is 1,700 ft^3/s (48 m^3/s).

The spillway (fig. 3), the subject of this report, has a morning-glory crest inlet that leads to a vertical bend, an inclined conduit, and a second vertical bend, then into a lower conduit with a slope of 0.0692. Flow from this conduit discharges onto an expanding vertically curved chute, into a hydraulic-jump basin, then through a tailrace channel and into the river. Included in the model were the entire spillway structure, a 300- by 300-foot (90- by 90-m) section of the reservoir topography immediately surrounding the crest inlet, and a 500-foot (150-m) length of the tailrace topography, which included the stilling basin.

The initial structure was sized based on an assumed discharge of coefficient that did not consider specific crest detail, pier, or approach flow conditions. Likewise, the initial vortex control pier (fig. 5) was selected with minimal consideration of the specific approach flow conditions. Consequently, it was quite likely that flow conditions through the crest intake, the spillway conduit, and the stilling basin for the initially proposed design would not be ideal. Thus, this hydraulic model study was conducted to define flow conditions and, where necessary, to guide modification of the design to yield a structure with satisfactory flow conditions at all potential discharges.

The basic objectives of the hydraulic model study were:

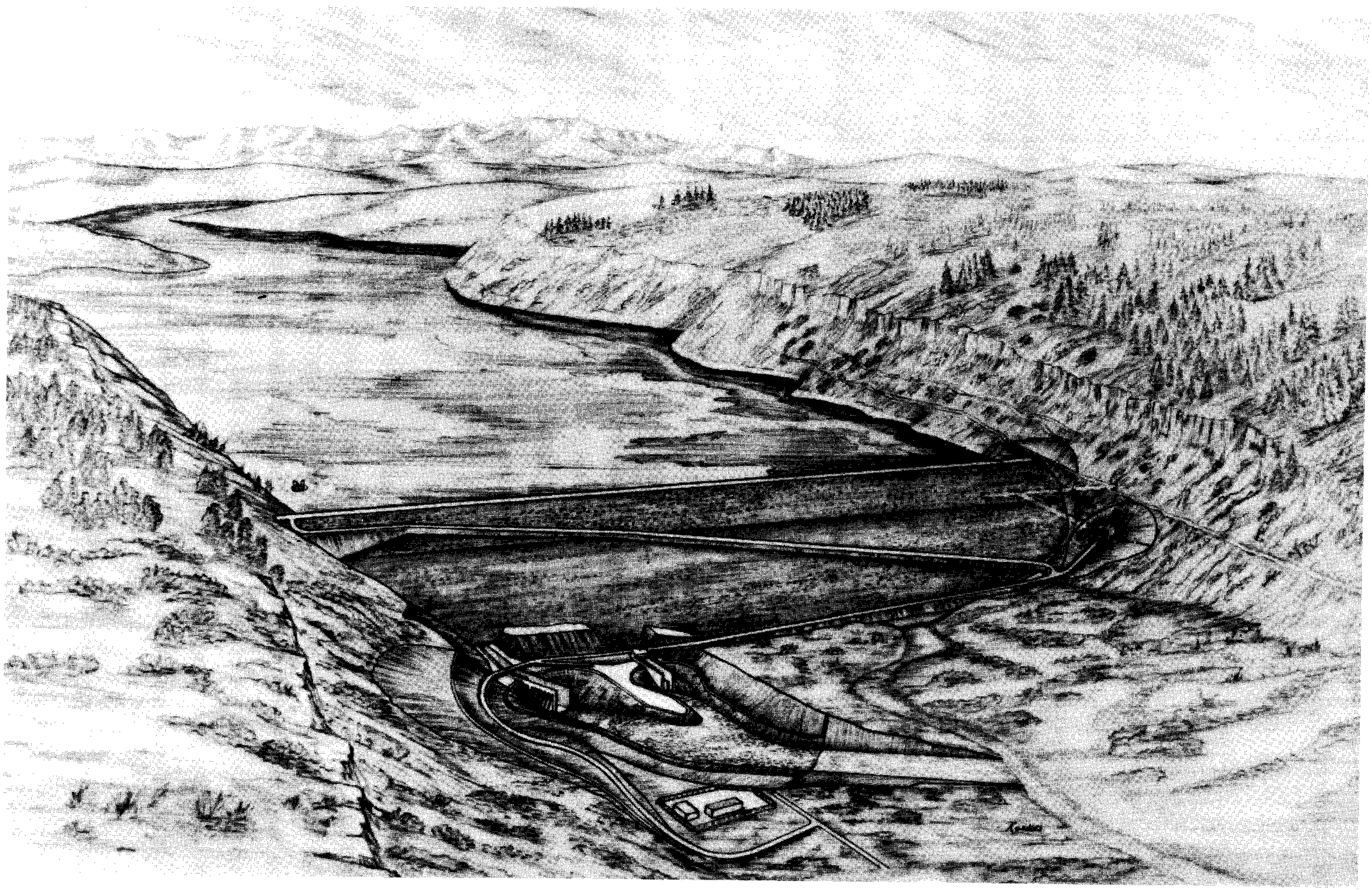


Figure 1. – Artist's conception of Ridgway Dam. P-801-D-80981

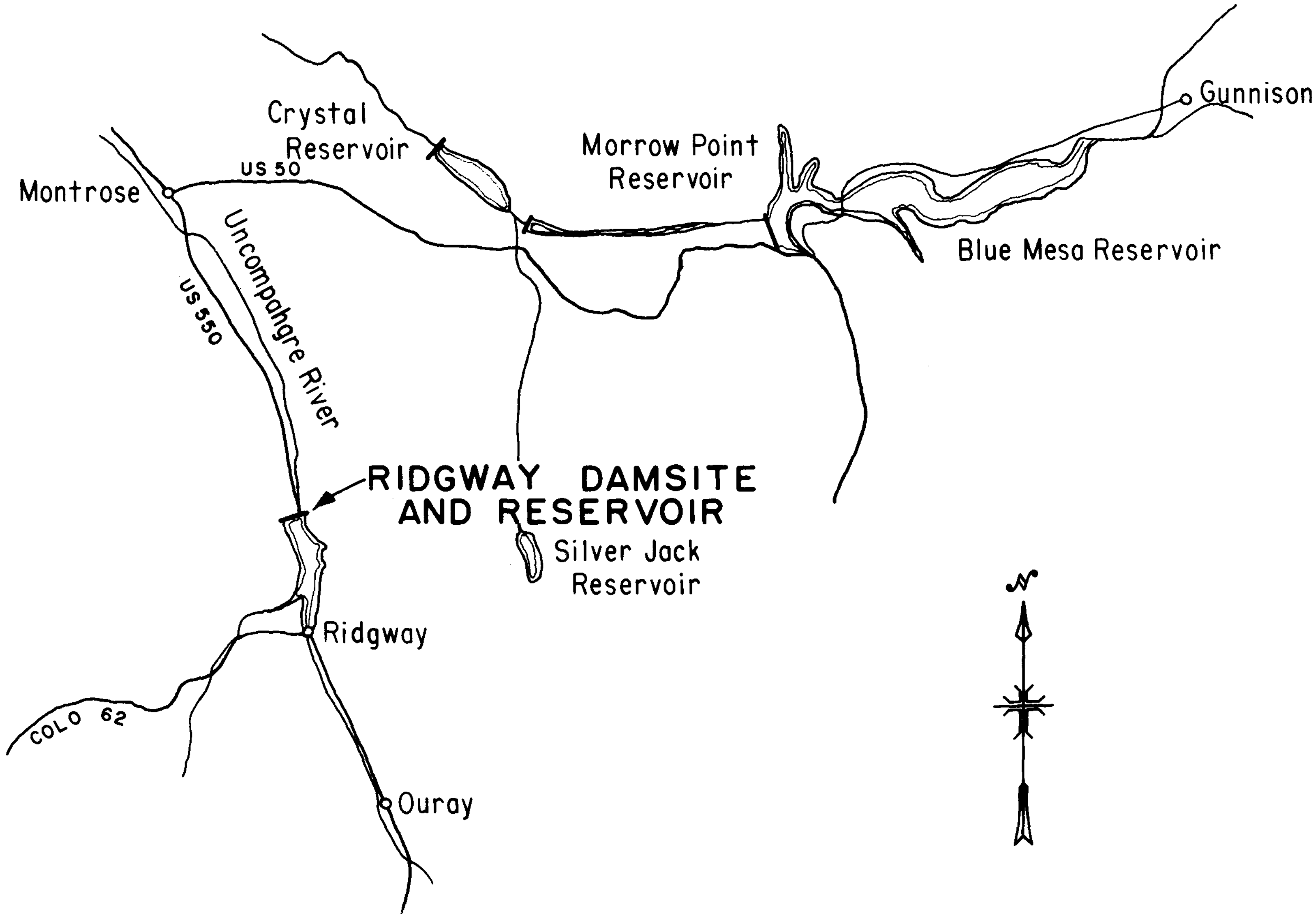


Figure 2. – Ridgway Dam location map.

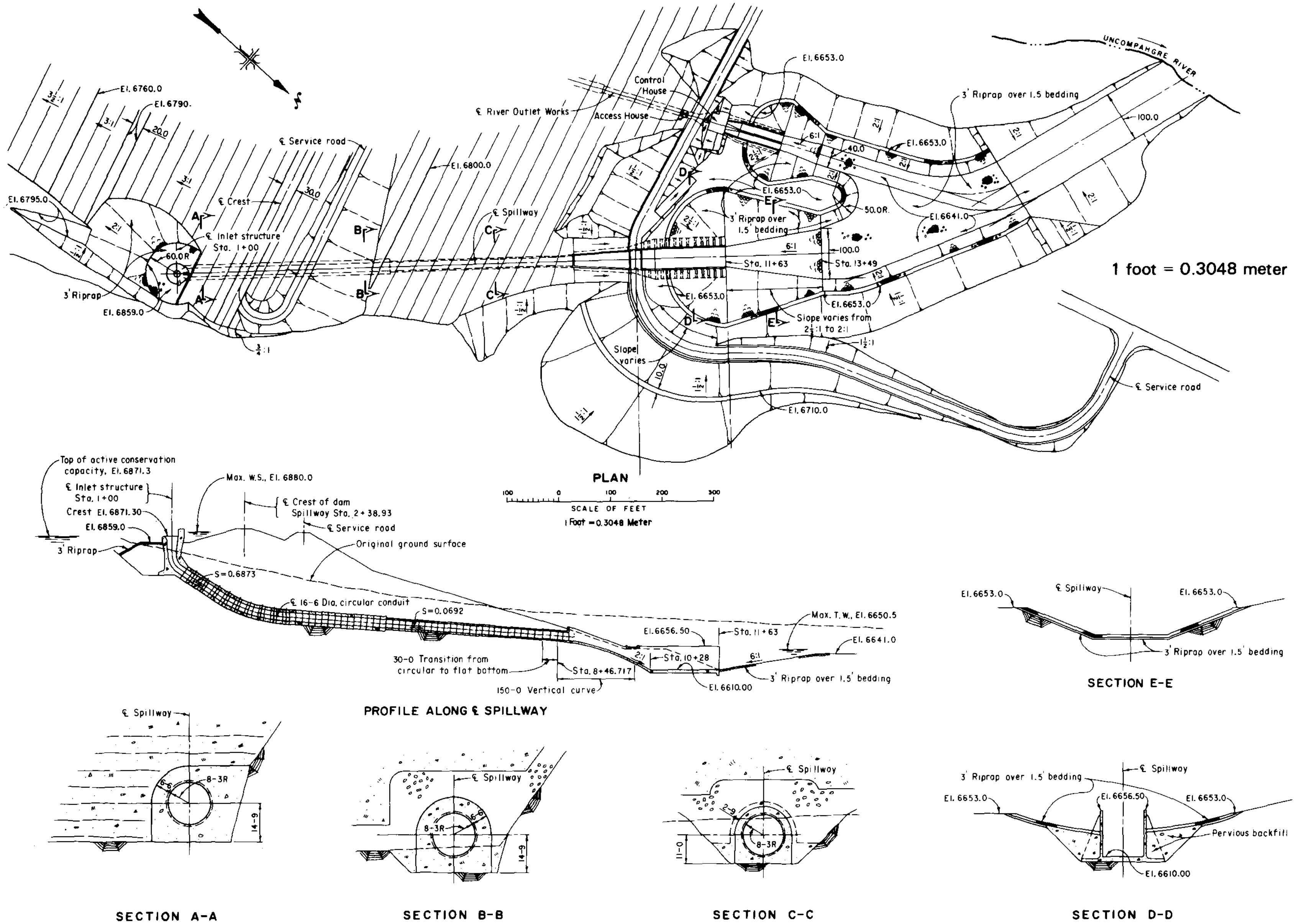


Figure 3. – Plan, profile, and sections – Ridgway Dam spillway.

1. If needed, to develop a vortex suppression crest treatment that maintains positive flow control and prevents vortex formation at the crest intake and that creates entrance conditions that result in stable conduit flow. These objectives had to be achieved while maintaining a satisfactory discharge coefficient to pass the maximum design release with the reservoir water surface at or below the desired maximum elevation of 6879.9 feet (2097.0 m). The potential for vortex formation is a function of the structure, the discharge, and the approach flow. Thus any device selected to suppress vortex formation must be tailored to the specific site. Vortices should be eliminated primarily because they reduce the coefficient of discharge and thus reduce the intake capacity. When the flow entering the intake has a high angular velocity component, as is the case with a vortex, the intake is not operating at optimum efficiency. By creating a radial flow entering the crest, the discharge per unit length of crest and thus the total discharge (depending on how much crest is blocked out by the flow control piers) is maximized.

2. To develop a discharge rating curve for the final proposed crest intake configuration. And while developing the rating curve, to verify that the crest configuration will pass the maximum design flood of 9,028 ft^3/s (256 m^3/s) with a water surface elevation at or below the maximum elevation of 6879.9 feet (2097.0 m).

3. To modify the crest to obtain entrance flow conditions that yield satisfactory flow conditions in the conduit. If the entering flow is concentrated to one side or the other, it may cause the flow to oscillate from side to side (rocking action) as it passes down the conduit (fig. 16). In severe form, the flow could even spiral over the crown of the conduit. Both rocking and spiraling flow can have negative influences on the structure. Rocking flow, if it does not dampen out, will extend through the full conduit length and cause unsymmetrical flow entering the stilling basin. This occurs when the flow is concentrated on one side of the conduit or the other as it exits to the stilling basin. The result is an unsymmetrical hydraulic jump on one side of the basin and a back eddy that could transport abrasive material back into the basin (fig. 19) on the other side. This inefficient performance can result in poor basin self-cleaning characteristics and erosion damage in the basin.

On the other hand, spiraling flow, or flow that crosses over the conduit crown, can create regions of negative pressure within the conduit. This occurs when the flow obstructs the continuous passage of air above the free water surface in the conduit. Therefore, an objective of the study was to maintain stable and symmetrical flow conditions in the conduit. Because modification to the crest will affect conduit flow conditions, the flow conditions associated with each vortex-suppression crest modification were closely monitored. Conduit flow conditions for each modification were observed over the full range of potential discharges.

4. To observe pressures on the conduit flow surfaces and to identify zones where severely negative pressures could result in cavitation and cavitation erosion. When flow velocities exceed approximately 40 ft/s (12.2 m/s), pressures on flow surfaces can become sufficiently subatmospheric to locally vaporize the water and cause cavitation and cavitation damage. Pressures on flow surfaces were measured and then considered in conjunction with the flow velocities to determine the potential for cavitation. In addition, a computer analysis was conducted to evaluate the potential for cavitation damage to the spillway. This analysis considered the effects of flow velocities, flow surface shape, and boundary layer development.

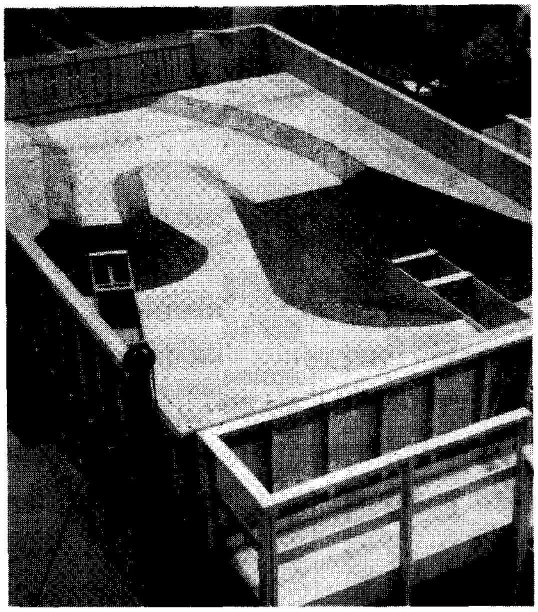
5. To evaluate air demand on the air vent beneath the deflector at the start of the upper vertical curve (figs. 7 and 10). Relationships were developed between water discharge, differential pressure across the air vent, and air demand. These relationships can be used to guide the design and sizing of the air vent. It should be noted that the differential pressure across the air vent is a function of air demand, vent diameter, and vent configuration. Because the vent diameter and configuration were not firm in the initial design, various sizes of orifice plates were used to obtain a range of airflow restrictions and to represent a range of potential vent sizes and configurations. Minor losses and friction losses through the air vent pipe can be computed using incompressible flow coefficients if airflow velocities are low. If air velocities are less than 60 ft/s (18.3 m/s), the error caused by the use of incompressible flow coefficients will be small even for long conduit-multiple minor loss applications. At an air velocity of 300 ft/s (91.4 m/s), use of the incompressible flow assumption will yield an approximately 2-percent error in individual minor loss evaluations. Such errors can compound and become significant for long conduit-multiple minor loss applications. Computed losses for a specific vent design can be correlated with model differential pressures to evaluate the influence of the vent on conduit pressures.

6. To evaluate stilling basin performance to ensure adequate energy dissipation and to ensure stilling action with good basin self-cleaning characteristics to minimize the chance for erosion damage to the basin structure. In addition, to evaluate flow velocities and wave heights in the channel immediately downstream of the stilling basin structure to establish adequate data for sizing riprap erosion protection.

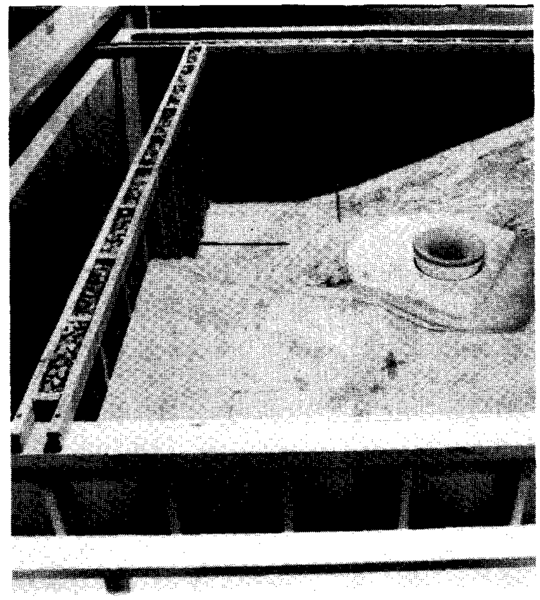
7. To minimize the size and complexity and, thus, the cost of the various structural features, while maintaining satisfactory hydraulic performance.

THE MODEL

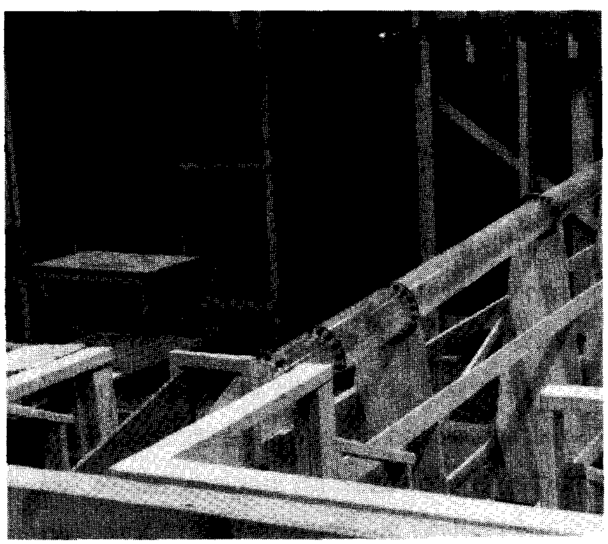
The hydraulic model (fig. 4) was constructed to a scale of 30.46:1, to allow use of 6.50-inch (165-mm) inside diameter clear plastic pipe to represent the 16.5-foot (5.03-m) inside diameter



(a) Overall view of stilling basin and tailrace channel. P-801-D-80982



(b) Overall view of reservoir topography and spillway crest. P-801-D-80983



(c) Spillway Conduit. P-801-D-80984

Figure 4. – The 30.46:1 scale hydraulic model.

circular portion of the spillway conduit. Because the 6.50-inch (165-mm) plastic pipe was commercially available, its use considerably reduced the cost of the model. The 30.46:1 scale was also selected to maximize model size with respect to the available space in the laboratory. The scale is large enough to generally minimize viscous influences on the model results. It was, however, recognized that even at this scale, viscous and surface tension influences would tend to reduce vortex intensity in cases where strong air core vortices would be expected to develop. It was likewise recognized that the model would not fully represent spray development, but that it could be expected to correctly represent finning and crossing flows within the conduit, crest-controlled flows entering the spillway structure, wave action in the spillway conduit and stilling basin area, air demand, and general flow patterns through the model.

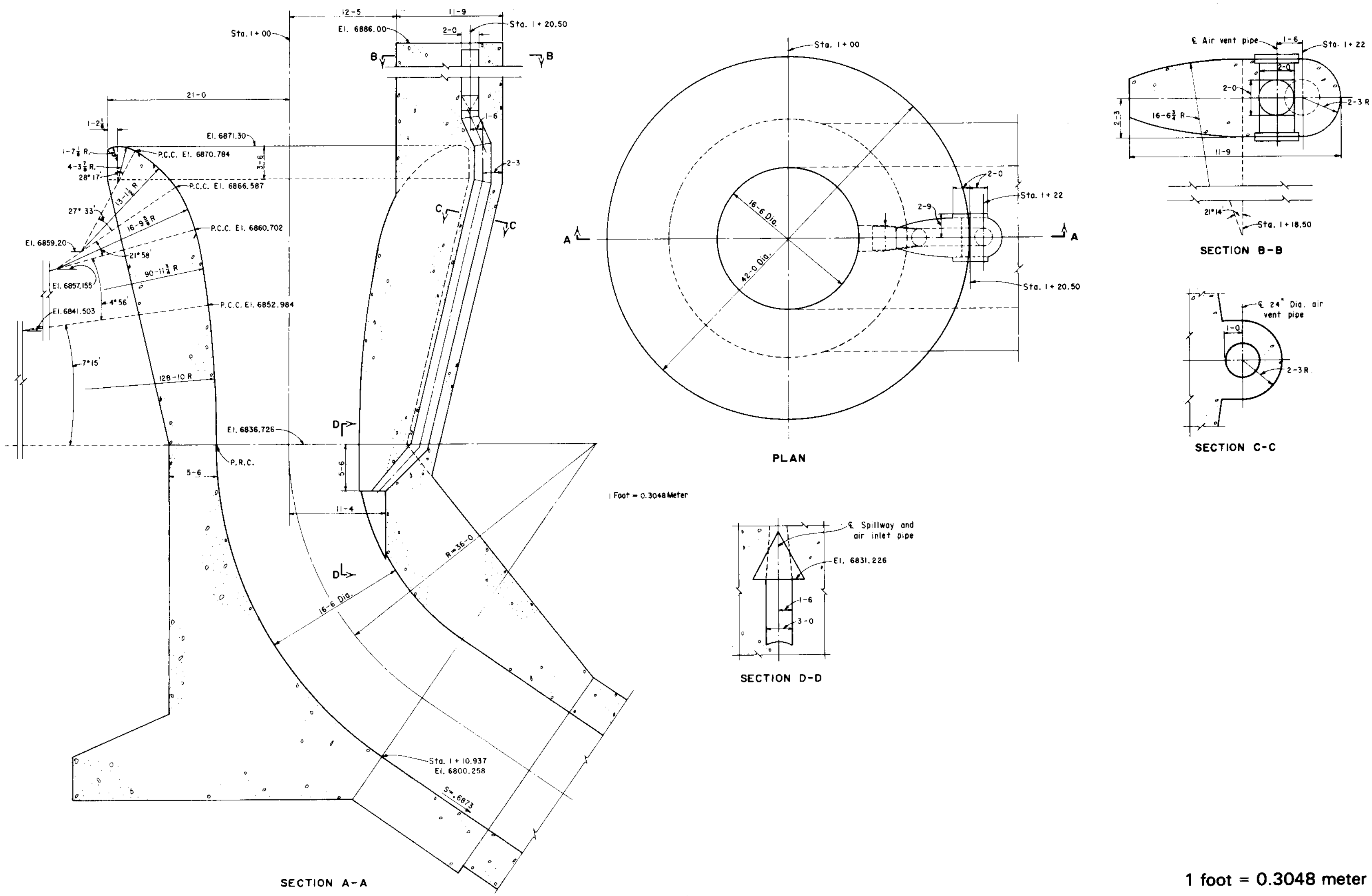
The model included:

- Head box with reservoir topography. – A rock baffle was included in the headbox (fig. 4) to still and distribute the inflow to the model. Also included was topography that extended from elevation 6886.0 feet (2098.9 m) to elevation 6790.0 feet (2069.6 m) and from the banks to sections approximately 225 feet (69 m) out into the reservoir from the crest intake centerline. There was sufficient topography in the model to accurately represent approach flow conditions to the crest.

- The crest intake (figs. 5, 6, 7, and 8), which extended from elevation 6859.0 feet (2090.6 m) to elevation 6836.73 feet (2083.84 m) (fig. 3). – The crest was fabricated so that various vortex-suppression pier configurations could be easily added. After a final pier selection was made and installed, three rows of piezometers were inserted (fig. 9) to monitor pressures on the crest flow surfaces. The piezometer rows were positioned to allow monitoring of representative flow conditions, noting localized pier influences on the flow.

- The spillway from the crest intake to the stilling basin (figs. 3 and 4a, b, and c). – Included with the spillway were the representative air vent immediately below the crest intake (fig. 10), the circular conduit, the transition to a rectangular section at the lower end of the conduit (fig. 3), and the open chute from the conduit to the stilling basin (fig. 3). Piezometers were placed along the conduit invert from the crest intake through the lower vertical curve (figs. 3 and 9). The initial design had also proposed an auxiliary outlet works that released flow into the spillway conduit immediately below the lower vertical curve. A raised section of the conduit crown (fig. 4) was included for this outlet. The conduit through this section, however, remained cylindrical below the springline. The auxiliary outlet works was deleted from the design as the study progressed. However, because the raised crown did not influence conduit flow conditions, a new model section was not fabricated.

- The spillway stilling basin with downstream topography (fig. 4). – Included in the model tailbox were the spillway stilling basin and channel topography at and below elevation 6653.0 feet (2027.8 m) from the stilling basin to a point approximately 330 feet (100 m) downstream of the basin end sill. A slotted tailwater control gate was also included in the tailbox.



1 foot = 0.3048 meter

Figure 5. – Plan, profile, and sections – preliminary crest and pier design.

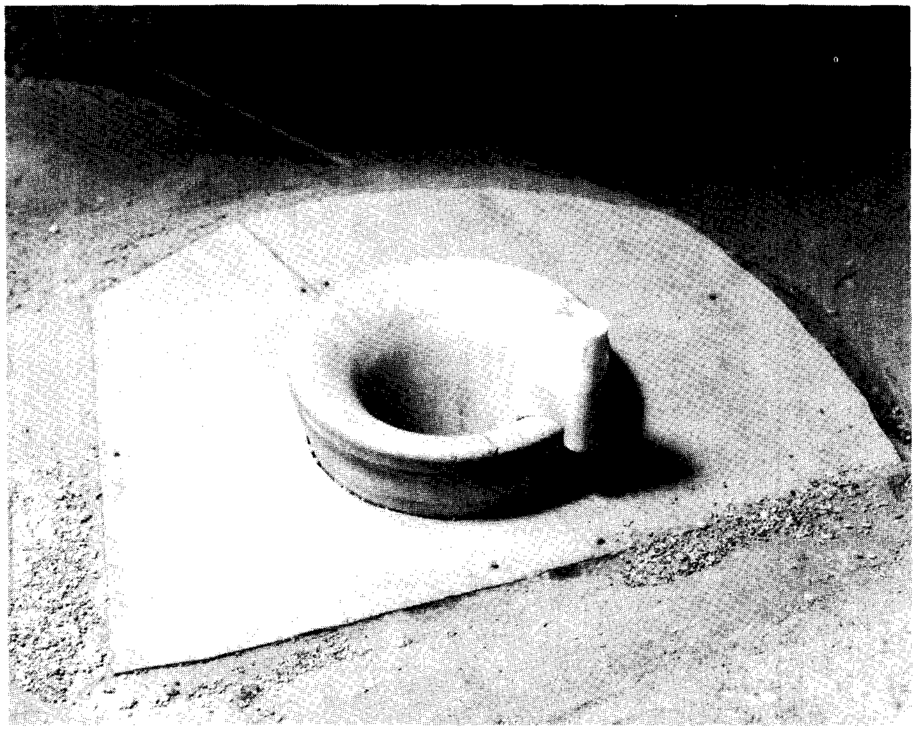


Figure 6. – Preliminary crest and pier. P-801-D-80985

The approximately 230-foot (70-m) drop from the reservoir surface to the tailwater surface modeled to 7.55 feet (2.3 m), the 39.65-foot (12.09-m) diameter crest modeled to 15.6 inches (396 mm), and the 16.5-foot (5.03-m) diameter conduit modeled to 6.5 inches (165 mm). The 9,028-ft^3/s (256 m^3/s) maximum spillway discharge modeled as 1.76 ft^3/s (0.05 m^3/s).

Discharges to the model were measured using venturi meters. Water surface elevations were generally measured using point gauges and staff gauges. Flow velocities were measured using electromagnetic current meters. Wave heights were measured using an electric point gauge in conjunction with an integrating voltmeter. Pressure differentials across the air vent were measured using a high accuracy deferential manometer.

THE INVESTIGATION

The distribution of the flow entering the headbox was evaluated to verify that it was representative of the flow approaching the crest in the prototype reservoir. This was done to ensure correct initial flow conditions. Flow conditions through the spillway and, in particular, vortex formation strongly depend on the distribution and direction of the approach flow. Flow enters the headbox through a single pipe and thus at a point location. Measurement of the flow downstream of the

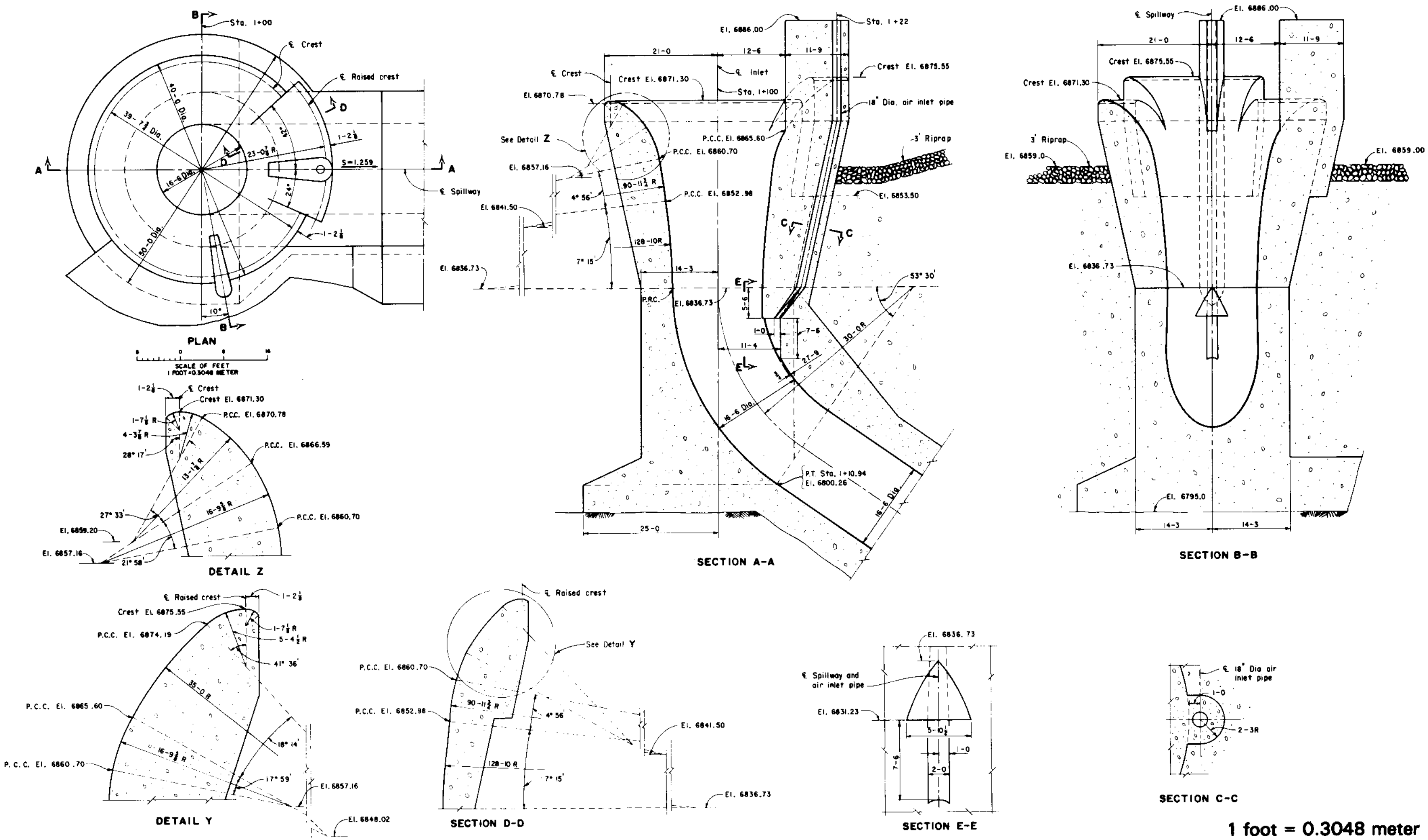


Figure 7. – Plan, profile, and sections – final crest and pier design.

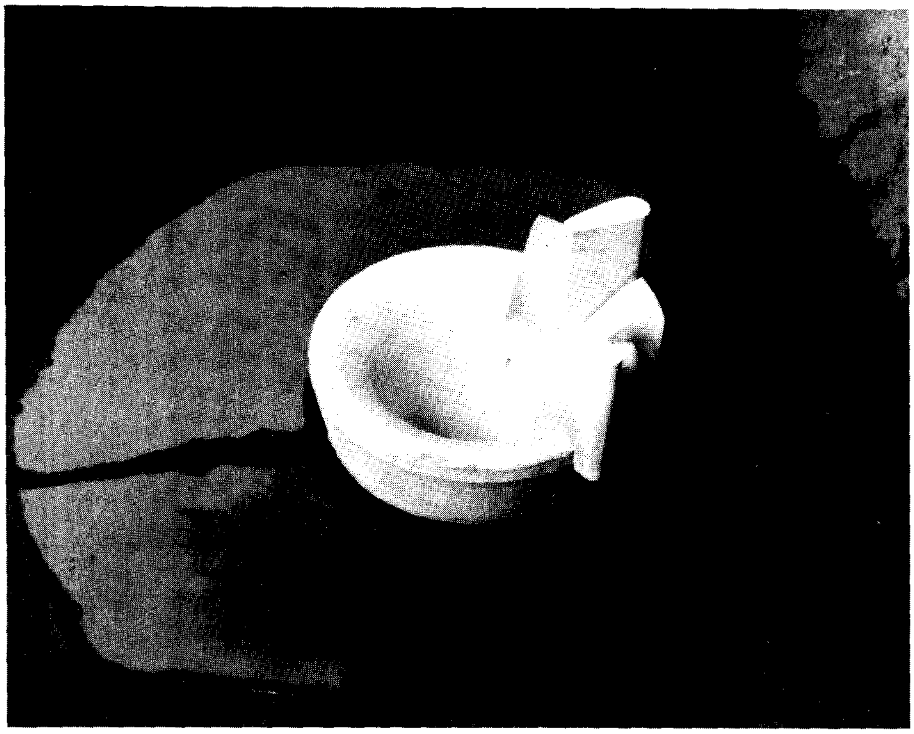


Figure 8. – Final crest and pier. P-801-D-80986

rock baffle showed improved, although not satisfactory, distribution. Consequently, fine screen was selectively attached to the baffle to adjust the flow resistance. Through a process of distribution measurement and baffle modification, a satisfactorily uniform entering flow condition was obtained.

The Crest

Initially the vortex potential of the crest intake was evaluated and a vortex control structure was developed. As previously noted, the potential for vortex formation depends on the distribution and the direction of the approach flow to the crest. Although the flow distribution in the model represented a best effort, irregularities in the model or unforeseen modifications to flow boundaries in the prototype could yield discrepancies in approach flow modeling. Because this could, in turn, yield discrepancies in vortex modeling, it was desirable to develop a vortex-control structure that would maintain positive vortex control even when additional vorticity was artificially imposed on the flow. Therefore, the vortex control of the schemes considered was evaluated both with the "best effort" approach flow and with a model in which additional counterclockwise or clockwise vorticity was imposed. The additional vorticity was created by arbitrarily placing a 9–foot (2.7–m) deflector step on either the right or left bank (fig. 11). The 9–foot (2.7–m) step blocks flow passage and deflects the flow. This causes more pronounced unsymmetrical approach flow which, in turn,

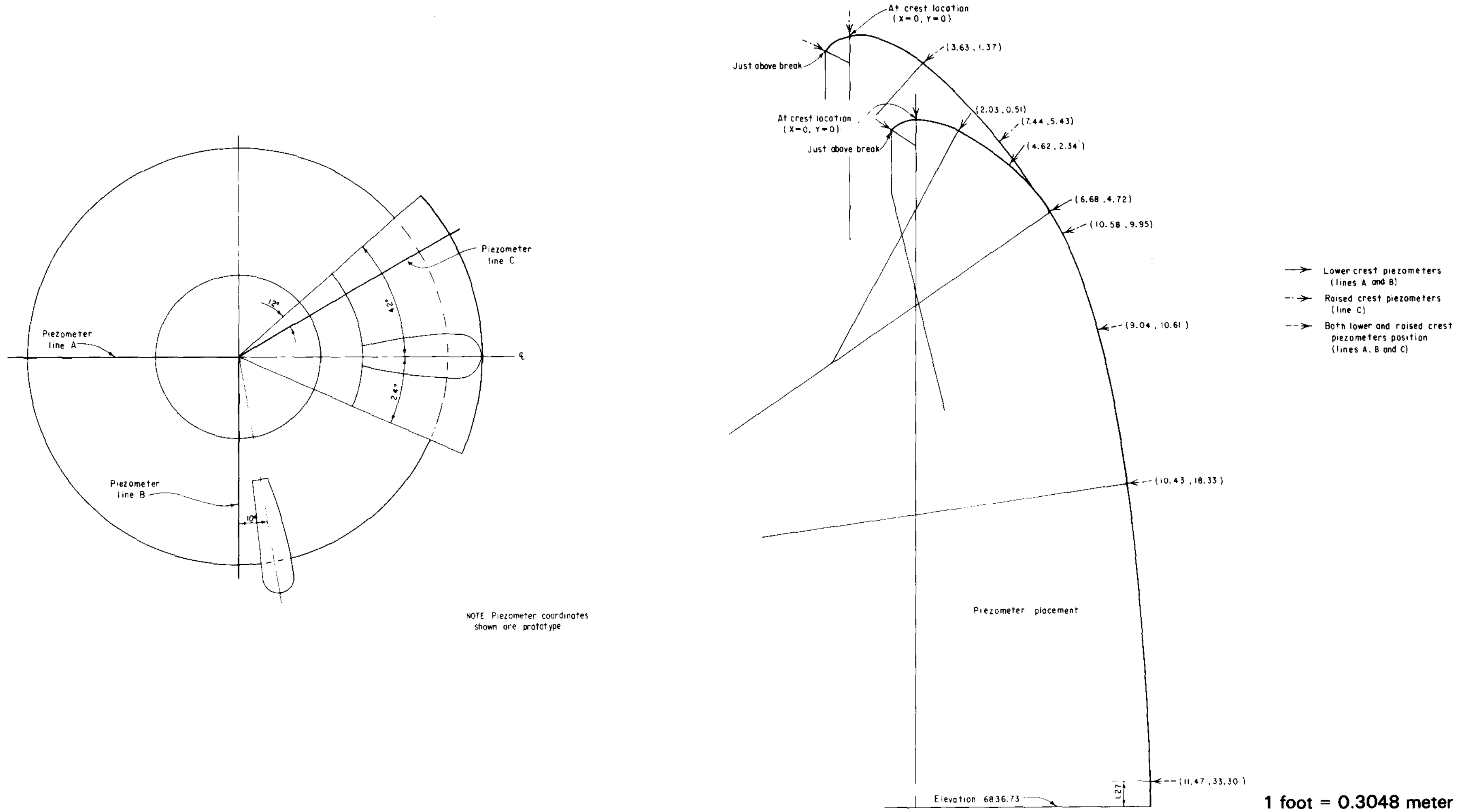


Figure 9. – Crest piezometer placement.

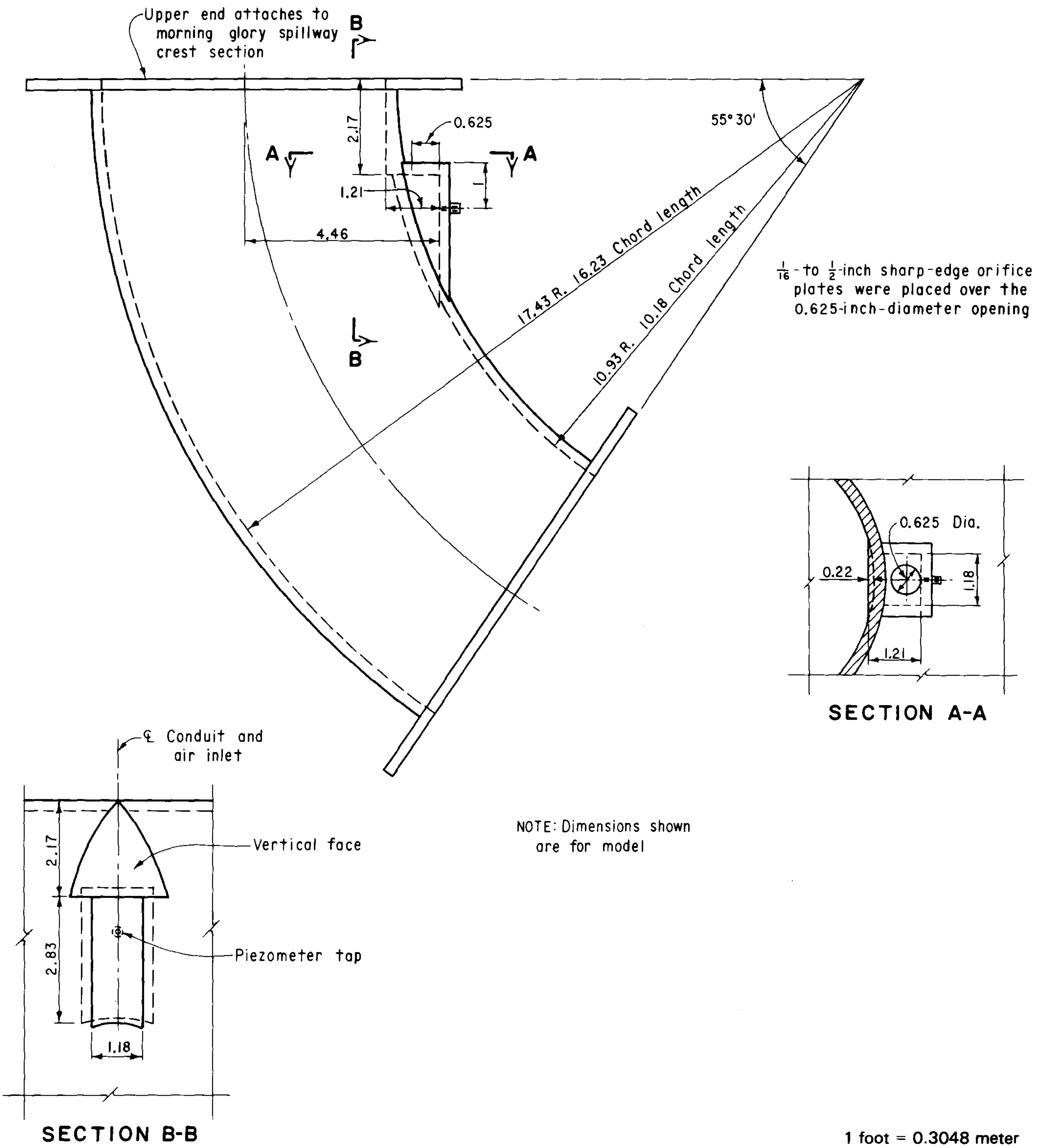
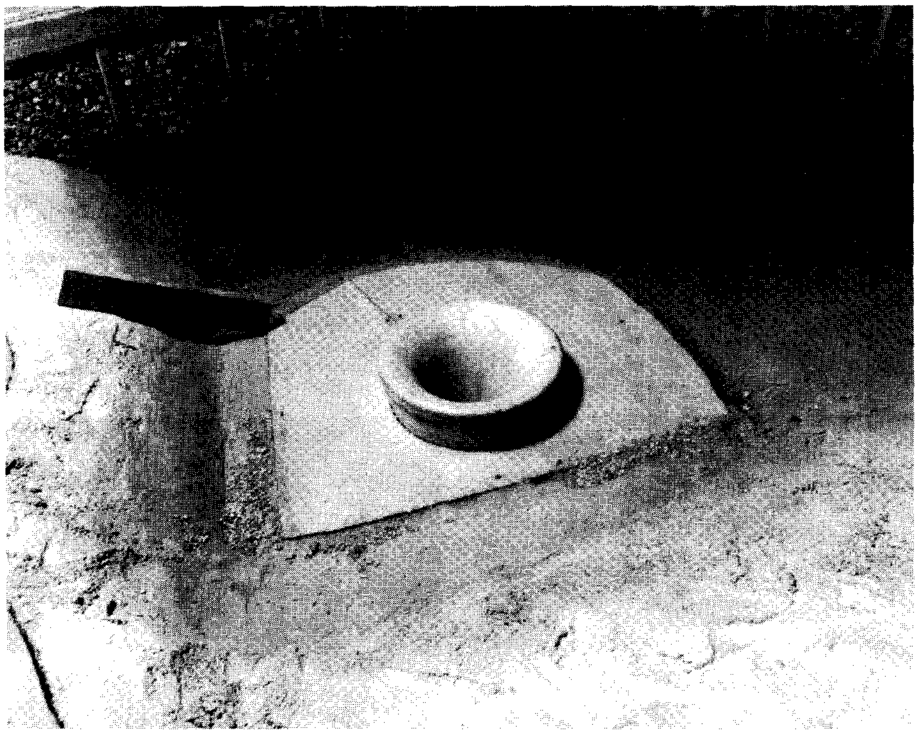
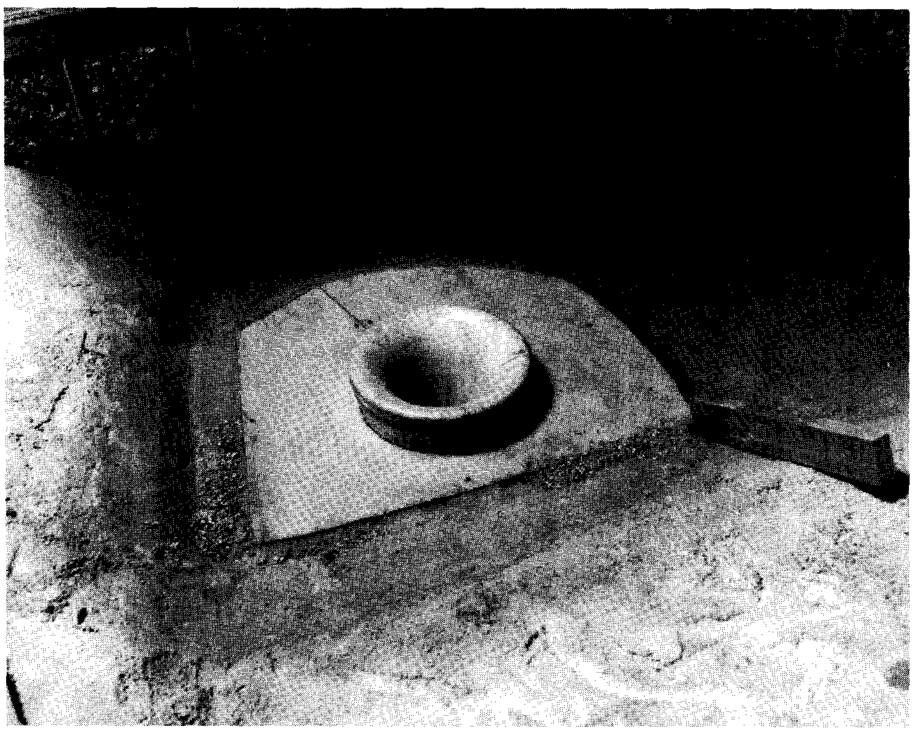


Figure 10. – Model air vent.



(a) Clockwise element. P-801-D-80987

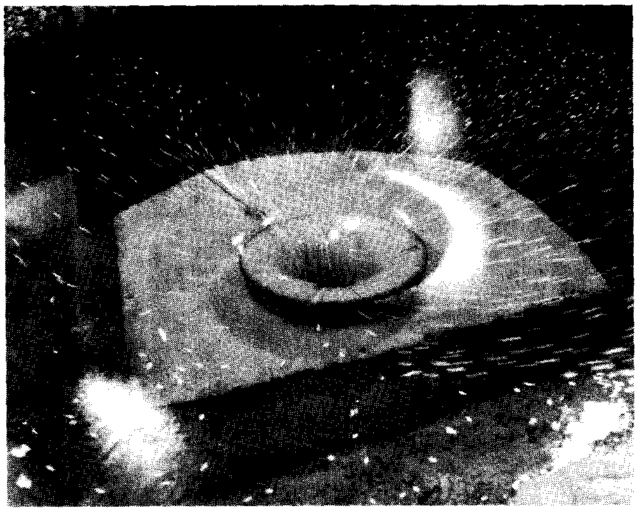


(b) Counterclockwise element. P-801-D-80988

Figure 11. – Forced vorticity step elements.

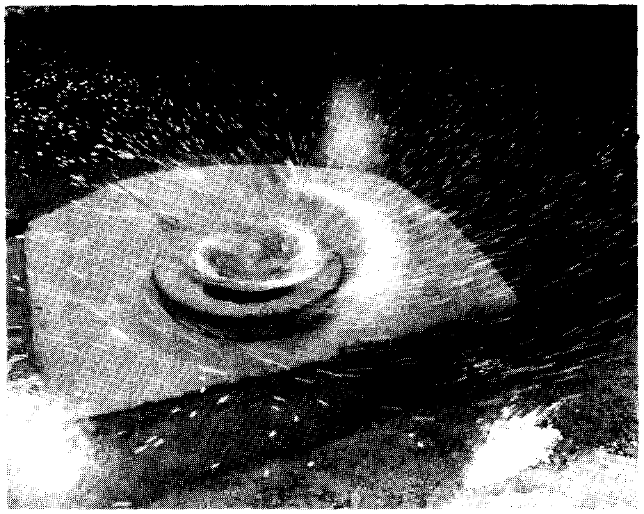
increases vortex potential. Figure 12 shows a comparison of flow conditions for the "best effort," clockwise-imposed, and counterclockwise-imposed vorticity conditions with no vortex control piers on the crest.

The crest intake configuration (including vortex-control structures) and the approach flow distribution and direction also effect the discharge rating of the crest and the resulting flow conditions



(a) "Best effort" flow. P-801-D-80989

(b) Counterclockwise-imposed vorticity. P-801-D-80990



(c) Clockwise-imposed vorticity. P-801-D-80991

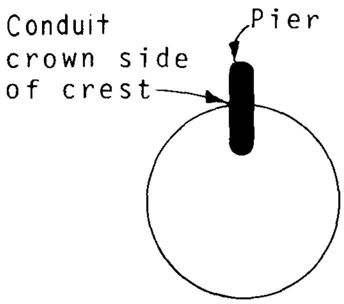
Figure 12. – Initial crest flow conditions – no piers.

through the remainder of the spillway. Therefore, for each crest intake structure configuration considered, vortex suppression, discharge rating, and conduit flow conditions were evaluated over the entire discharge range.

Initially, the proposed crest intake with no piers was observed. It was found that at a discharge of 9,028 ft^3/s (256 m^3/s), no vortex formation occurred with the "best effort" approach flow conditions. However, when vorticity was imposed, either clockwise or counterclockwise, strong vortices developed (fig. 12). The vortices resulted in a substantial reduction in the discharge coefficient, which raised the reservoir water surface to elevations above 6886.0 feet (2098.9 m). With the "best effort" approach conditions, the 9,028-ft^3/s (256-m^3/s) discharge was passed with a reservoir water surface elevation of 6878.0 feet (2096.4 m), 1.9 feet below the original design maximum water surface elevation. Because of the strong vortex formation when the vorticity was imposed, it was felt that the potential for prototype vortex development was significant and that a vortex-control structure was needed. It was also recognized that the supply conduit for the air vent is typically brought to the atmosphere through a crest pier. Therefore, the next step was to evaluate vortex-control structures that included piers placed on the crest.

The alternative structures considered are shown on figure 13, which includes a schematic and description of each concept, with a brief description of the crest and conduit flow characteristics that resulted from use of that concept. Note that for each of the concepts tested that used piers placed exclusively on the crest, either the vortex suppression characteristics or the resulting conduit flow conditions were not satisfactory. Therefore, additional concepts were considered. Control structures such as piers placed off the crest, dikes placed between the crest and the shore, and vanes placed within the crest intake were studied (fig. 13). Again, an optimum combination of acceptable conduit and crest flow conditions was not obtained with any of these alternative structures. In addition, most of the options tested with vanes showed that the vanes reduced the intake throat area and caused a flow control shift from the crest to the intake throat at the higher discharges. Control shift is generally not predictable. There tends to be a discharge range over which the control will shift from the crest to the throat and back with a prototype frequency of approximately 1 to 2 cycles per minute. The Bureau of Reclamation has built and operated many structures that were designed to shift from crest to throat control at the higher discharges. These structures have operated satisfactorily. However, if there is no substantial economic or structural advantage (such as reduction of conduit size), it is desirable to design the structure so that it will always be in crest control. Most of the adequate vortex control structures studied stayed in crest flow control over the full discharge range.

The structure found to yield the best combination of acceptable vortex control and acceptable conduit flow, and thus the recommended crest treatment, is shown on figures 7 and 8. Note that

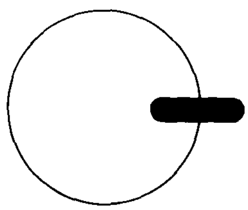


DESCRIPTION

Single pier located on conduit crown side of crest.

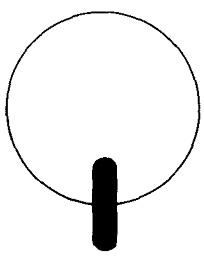
EFFECTIVENESS

Fails to adequately suppress clockwise or counterclockwise vortex action.



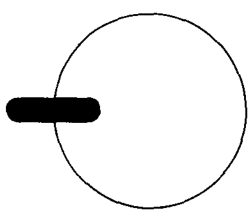
Single pier located on crest 90° to the right of the conduit crown side.

Fails to adequately suppress clockwise vortex action.



Single pier located on conduit invert side of crest.

Fails to adequately suppress clockwise or counterclockwise vortex action.

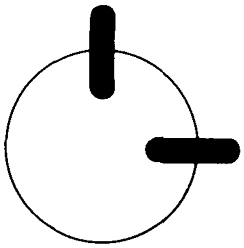
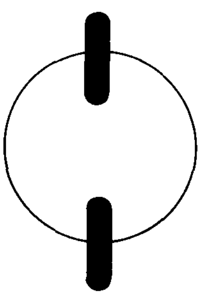
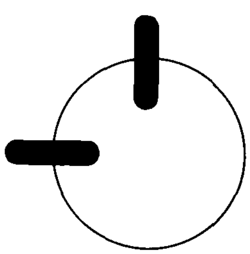


Single pier located on crest 90° to the left of the conduit.

Fails to adequately suppress clockwise or counterclockwise vortex action.

(a) One pier in any location on the crest will not adequately suppress vortex action. Additional crest treatment is required.

Figure 13. – Crest treatment alternatives (sheet 1 of 7).

	DESCRIPTION	EFFECTIVENESS
	Two piers located on crest, one at conduit crown and one 90° to the right.	Adequate vortex suppression in both clockwise and counterclockwise directions. Moderate rocking of conduit flows for discharges of from 2,500 to 5,500 ft^3/s (71 to 156 m^3/s). Rough flow through and below upper vertical curve with finning and strong tendency for crossover, in particular for discharges of from 4,000 to 5,500 ft^3/s (113 to 156 m^3/s). Good flow conditions at high and low discharges.
	Two piers located at conduit crown and invert locations on the crest.	Fails to adequately suppress vortex action in counter-clockwise direction.
	Two piers located on crest, one at conduit crown and one 90° to the left.	Fails to adequately suppress vortex action in counter-clockwise direction.

(b) All other two-pier configurations tested tended to yield inadequate vortex control.

Figure 13. – Crest treatment alternatives (sheet 2 of 7).

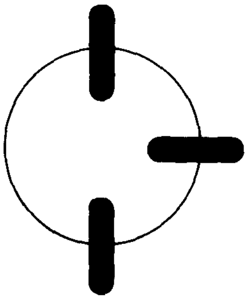
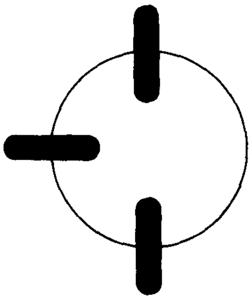
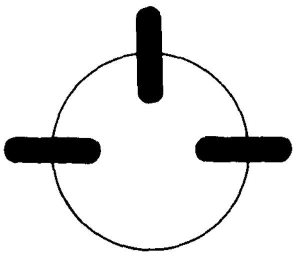
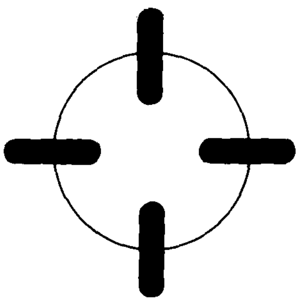
	DESCRIPTION	EFFECTIVENESS
	Three piers on crest.	Good vortex suppression. Fair to poor conduit flow conditions with moderate to heavy rocking and finning at discharges between 3500 and 5500 ft^3/s (99 and 156 m^3/s).
	Three piers on crest.	Poor vortex suppression. Fair conduit flow conditions with moderate rocking and finning for discharges between 4000 and 5500 ft^3/s (113 and 156 m^3/s).
	Three piers on crest.	Good vortex suppression. Fair conduit flow conditions with moderate rocking and finning for discharges between 4000 and 5500 ft^3/s (113 and 156 m^3/s).
	Four piers on crest.	Good vortex suppression. Fair conduit flow conditions with moderate rocking and finning for discharges between 4000 and 5500 ft^3/s (113 and 156 m^3/s).

Figure 13. – Crest treatment alternatives (sheet 3 of 7).

DESCRIPTION	EFFECTIVENESS
Piers off the crest were investigated with regard to vortex suppression. All configurations studied on the crest were also investigated at positions off the crest.	In all cases, piers positioned off the crest were less effective in vortex control than similar piers placed on the crest.

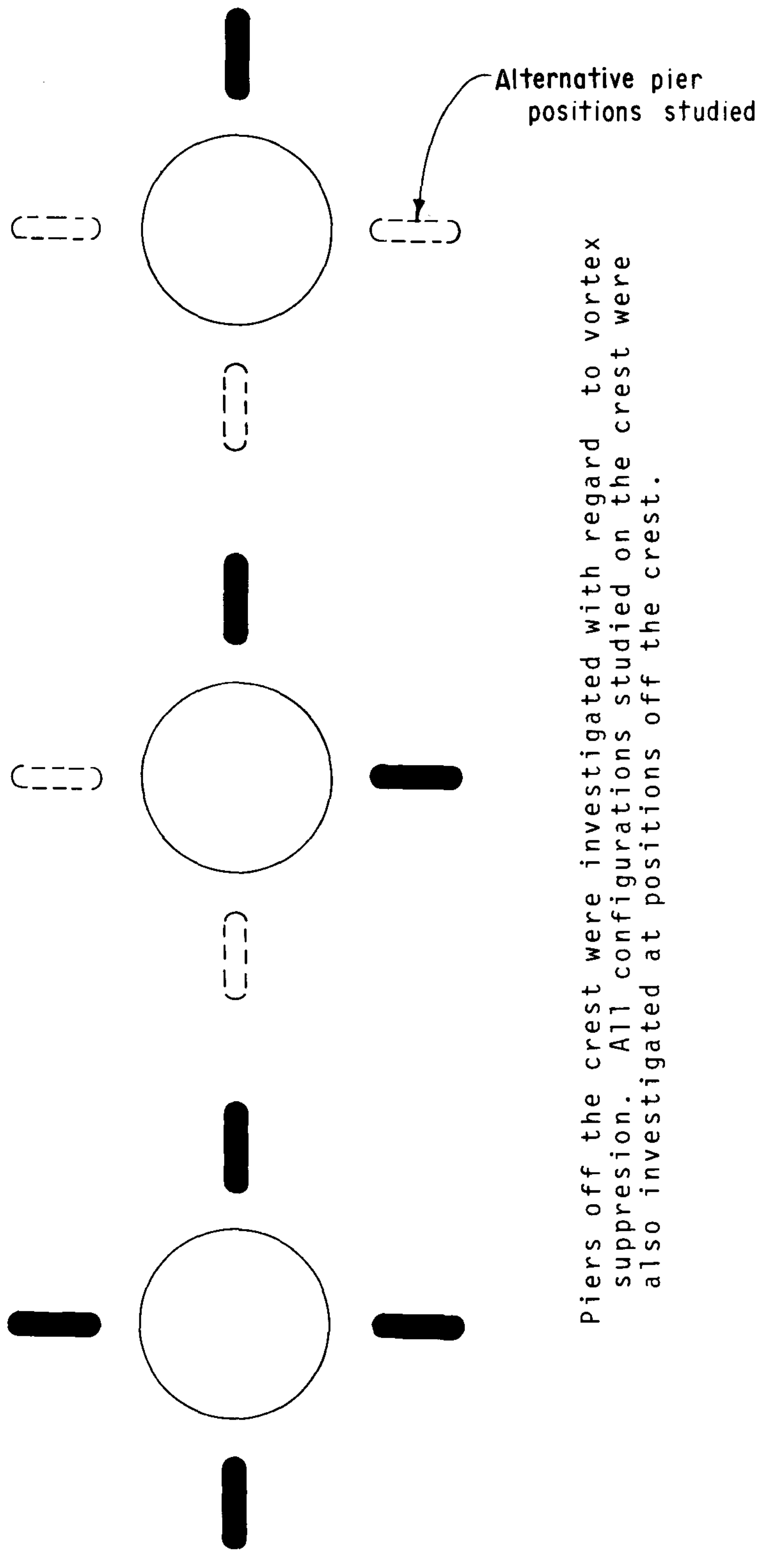
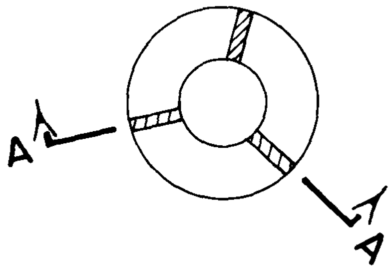
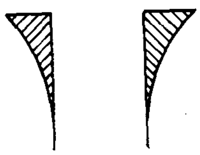


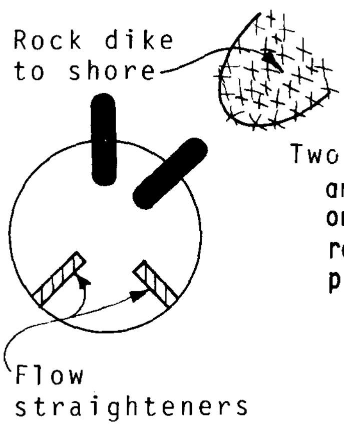
Figure 13. – Crest treatment alternatives (sheet 4 of 7).



DESCRIPTION	EFFECTIVENESS
Flow straighteners or guide vanes that extend from the crest to the throat - various numbers of vanes and positions were tested.	At least three vanes are required to obtain good conduit flow conditions. Vanes cause flow control to shift from crest to throat at high discharges. Piers on the crest can reduce the potential for control shift.



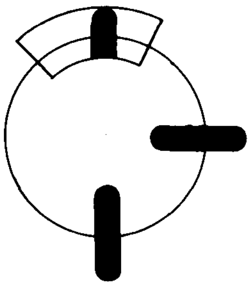
SECTION AA

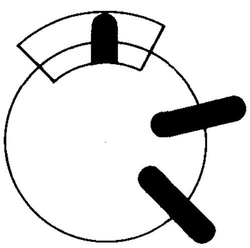


Two flow straighteners and two piers placed on the crest with a rock dike from one pier to the shore.	Adequate conduit flow conditions. Good vortex suppression.

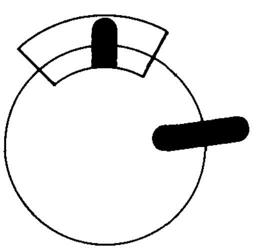
Figure 13. – Crest treatment alternatives (sheet 5 of 7).

DESCRIPTION	EFFECTIVENESS

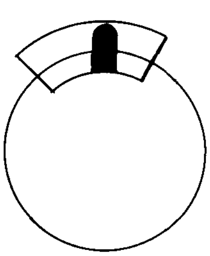




Raised crest with two additional piers placed on the crest.	Generally adequate vortex control. Generally good conduit flow conditions with light to moderate rocking for discharges of 6,000 to 7,500 ft^3/s (170 to 212 m^3/s)



Raised crest with one additional pier placed on crest and positioned 80° right of crown.	Good to adequate vortex control. Generally good conduit flow conditions with light rocking for discharges of from 3,000 to 4,500 ft^3/s (85 to 127 m^3/s).



In addition, the dimensions of the raised crest were evaluated. The optimum dimension with respect to resulting conduit flow conditions is shown on figure 14.

Figure 13. – Crest treatment alternatives (sheet 6 of 7).

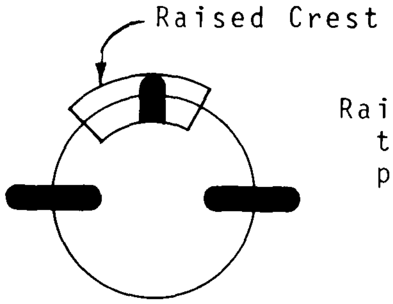
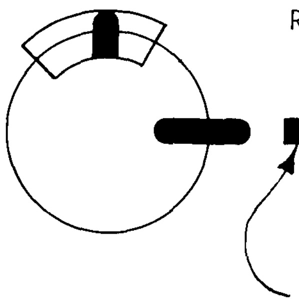
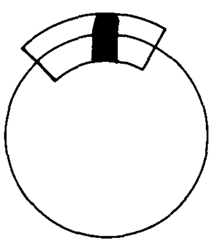
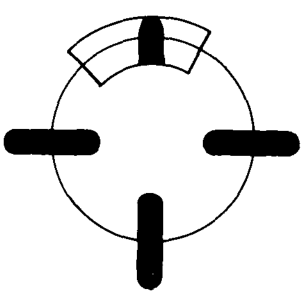
	DESCRIPTION	EFFECTIVENESS
	Raised crest with two additional piers on crest.	Adequate vortex control, however, resulted in rough entrance flow conditions (boils - rotational finning).
	Raised crest with one crest pier and with structural splitter wall from pier to shore.	Good vortex control. Good entrance flow. Good conduit flow.
	Raised crest with structural splitter wall from crest to shore.	Marginal vortex control. Outstanding conduit flow conditions.
	Raised crest with three additional piers on crest.	Good vortex control. Generally good conduit flow conditions with slight rocking for discharges of from 3,500 to 4,500 ft^3/s (99 to 127 m^3/s).

Figure 13. – Crest treatment alternatives (sheet 7 of 7).

a portion of the crest on the conduit crown side of the intake is raised. This blocks the flow from entering the intake from this side for small and intermediate discharges. For discharges above 3,200 ft^3/s (91 m^3/s), flow passes over the raised crest and enters the intake. By blocking the flow at the low discharges, the raised crest prevents flow from dropping from the crown side and impinging on the conduit invert in the first vertical curve. Observations indicated that this impingement was the primary cause of finning, crossing flows, rocking flows, and generally poor flow conditions in the conduit. At the higher discharges the intake throat is nearly full of water. Thus, the throat is near control and there is no free jet impingement on the invert. Therefore, at the higher discharges, conduit flow conditions were generally good.

Also included in the recommended crest treatment are two piers (figs. 7 and 8), which function primarily for vortex control. Numerous pier arrangements were tested in conjunction with the raised crest (fig. 13). The arrangement shown on figure 7 was found to be an optimum balance between hydraulic performance and structural simplicity. This crest treatment yielded positive vortex control for both the "best effort" approach flow conditions (fig. 12) and for the approach flow conditions with both clockwise- and counterclockwise-imposed vorticities. The required cross-sectional size and shape for the piers were also considered. A pier depth of 11.75 feet (3.6 m) proved adequate. Pier width was dictated by structural considerations. Minimum pier widths were the best hydraulically because reduction of effective crest length is minimized. The

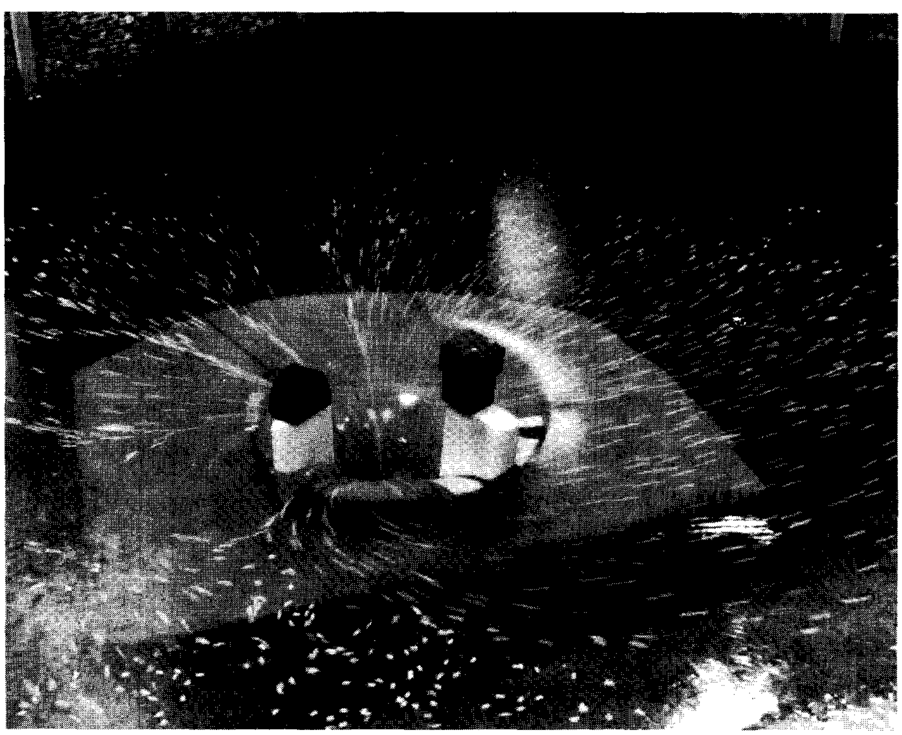


Figure 14. – Final crest flow conditions, 9,028 ft^3/s (256 m^3/s). P-801-D-80992

pier located on the raised crest was sized to allow placement of the air vent conduit within the pier. Simple streamlining of the pier shape proved adequate. Because the piers function as flow straighteners, they intercept the flow at oblique angles. It is not desirable to intercept the flow cleanly and minimize flow disruption. Consequently, there is no advantage for extreme pier streamlining. A simple radius nose with a tapered body is adequate. The cross-sectional shape of the piers included in the final design (fig. 7) is more than satisfactory. The pier height should extend above the maximum water surface elevation.

With the recommended crest treatment (fig. 7), entrance flow conditions for the structure and therefore other details of the spillway flow were set and could then be evaluated. A discharge rating for the crest intake was taken; it is shown on figure 15. Note that although a section of the crest was raised and two piers were placed on the crest, the maximum design discharge was passed with a reservoir water surface elevation of 6879.35 feet (2096.83 m), which is 0.55 foot (0.17 m) below the originally desired maximum water surface elevation of 6879.9 feet (2097.0 m).

Because the maximum design discharge was passed with a reservoir surface elevation lower than the elevation originally desired, the possibility of reducing the diameter of the structure was investigated. Diameter reduction was briefly evaluated using model scale manipulation. It was found that it would be possible to reduce the crest diameter from 39.65 to 38.5 feet (12.1 to 11.7 m) and to reduce the throat and conduit diameter from 16.5 to 16.0 feet (5.0 to 4.9 m) and still pass the maximum discharge of 9,028 ft^3/s (256 m^3/s) with a reservoir surface elevation of 6879.9 feet (2097.0 m). This reduction, however, would result in a control shift from crest to throat at the maximum discharge and, consequently, may not be worthwhile.

The Conduit

Flow conditions through the conduit were observed in detail at discharges of 2,000, 4,000, 6,000, 8,000, and 9,028 ft^3/s (57, 113, 170, 227, and 256 m^3/s) for numerous crest treatments. Intermediate discharges were also observed, but in less detail. For the recommended raised crest and pier arrangement at the higher discharges of 6,000, 8,000, and 9,028 ft^3/s (170, 227, and 256 m^3/s), the water surface and flow conditions throughout the conduit were quite stable; this was partly due to the stabilizing influence of the throat. At 4,000 ft^3/s (113 m^3/s) and other intermediate discharges between 3,000 and 4,500 ft^3/s (85 and 127 m^3/s), moderate finning was observed in the upper vertical curve and between the two vertical curves of the spillway conduit. Centerline fins that were parallel to the direction of the flow and up to 6 feet (1.8 m) high were noted. At these intermediate discharges, some rocking of the flow in the lower conduit was observed, although the rocking was gentle with trough-to-crest amplitudes less than 1.5 feet

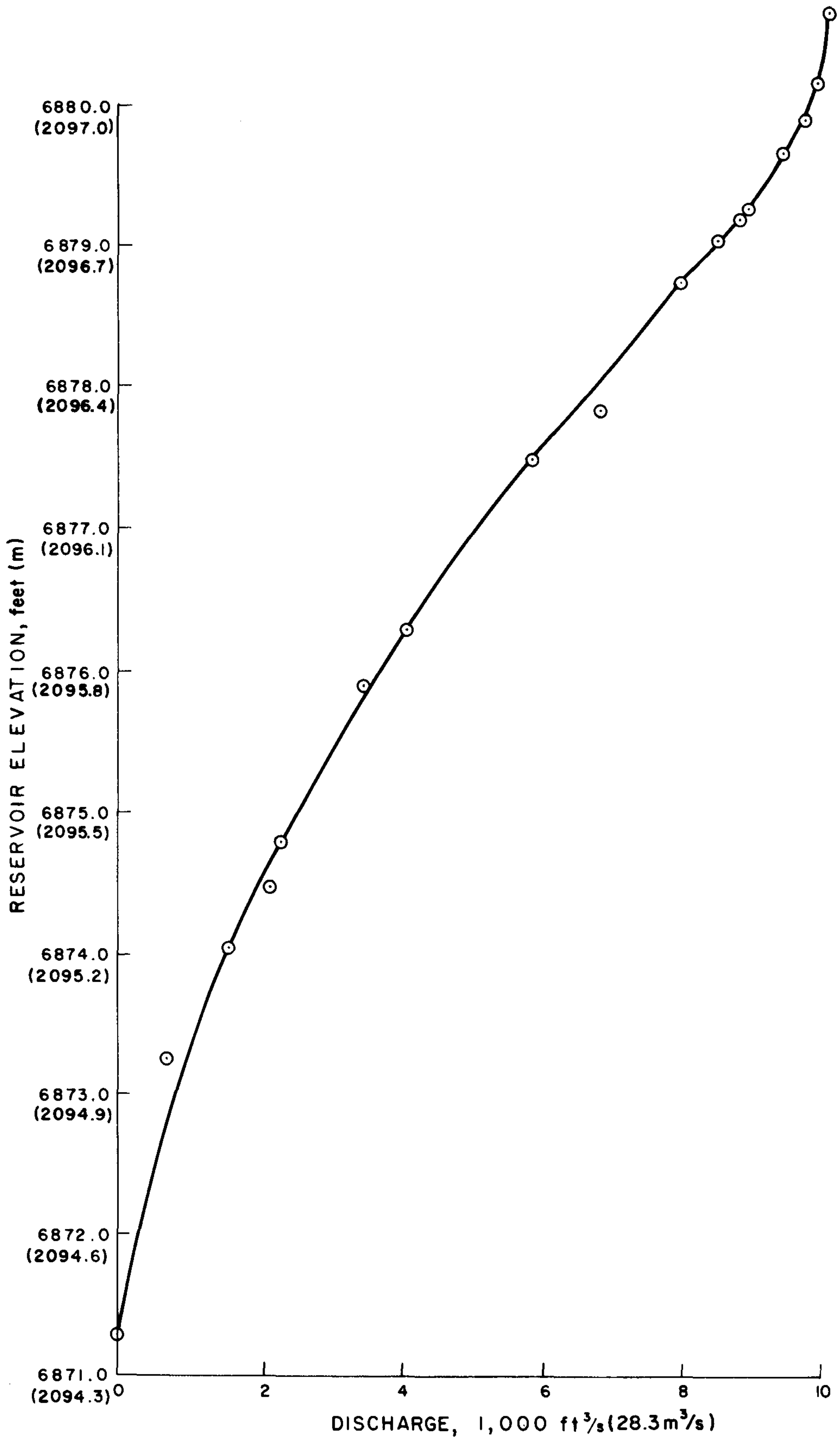


Figure 15. – Discharge rating curve.

(0.5 m) (fig. 16). The rocking action did not result in severely asymmetrical action in the stilling basin. For discharges below 3,000 ft^3/s (85 m^3/s), fin heights were approximately equal to those for the intermediate discharges. However, boundary friction tended to dampen the rocking in the lower conduit and, thus, yield a more stable water surface. In general, with the final crest treatment no severe finning or crossover flows were observed, and flow through the lower tunnel was good with minimal rocking.

As previously noted, pressures were measured on the flow surfaces. Three rows of piezometers were placed in the crest intake (fig. 9). These piezometers were installed after the final crest treatment was developed. They were positioned to yield representative pressures for the various flow conditions on the crest. As seen on figure 9, one row (row C) was placed in the raised crest section about halfway between the edge of the raised crest and the pier. This is a section that had minimal influence from either the edge of the raised crest or from the pier and is representative of typical flow conditions across the raised crest. Another row (row B) was placed just to the side of the off-centerline pier. In this region the pier intercepts the flow and creates a wake fin. The piezometers in this row measure the surface pressures that result from this wake disturbance. Finally, the last row (row A) was placed along the conduit centerline on the conduit invert side of the intake. This region is not affected by the pier or the raised crest. Pressures measured by piezometer row A are representative of pressures on typical crest sections. This row was extended down the invert of the conduit through the upper vertical curve, through the straight conduit section between vertical curves, and into the lower vertical curve.

For the recommended crest treatment, the spillway model was operated at discharges of 2,000, 4,000, 6,000, 8,000, and 9,028 ft^3/s (57, 113, 170, 227, and 256 m^3/s), and the mean pressures were monitored. The results are shown on figure 17. Note that on the upper portion of the raised crest, piezometers 1, 2, 3, and 4 of piezometer row C were positive; this indicates substantial jet support by the flow surface. In this region the pressure was a function of the discharge: The higher discharges and, thus, the deeper flows yielded the higher pressures. Piezometers 5 and 6, however, tend to show negative pressures, which result when the combined effect of surface curvature and flow trajectory causes the flow to attempt to lift away from the surface. For these piezometers, the subatmospheric pressures were greatest at the higher discharges. The maximum average subatmospheric pressure observed was with a discharge of 9,028 ft^3/s (256 m^3/s) at piezometer 5. This observed pressure was 2.0 feet (0.6 m) of water below atmospheric. At piezometers 7 and 8 in the lower portion of the crest intake, pressures observed at all discharges were basically atmospheric. This indicates a neutral support of the jet and shows no cavitation potential.

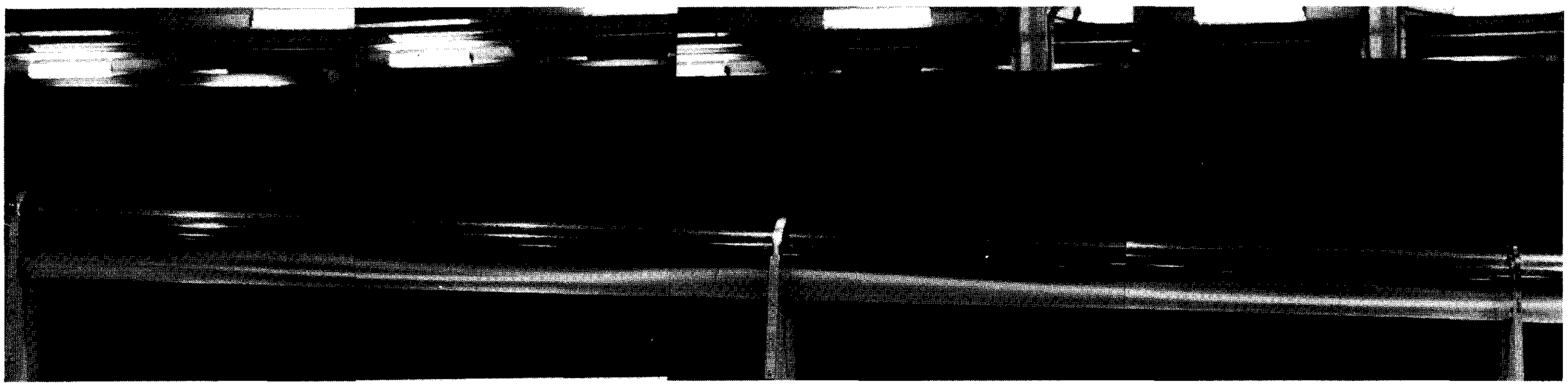


Figure 16. – Rocking conduit flow. P-801-D-81003

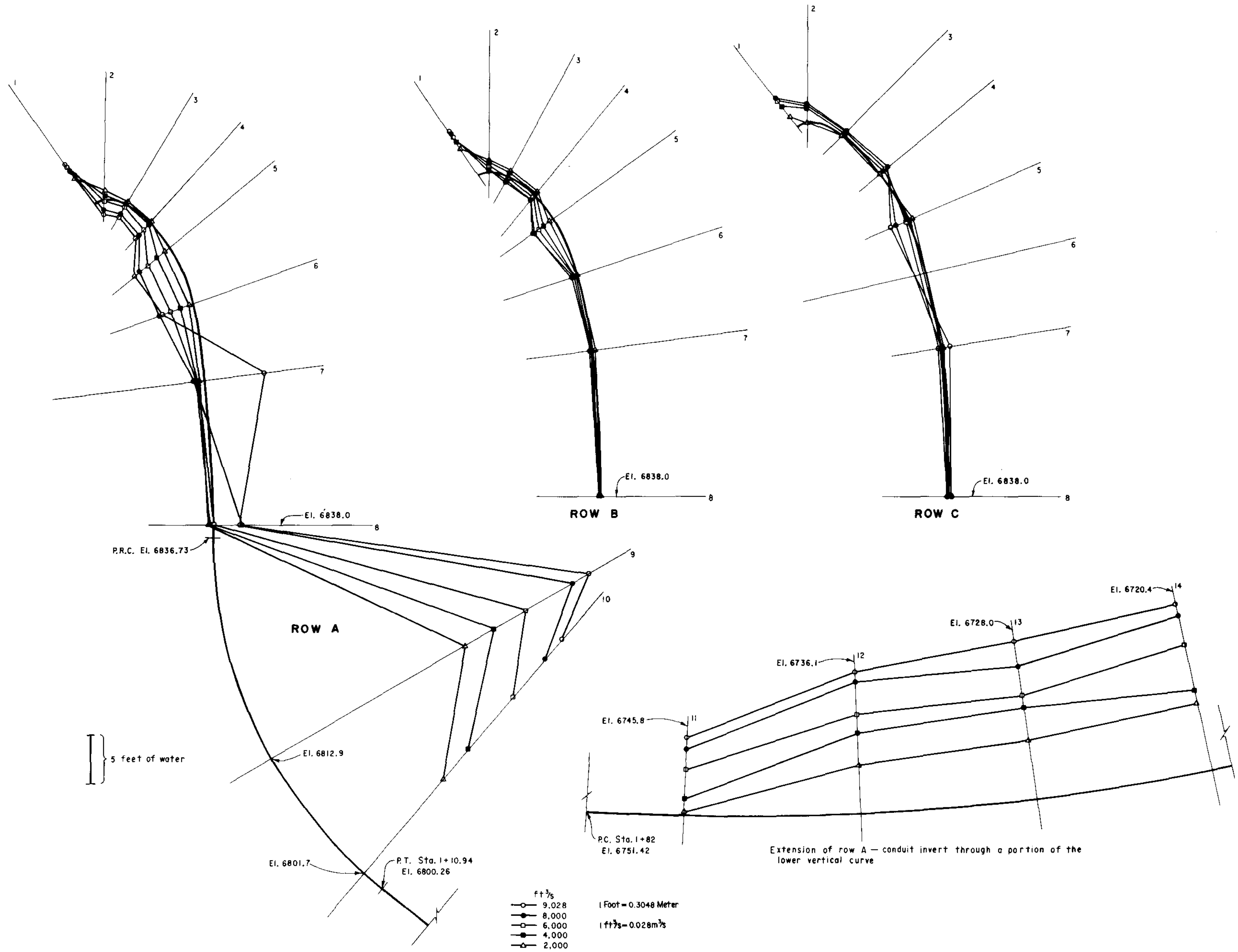


Figure 17. – Observed flow surface pressures.

Piezometer rows A and B show similar pressure distributions (fig. 17). In both cases the increased intake curvature results in more extensive subatmospheric pressure regions, which extend from the crest down to approximately the location of piezometer 7. As with piezometer row C, the pattern tends to show that larger discharges yield greater subatmospheric pressures. For row A, the maximum observed negative pressures was −5.0 feet (−1.5 m) of water. This was observed at piezometer 5 with a discharge of 9,028 ft^3/s (256 m^3/s). Even though this pressure is substantially negative and potentially dynamic fluctuating pressures could be lower, it should be noted that the elevation of piezometer 5 is approximately 18.6 feet (5.7 m) below the maximum water surface elevation. Thus, there is not sufficient energy in the flow to develop cavitation pressures and, therefore, cavitation damage. Pressures on piezometer row B (in the pier wake) tend to be higher than those for row A. Thus, although the subatmospheric pressure region for row B is still quite extensive, pressures on the flow surface tend to be closer to atmospheric. Maximum subatmospheric pressures were again observed at piezometer 5, where a pressure of −3.7 feet (−1.1 m) of water was observed at a discharge of 9,028 ft^3/s (256 m^3/s). No potential for cavitation damage is indicated.

Pressures observed on the invert of the spillway conduit are shown on figure 17. All pressures observed were positive. In particular, pressures in both the upper and lower vertical curves were quite high because of the pressures and forces associated with the flow momentum change.

As a final check or evaluation of the cavitation damage potential of the structure, a computer program analysis of the structure was conducted. The study used the computer program HFWS developed in the Hydraulics Branch by H. T. Falvey. The program considers discharge, flow velocity, flow surface shape, and boundary layer development, and it predicts potential cavitation damage. The program does not consider air entrainment and its potential damage-reducing influence. Although there will be less air entrainment in the Ridgway Dam spillway than in conventional morning-glory spillways, there will still be substantial entrainment at, and downstream of, the upper vertical curve. The computer analysis showed that without air entrainment there is very little potential for cavitation damage, even after years of continuous operation. The analysis indicates that aeration slots are not necessary. It is, however, recommended that to reduce the risk of damage, all surface offsets should be tapered with 1:20 chamfers. The most critical area requiring care in surface tolerances is between station 9+50 and station 10+50, which is in the open chute just above the stilling basin.

With intake and conduit flow conditions set and evaluated, demand at the air vent is set and can be evaluated as a function of water discharge. It was noted that the size and configuration of the air vent conduit was not set in the initial design and would be sized and designed based on the findings of the model study. Therefore, different size orifice plates representing various air vent conduit flow restrictions were placed on the modeled air vent (fig. 10). Sharp-edged orifices with diameters of 1.27, 1.11, 0.95, 0.79, 0.63, 0.48, 0.32, and 0.16 feet (0.39, 0.34, 0.29, 0.24, 0.19, 0.15, 0.10, and 0.05 m) were used. The model was then operated at different water discharges, the corresponding pressure differentials were measured, and the air discharges were computed. Consequently, the data obtained define the relationship between water discharge, air discharge, and differential pressure across the air vent and air vent conduit (fig. 18). The differential pressure, in the final design, is a function of the air vent size and of the air vent conduit configuration. The design process using the information shown on figure 19 is to first establish the minimum acceptable air pressure in the spillway conduit. With this pressure established, the allowable differential pressure across the air vent can be determined. Figure 18 is then used, and a required air discharge that corresponds to the acceptable differential pressure is obtained. The air vent and air vent conduit may then be designed to supply this maximum air discharge with the acceptable differential pressure.

As can be seen on figure 18, it was found that for this particular spillway and crest configuration (figs. 7 and 8), the differential pressure across the vent was very small for all water discharges. This prototype differential ranged from approximately 0.095 foot (29 mm) of water at a water discharge of 3,000 ft^3/s (85 m^3/s) to approximately 0.38 foot (116 mm) of water at the maximum water discharge of 9,028 ft^3/s (256 m^3/s). It can also be seen on figure 18 that for a particular water discharge the differential pressure is constant and independent of the air discharge and, thus, of the vent size over the range of vent sizes considered. The largest vent considered in the model (which represents the minimum vent conduit restriction) was a 15.23-inch (387-mm) diameter sharp-edged orifice with no conduit. The smallest vent (the maximum restriction) considered was no vent at all. In other words, the 15.23-inch (387-mm) diameter vent yields the same pressure within the conduit as no vent at all, and the conduit pressures are very near atmospheric. This indicates that the vent has no significant influence and is not needed.

Observation of the spillway shows that there are two sources of air venting other than the air vent. First, to a greater or lesser degree, venting will occur down from the crest. At discharges below 3,200 ft^3/s (91 m^3/s), the raised crest section functions as a splitter pier. It creates a large air passage through the flow entering the crest intake. Under these conditions, substantial venting that dominates over the air vent occurs. At higher discharges, as the flow passes over the raised crest, this air passage from above is gradually sealed off. However, even at the maximum discharge there is likely some air venting from the crest. The second source of air venting is the reverse, or upstream, flow of air above the free water surface from the downstream end of the conduit.

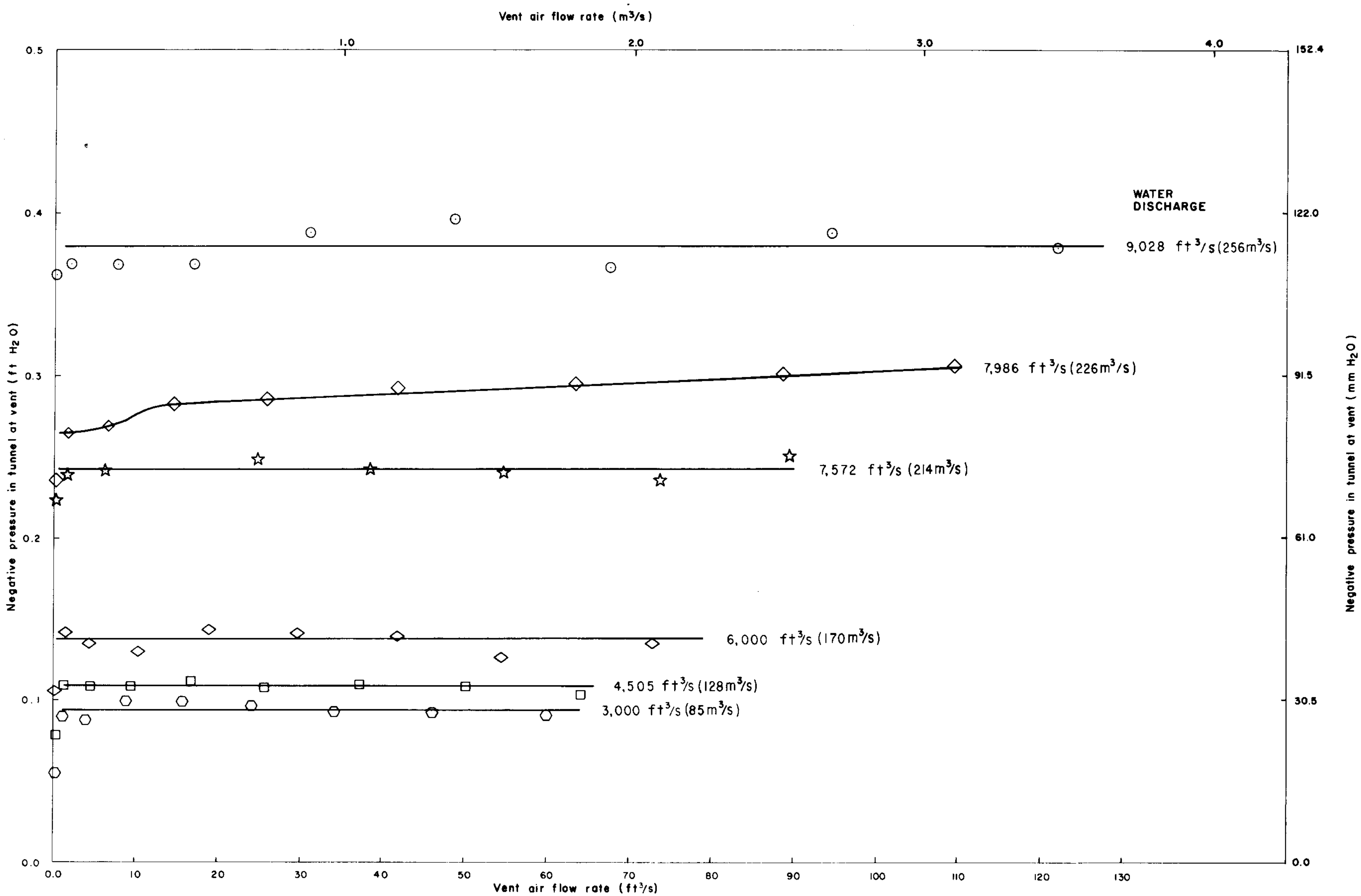


Figure 18. – Air vent demand.

Figure 19. – Unsymmetrical hydraulic jump. P-801-D-80993

Leutheusser and Chu [1]* have studied turbulent reverse air flow above an interface and have developed a dimensionless parameter that indicates when reverse flow (to the water) will occur. This parameter is a function of the size of the airflow passage, the pressure gradient in the air, the water velocity, and the dynamic viscosity of air. Because the flow accelerates throughout the spillway conduit, water velocities and the size of the airflow passage constantly change. However, using average conditions, Leutheusser and Chu indicate that venting will occur from downstream even at the maximum water discharge. The combined venting from the crest and from the lower end of the conduit is more than adequate to prevent the development of significant negative pressures. The air vent has very little additional impact.

The Stilling Basin

The action in the stilling basin is a function of flow conditions in the spillway conduit. Severe rocking of the conduit flow may result in unsymmetrical flow entering the stilling basin. This could

* Number in parentheses refer to entry to the bibliography.

yield unsymmetrical stilling action with potential back eddies, reduced basin self-cleaning, and an increased chance for erosion damage to the basin structure. Poor stilling action was observed for many of the alternative crest treatments studied. An example of these poor conditions is shown on figure 19. However, for the final recommended crest treatment, action within the stilling basin was satisfactory for all discharges (fig. 20). The hydraulic jump was uniform and no back eddies were observed within the basin over the full discharge range.

Substantial wave action and higher velocity bottom flow occurred downstream of the stilling basin structure at the higher discharges (fig. 20). Wave heights were monitored along the riprapped banks in the immediate area of the stilling basin. The observed trough-to-crest wave heights as a function of location and discharge are shown on figure 21. The wave heights shown on figure 21 are the 99.98-percent maximum. The 99.98-percent wave was evaluated through the use of probability plots of observed data. Because riprap stability depends on the occasional maximum wave, the 99.98-percent wave is recommended for use in riprap sizing. Note that the greatest waves tend to occur at the maximum discharge, and that the largest waves occur 50 to 150 feet (15 to 45 m) downstream of the exit from the stilling basin. The 99.98-percent maximum wave height observed was 4.4 feet (1.3 m) on the left bank and 4.8 feet (1.5 m) on the right bank.

Flow velocities were measured downstream of the basin both along the centerline and near the toe of the 2.5:1 and 2:1 slopes. Velocities were measured at elevations approximately 3.0 feet (1.0 m) above the bottom. Figure 22 shows the instantaneous peak velocities observed. Again riprap stability depends on these instantaneous maximums and, thus, design should be based on these values. Note that the maximum discharge tends to, but does not always, yield the highest velocities. The highest velocities occur either near the stilling basin exit or at the downstream end of the 6:1 sloping bottom. As can be seen, maximum peak velocities are approximately 13 ft/s (4.0 m/s), and maximum average velocities are approximately 7 ft/s (2.1 m/s).

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[1] Leutheusser, H. J., and Chu, V. H., "Experiments on Plane Couette Flow," Proceedings, A.S.C.E., J. Hyd. Div., vol. 97, No. HY9, pp. 1169-1283, September 1971.

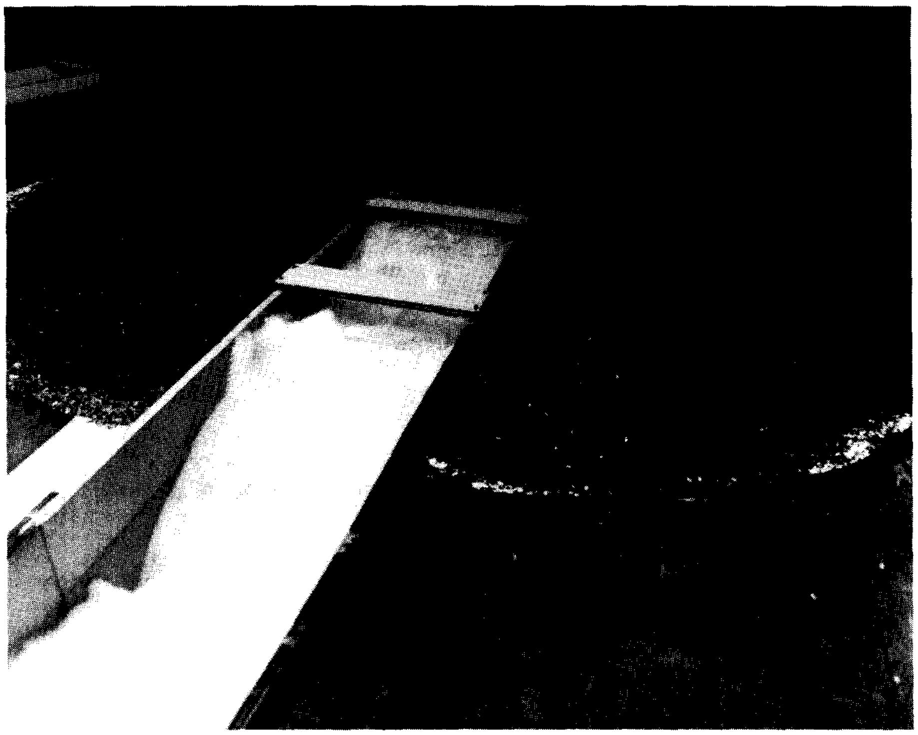

Figure 20. – Stilling basin and tailrace flow, 9,028 ft³/s (256 m³/s). P-801-D-80994

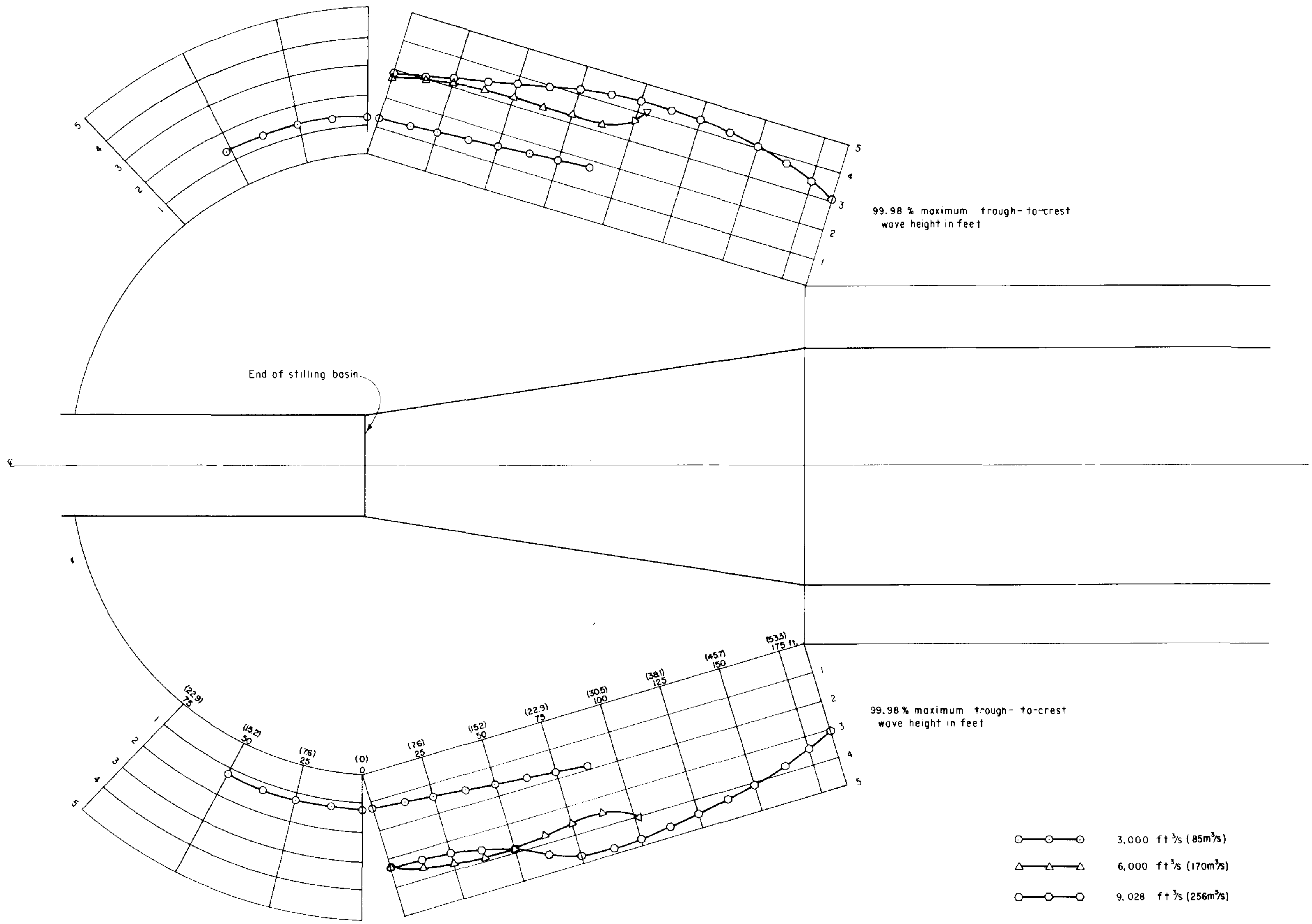

Figure 21. – The 99.98-percent maximum tailrace wave heights.

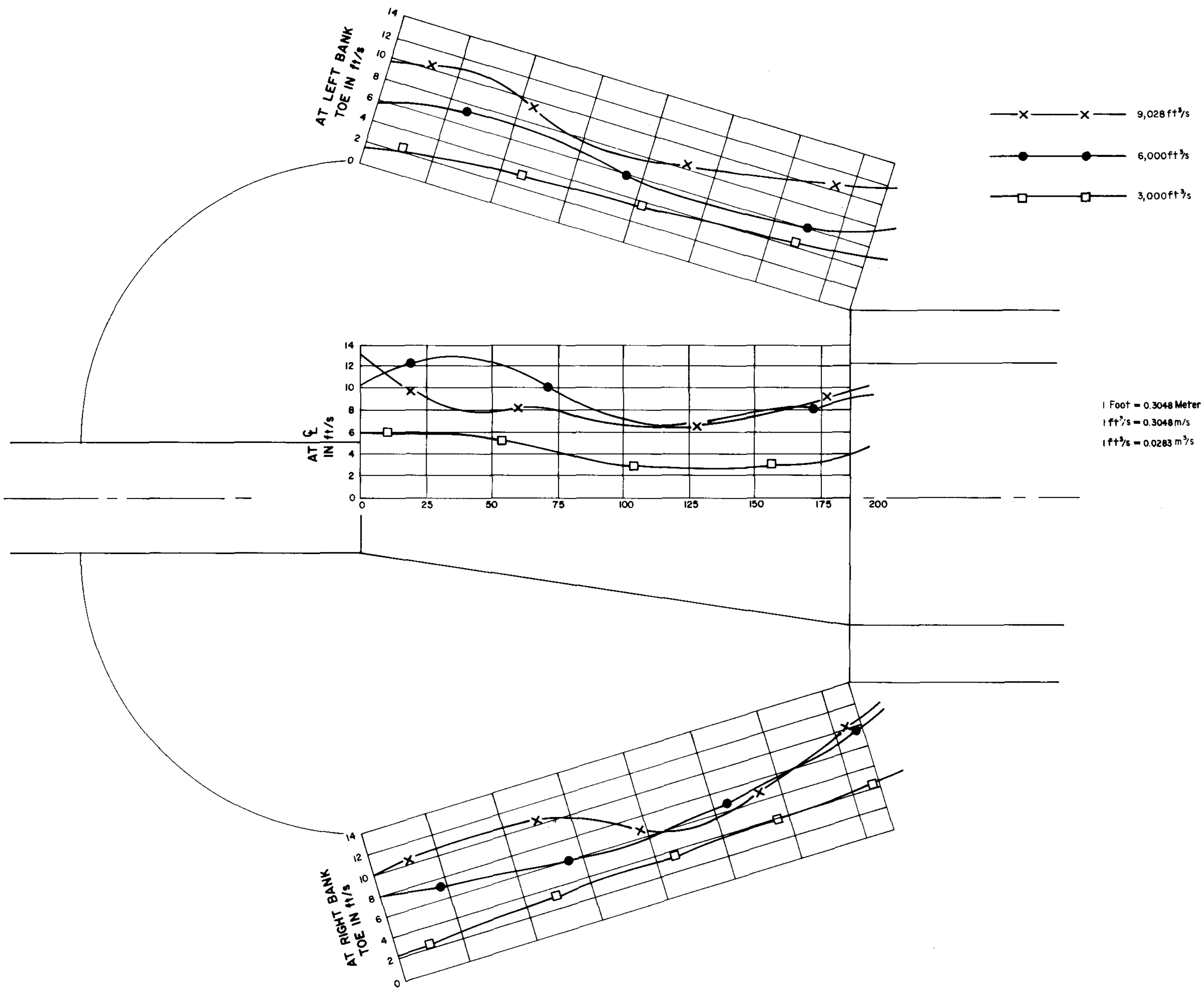

Figure 22. – Maximum instantaneous tailrace bottom velocities.

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