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SOUTH FORK TOLT DAM: SPILLWAY MODEL STUDY

Eugene P. Richey
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Water Resources Series
Technical Report No. 60
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TOLT RIVER DAM SPILLWAY

photo courtesy of Seattle City
Engineering Department

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PREFACE

A hydraulic model study of the spillway on the South Fork Tolt River Dam was authorized in the Scope of Work statement from the Seattle Engineering Department December 1978, entitled "TOLT RIVER DAM SAFETY ANALYSIS--HYDRAULIC MODEL STUDIES". This dam is one of those inspected under the National Dam Safety program, enacted under Public Law 92-367 with a Phase 1 Inspection Report "Snohomish/Snoqualmie River Basin South Fork Tolt River Dam WA-177..." prepared by the Seattle District, U.S. Army Corps of Engineers, September 1978. The Scope of Work responded to certain recommendations in the Corps report regarding spillway performance characteristics.

The study was performed in the Charles W. Harris Hydraulics Laboratory by Professors E.P. Richey and R.E. Nece, and Research Engineer H. Norman Smith under an Intergovernmental Agreement between the University of Washington and the Seattle Engineering Department during the period January 1, 1979 to April 30, 1979, and administered through the University's Office of Grants and Contracts under Budget Number 63-1642.

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I. INTRODUCTION

The Tolt South Fork River Dam completed in 1962, is a major element of the Tolt River water supply system for the City of Seattle. The dam, located in the Cascade Mountains about 30 miles east of Seattle, is an earthfull structure 200 feet high, and with a crest length of 980 feet at the design crest elevation of 1775 MSL. The reservoir capacity is 56,000 acre-feet at normal pool elevation.

The dam has a morning glory spillway with a 40-foot diameter mouth at its crest elevation of 1757 feet MSL, which transitions into an 18-foot diameter vertical shaft at Elevation 1737.1 feet. This shaft turns through a 90°, 35-foot radius elbow and then into an 18-foot horseshoe conduit having a centerline elevation of 1609.5 feet. A 10-foot by 10-foot outlet and diversion conduit enters the main conduit at the heel of the elbow. The 570-foot long horseshoe conduit transitions to a 24-foot wide, 480-foot long, open rectangular concrete chute. These sections have a slope of 0.01. The chute makes a drop to a stilling basin that connects to the Tolt River through a discharge channel. The spillway, chute and stilling basin were designed for a flow rate of 10,000 cfs, and this design was tested in a 1:48 scale model by Richey and Strausser (1958). Strausser and Unrue (1967) tested the diversion control valve and diversion conduit.

A moveable ring gate 8 feet high and 37 feet in diameter, operated by a hydraulic jacking system, has been used as a reservoir stage regulator to increase storage capability to elevation 1765 for dry-season water supply. This gate was designed to be in either the closed or the open position, but not as a regulating valve or overflow section; it was not a part of the 1958 spillway study.

The recommendations cited in the U.S. Army Corps of Engineers Phase 1

Inspection Report of the South Fork Tolt River Dam (September 1978) formed the basis for the Scope of Work prepared by Seattle Engineering Department to "...research by means of a physical model the hydraulic capacity of the morning glory spillway and ring gate, and the hydraulic effects on the ring gate as described in more detail in the following sections." These sections are abstracted as follows:

> The study will involve the construction of a hydraulic model and conducting tests and analyses to determine the hydraulic capacity of the spillway system and determine forces, stresses, air requirements and indications of vibration and problems that may be predicted from the model tests.
>
> The model will be tested to obtain rating curves for the following conditions:
> 1. Ring gate in fully elevated (open) position
> 2. Ring gate in lowered (fully closed) position.
>
> Particular attention will be focussed on that range of flows when the discharge changes from control by the weir to control by the downstream shaft-conduit system.
>
> Model tests involving the ring gate will include observations and tests to determine potential for flow problems created by lack of air vents, nappe instability, poor alignment on top of the morning glory section, by interference of tower pier supports, or other features of the ring gate and spillway system as they exist at the dam.
>
> The gate shall be tested to show flow characteristics throughout a range of representative combinations of gate openings and reservoir elevations. Nappe conditions will be observed carefully to detect any conditions conducive to gate vibrations. Problems in simulating elastic properties of materials and frictional effects in the gate control mechanisms cannot be measured in the model, so it is proposed to evaluate the hydrodynamic forces by computational procedures for cases with flow beneath the ring gate as well as for the closed position. These procedures will lead to a description of the pressure field on the gate for input to a structural model.
>
> A discussion of the state-of-the-art theories to compare model results and to explain problems discovered and possible solutions shall be addressed.

II. MODEL DETAILS AND TESTING PROCEDURES

The Model

Some components of the 1958 model, those extending from the spillway to the downstream end of the 90° elbow, had been kept in the Harris Hydraulic Laboratory. These sections had been expensive to fabricate in 1958, so the obvious choice for the new model was to key its dimensions around the early study, for which a 1:48 scale had been selected because of its convenient match with standard sizes of acrylic pipe and the capacity of the machine shop lathe to handle the rough dimensions of the laminated 3-inch acrylic plate used in the fabrication of the spillway section. A 4.5-inch diameter pipe converted neatly to the 18-foot shaft diameter. The horizontal elbow and some straight sections of the conduit had to be re-fabricated for the present study. The respective areas and hydraulic radii, circular in model, horseshoe in prototype, compared very closely with each other, so the same conduit was used in the current model. The reservoir, with the upstream dam face sloped at 1:2, was made as a plywood tank 8 feet wide and nearly 11 feet long. The 8-foot width gave a ratio of spillway diameter to tank width of nearly 1 to 10, a value that adequately approximates near-spillway flows in the very wide reservoir. The incoming water supply was measured with a Dall tube, and admitted to the model though a 4-inch diameter PVC pipe, terminating in a diffuser running the width of the tank. A 1-foot thick rock wall baffle was installed to serve as a final flow distributor. Water surface heights were measured with conventional hook and point gages; an air-water manometer was attached to a piezometer tap used to measure pressures in the throat of the spillway. A sectional view of the model is depicted in Figure 1. Photograph 1, Figure 2, shows the model spillway with piers, ring gate on the crest, and ventilation tubes used in a part of the study protruding from the gate control platform.

The model was tested using conventional Froude law scaling. This relationship is expressed:

$$\frac{V_r}{\sqrt{g_r L_r}} = 1$$

where $V_r = \frac{V_{model}}{V_{prototype}}$, the velocity ratio, where V_m and V_p are fluid velocities at corresponding ("homologous") points in the model and prototype, respectively.

$L_r = \frac{L_{model}}{L_{prototype}}$, the physical length scale ratio.

g_r = ratio of gravitational attrations (unity).

The corresponding ratio of discharges can then be expressed

$$Q_r = \frac{Q_m}{Q_p} = A_r V_r = (L_r)^2 (L_r)^{1/2} = (L_r)^{5/2} .$$

For the present model:

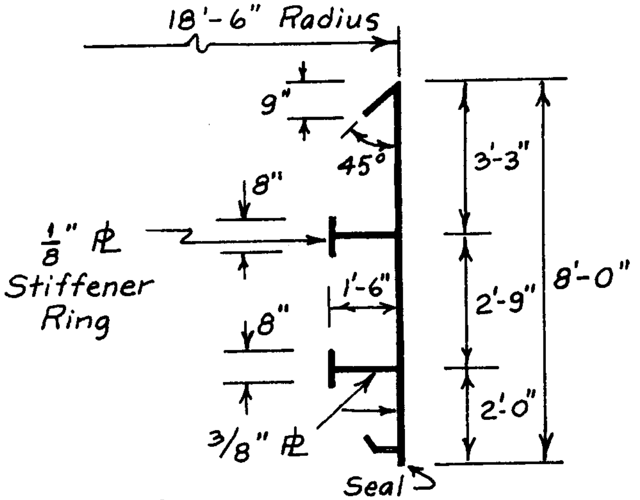
$L_r = 1:48$

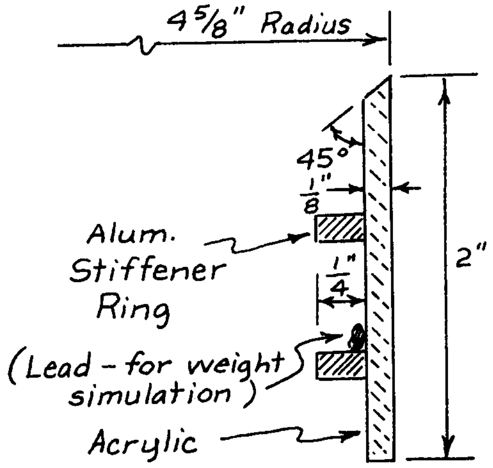
$Q_r = (1:48)^{5/2} = 1:15962.58$

Also, based on similar dimensionless hydrodynamic pressure distributions in the model,

$$F_r = A_r (\Delta p)_r = (L_r)^2 (V_r)^2 = L_r^{\ 3} ,$$ where F_r is the force ratio.

The 8-foot high ring gate (2 inches in the model) was made from 1/8-inch acrylic plate heated and molded over a plug machined to its 37-foot (0.771 feet in the model) diameter for seating on the crest of the spillway. The upper edge of the gate was machined to a sharp edge conforming to the design configuration of the prototype gate. The circumferential T-section stiffening rings were simulated with aluminum bar having the outside dimensions of the T-section. No attempt was made to simulate any of the elastic characteristics of the prototype structure, but the weight of the ring gate was adjusted so that its submerged weight would be in scale with the submerged weight of the prototype gate. Cross-sections through the prototype gate and model gate, respectively, are shown in the sketch below.





Operating procedures

Spillway rating curves, i.e., Flow Rate versus Head (Reservoir Elevation) were obtained for the following combinations of the spillway:

1. No piers, no gate
2. With piers, no ring gate
3. With piers, ring gate in raised position
4. With piers, ring gate in lowered position (on crest), no ventilation
5. With piers, ring gate in lowered position, with ventilation

For each spillway combination, flow rates were measured for incremental heads of about 0.5-foot prototype. Special care was taken at each flow to record indications of vibration, development of air pockets, tendencies for throttling in the vertical shaft, special streamline patterns, jet profiles, the effects of ventilation, and other unusual responses.

A piezometer tap was made in the inside wall of the vertical shaft at Elevation 1723.75 (33.25 feet below the spillway crest elevation) on the side closest to the dam face (see Figures 1 and 7) for the purpose of exploring how the pressure at that location varied with the flow rate. Runs were made for the cases with and without piers, with no ring gate.

III. MODEL TEST RESULTS

Spillway Discharge Performance

The spillway calibration curves for the different combinations of piers, ring gate position, and ventilation are shown in the Figures 8, 9, and 10, with the basic data and additional comments given in Tables 1-5. Data points for the cases with "no piers, no gate", "piers, no gate", and "ring gate lowered, ventilated", have been added to the predicted rating curves appearing as Plate 5 in the Corps of Engineers Phase 1 Report (1978) and reproduced herein as Figure 11.

No Piers

The test sequence for the case with no piers and no ring gate was run to cross-check the results given in the 1958 report, and to extend the rating curve to an upper limit as dictated by the dam crest elevation or some other, lower critical control. The calibration curve in the 1958 study had been taken up only to 12,000 cfs, a rate limited by the performance of the stilling basin; the rating curves for the two studies up to that flow rate are in very good agreement. As noted on Figure 8, the first critical point appears at a flow rate near 16,000 cfs, where the condition for conduit control begins. There was no evidence of an orifice control. Full conduit control, with the attendant rapid rise in the H-Q curve, took over at about 18,000 cfs.

The sloping dam face has a marked influence on the approach velocities to the spillway. The upper nappe develops a rooster-tail like profile on the dam axis side, as illustrated in the photographs of Figures 4 and 5 and profile plots of Figures 14 and 15. The dye patterns in Figure 6 show the curvilinear flow, the absence of radial symmetry, and a stagnation zone along a vertical plane normal to the spillway circumference at its nearest point to the dam axis. This point was the location recommended in the 1958 report for one of the three piers supporting the gate structure. Any tendencies for vortex motion are damped out in the vicinity of this stagnation plane.

With Piers

The calibration test results with the piers in place and ring gate raised, Figure 9, show no change of consequence in the head-discharge relationship, due to the piers, for flows less than about 8000 cfs. Above this level the head for a given discharge is about 0.1-foot higher with the piers in place. The water surface begins to touch the bottom of the ring gate at a flow of just over 12,000 cfs, and becomes somewhat unsteady thereafter. Tests were not continued to higher flows.

Ring Gate On Crest, Unvented

The calibration test results with the ring gate in position on the dam crest are shown in Figure 10 for the two cases, with and without ventilation provided to the underside of the nappe. In this test series, the ring gate was sealed to the dam crest with a silicone cement. With the upper edge of the ring gate now serving as a sharp-crested weir, the jet initially trapped an air pocket above the spillway. This pocket decreased with time and increasing flow rate. For the sequence given in Table 4, the air pocket was depleted by the time the flow rate had been increased to about 5500 cfs. The flow rate has to be large enough, about 2000 - 2500 cfs, for the nappe to spring from the ring gate and strike the spillway for the air pocket to be formed. Bubbles were noted inside the gate, the flow in the shaft became quite noisy, and vibrations could be felt in the structure as the flow rate was increased. Some gulping in the spillway shaft started at a flow of about 7000 cfs. The symptoms of a non-ventilated weir were quite evident. The water surface reached the bottom of the platform beam on the dam-axis side at a flow rate of about 12,000 cfs.

Ring Gate on Crest, Vented

The gate support piers did not create the conditions necessary for the ring gate to operate as a ventilated weir, so a tube was inserted behind each pier. These were 1/4-inch diameter (one foot prototype) held in place by slide-fit holes in the gate platform. Their location in the wake region behind the piers is advantageous since there is no interference with the flow over the spillway, the force on the tubes is lowest, and the pressure field is favorable for aerating the spillway jet. The top of the tube was open to the atmosphere, and the bottom of the tube was located below the lower stiffener on the inside of the ring gate. Just one tube supplied enough air for complete ventilation. The ring gate with the tubes is shown in the raised position in Figure 3. For the case with the ventilated ring gate, shown on Figure 10, an increase in head of 0.2-0.3 feet above that for the un-vented case is needed to discharge an equal flow (above about 4000 cfs). At a flow of 3000 cfs, the nappe becomes fully ventilated and remains so to the maximum flow tested. The water surface touches the bottom of the platform beam at a flow just under 12,000 cfs, and reaches the dam crest elevation of 1775 at a rate of 14,000 cfs. With ventilation, the flow was steadier, and much quieter than in the unvented case. No measurements of air demand rates were attempted.

Comparison with Predicted Rating Curve

The data points from the model fall slightly above the curve predicted in the Corps of Engineers Phase 1 Report (Figure 11) for the case with the ring gate in the raised position for flows less than about 8000 cfs. The departures may be due to a different design procedure used for the spillway as constructed from that selected for prediction in the Phase 1 Report (page 14). The significant difference between the two curves, however, lies in the fact that the orifice control does not develop in the model. This subject will be discussed in more detail in the next section. The agreement between the predicted rating curve and the model results for the case with flow over the ring gate is very good, indeed, up to about 9500 cfs, when the model data show a slightly more efficient performance, but at that flow rate, the reservoir elevation had reached within 1.5 feet of the top of the embankment.

Throat Pressure

A piezometer tap was placed at point "P", Figures 1 and 7, to explore in a limited way the expected negative pressure in the throat section of the spillway. Orifice control had been predicted to begin (Phase 1 Report, page 14) at a flow rate of approximately 10,000 cfs, but did not occur in the model at any flow rate. Obviously a negative pressure had to have formed in the throat of the vertical shaft. The measurements of the pressure head are given in Tables 6 and 7, and are plotted on Figures 12 and 13 for the two cases, No Piers and With Piers, No Gate. The pressure head is slightly positive up to a flow of about 9000 cfs with no piers, about 8000 cfs with piers, then becomes increasingly negative with increasing flow rate, reaching -20 feet at a flow of about 12,000 cfs, and would reach cavitation levels in the vicinity of 16,000 cfs.

Discussion of Spillway Performance

Without ring gate. The spillway performed in a predictable manner in most respects. The formation of the rooster tail attributable to the effect of the variable approach depths, with the shallow depth on the dam-axis side, had appeared in the 1958 study. The orifice control did not develop; the formation of the negative pressures in the throat, verified by measurements, explain why it did not. A telephone conversation (April 1979) with Mr. J.S. Smith (formerly with the design firm of Carey and Kramer) was set up to discuss the bases for the original design. It was Mr. Smith's recollection that the spillway geometry had been shaped for a flow rate "between 7500 and 8000 cfs", and that the diameter was made "just a little bit bigger" than design numbers would indicate necessary, to insure that the orifice control would not develop. His prediction was very good. It follows, then, that the pressures over the spillway will be negative for those flows in excess of the 8000 cfs for which the spillway was shaped. This performance is confirmed by the shaft piezometer measurements that show the pressure changes from slightly positive to negative at flows in excess of 8000-9000 cfs, depending upon whether or not the piers were in place. The position of the piezometer tap, point P, was set by structural and access limits in the model, rather than at the location where negative pressure might first develop. Due to the asymmetry in the flow, it should be noted that the pressure in the shaft at any elevation, as at Point P, will vary circumferentially. Diersch, et al, (1977) apply a finite element analysis to flows over spillways, and include an example of a morning glory tube, showing computed free surface and pressure distribution with large negative heads. His work on the two dimensional spillways is more complete, showing the increase in weir coefficient with increasing ratio of H/H_D, the ratio of head on the spillway to design head, the condition that develops in the Tolt Spillway.

With Ring Gate on Crest. The model based strictly upon the Froude similarity criterion does not simulate the air demand or entrainment characteristics in the prototype. There are offsetting effects, as discussed by Babb, et al (1973), so it is not always clear whether model results are conservative or not. The shaft spillway modeled by Babb was much different from the Tolt design, but did make use of piers with blunt downstream faces to provide ventilation. His model showed this ventilation effect and he makes the statement:

> "To prevent subsequent nappe pulsations, three of the twelve spillway piers are thicker than the others and have blunt downstream faces. This creates a discontinuity in the nappe immediately downstream from the piers ... which permits free air flow and this complete ventilation."

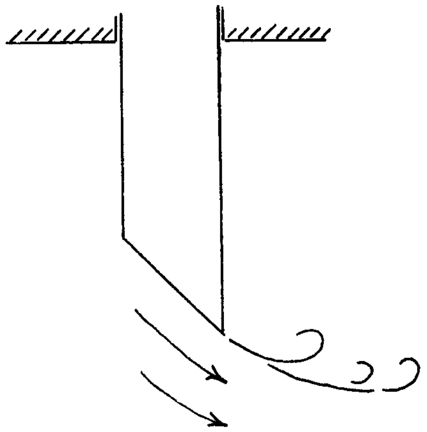
The piers in the Tolt model did not provide a sufficient "discontinuity" to develop the ventilated case.

Ring Gate Stability

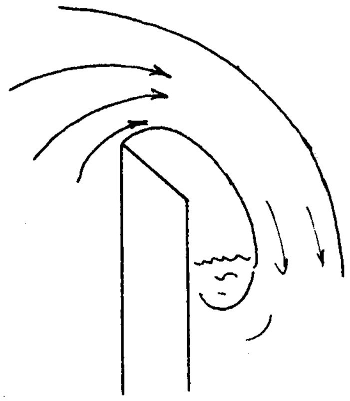
The characteristics of the flow over the ring gate were checked with the gate sitting on the spillway crest without any restraint. (As noted earlier, the ring gate had been cemented to the crest during the development of the rating curve for flow over the ring gate). In the un-vented case, the air pockets formed as they had done with the model gate cemented to the crest. However, at the instant the last bit of air was exhausted from the pocket, the ring literally jumped off the spillway crest. Of course, the moment that it was lifted even slightly, it became unstable. When the ventilating tubes were inserted behind the ring gate, it remained stable on the dam crest for all flow ranges. The buoyant forces had been simulated by the model ring; its behavior in the un-vented case indicates the occurrence of unsteady hydrodynamic forces, with a net upward component that could initiate undesirable vibrational effects in the gate.

The abrupt way the gate raised off the crest as soon as the air pocket was exhausted suggests a sudden change in pressure around the gate, perhaps analogous to the "gate downpull" phenomenon, but with the force direction upward. The weir crest may act as a lifting vane when completely submerged. To check this supposition, the square edges of the gate bottom face making contact with the spillway crest were rounded off, and the gate was turned upside down, with the now sharp weir crest sitting on the spillway crest. The gate was quite stable in this position.

Campbell (1961) discusses the "downpull" of control gates and vibrational problems in hydraulic structures. He sketches the development of the "Standard 45°-Lip" for gates which reduced vibrational effects and the downpull. The top edge of the Tolt ring gate has a slope of 45", but in the opposite direction to that in the "Standard 45°-Lip", i.e., it slopes away from the approaching flow, instead of toward it. (It was not designed to serve as an overflow structure). This comparison is shown in the sketch below.



Standard 45° Lip

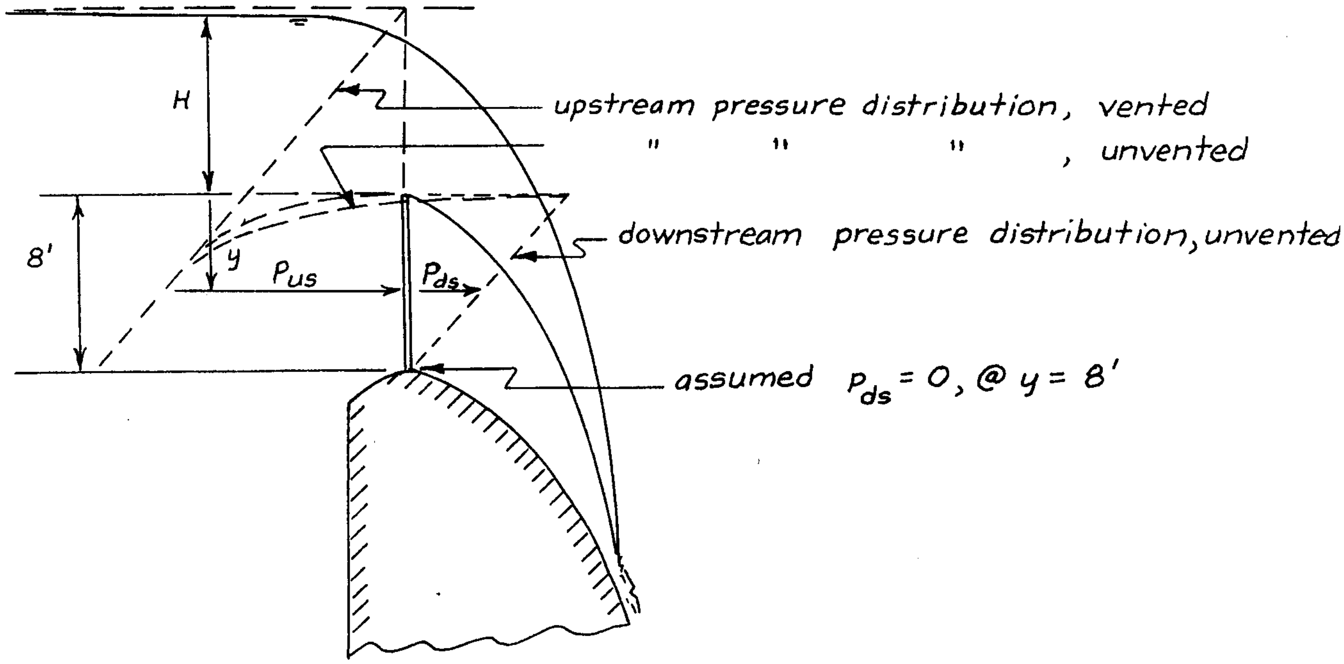


Tolt Ring Gate Lip
(air not completely
evacuated)

Gate Forces

When the flow over the top of the ring gate is not ventilated, an upward force develops which is large enough to lift the model gate (buoyancy forces in scale) off the crest. The gate control rods in the prototype thus would be placed in compression. The net horizontal force on the ring gate, when flow occurs over it, is not zero because of the sloping dam face and variable approach depths.

The calculations of the radial force on the ring gate when it is serving as a spillway are based upon a pressure distribution on a weir as shown by Rouse (Elementary Fluid Mechanics, John Wiley and Sons, 1946, p. 93) for the vented case. For the unvented case it is assumed that the pressure head at the lip of the weir is -8.0 feet, the amount needed to raise the water to the elevation of the lip as the air pocket is evacuated if the pressure is assumed to be zero at the bottom of the gate on the downstream side. This assumes a hydrostatic distribution in the "water pocket" which replaces the evacuated air, and may be on the low side at high flow rates, but is in line with other estimates. The pressure field varies circumferentially due to the varying approach depths. An experimental program to measure the pressure distributions and/or forces on the gate was beyond the scope of the present study, but such a program would be required for a precise determination of the pressure field.



From the above sketch, ignoring the velocity head at the crest, the pressure distributions are

$$p_{us} = \gamma(H + y)$$

$$p_{ds} = \gamma(8 - y)$$

For the vented case,

$$p = p_{us} = \gamma(H + y)$$

for the unvented case, ignoring in the force calculations the requirement that the pressures are equal on both sides of the gate lip,

$$p = p_{us} + p_{ds} = \gamma(H + 8).$$

The radial force per foot of circumference is $\int p\, dy$ (1), and for H up to 10 feet:

	Ventilated		Unventilated	
Head, H, ft	p_{max}, psf	Force ppf	p_{max}, psf	Force ppf
0	500	2000	500	2000
2	624	3000	624	5000
4	748	4000	748	5980
6	874	5000	874	7980
8	998	6000	998	7980
10	1123	7000	1123	8980

Spillway Noise and Vibration

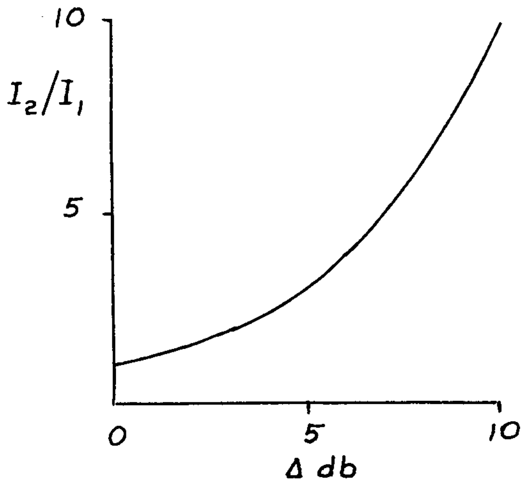
The changes in sound and vibration in the spillway-conduit system as dependent upon flow rate and gate operation (open, ventilated, and unventilated) were found to be inadequately described in notes taken during the spillway discharge calibration runs. (The comments on the data sheets were the aural impressions of the observers during these runs). To reduce reliance upon the human senses, a brief supplemental experiment was run in which the "noise" was measured with a sound level meter (Model 40, Pulsar Instruments, Redwood City, California) held above the spillway. Accelerometer Number 1 was mounted on the flange at the top of the elbow at the base of spillway shaft and unit number 2 on the conduit about 8 diameters downstream of the elbow. See Figure 1 for instrument locations. Outputs from the accelerometers were put on an oscilloscope for instantaneous viewing and onto a Brush oscillograph for recording purposes. No special effort to damp vibrations in the conduit had been made in the model during the spillway calibration runs. To check potential contributions to the noise and vibration levels on the conduit, accelerometer data were taken for several flow rates with the without sandbags at each conduit support. The accelerometer outputs were not calibrated to the oscillograph scales, so only relative comparisons can be made between readings.

The sound level meter registers in decibels, N, where

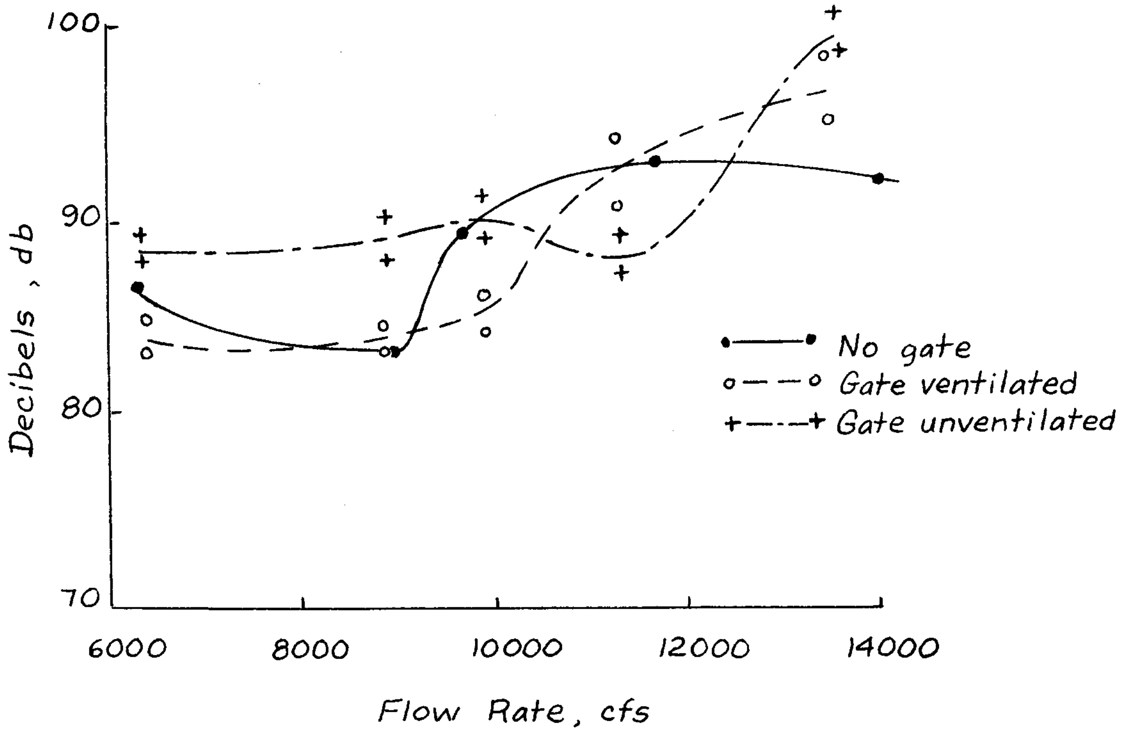
$$N = 10 \log_{10}(I_2/I_1),$$

where I_2/I_1 is the ratio of the relative values of sound at two levels. The following table and sketch illustrate the relationship

N, Δdb	I_2/I_1
1	1.26
2	1.58
3	2.00
4	2.51
5	3.16
6	3.98
7	5.01
8	6.31
9	7.94
10	10



The sound level measurements as dependent upon flow rate for three spillway cases (1) no gate, (2) gate ventilated, and (3) gate unventilated are given in Table 8 and graphed below. The "no gate" case shows a minimum in the vicinity of 8000 cfs, i.e., near the flow rate used in shaping the spillway, with an abrupt rise starting at about 9000 cfs. The slight decrease from the 14,000 to 12,000 cfs occurs as the conduit approaches the full condition.



The sound level for the unvented case stays in the 88-90 db range to above 11,000 cfs, then increases rather sharply thereafter. A comment on Table 4 recorded during a calibration run says "... flow in spillway in noisier" at Q = 11,640 cfs. This unvented case registers 4 db higher than the ungated spillway, but registers a lower value in the 11,000 cfs range; venting reduces the sound level for flows less than about 11,000 cfs. Table 5 has the remark that the flow (vented) was "fully aerated, quiet" at Q = 8230 cfs, which is consistent with the sound level readings, but the ear missed many of the changes in sound levels detected by the meter.

Samples of the oscillograph records (paper speed 25 mm/sec) for the two accelerometers for the ungated flow and for the gated flow both vented and unvented are reproduced as Figure 16. The "damped" and "undamped" notes refer to whether the sand bags were on or off the conduit at its supports. The damping reduces vibrations in the conduit as sensed by Gate 2, but does not appear to affect the response at Gage 1 located on the elbow at the base of the spillway shaft.

For the ungated case, the flow rate increase of just 800 cfs from 8800 cfs to 9600 cfs caused a bigger increase in vibration levels than did the first increase of 2500 cfs to the 8800 cfs flow. Changes are small above the 9600 cfs level, and there is apparently a slight decrease between 11,600 cfs and 14,000 cfs. These trends are consistent with those shown by the sound level meter.

For the gated cases, the changes are slight between successive flows; the large change between 8800 and 9600 cfs that occurs in the ungated case does not develop with the flow over the gate. There is little distinction between the vented and unvented modes. The accelerations appear to be greater in the gated cases than for the ungated case below about 9000 cfs, but lower for higher flows.

The sound and acceleration data substantiate other observations on the occurrence of conditions conducive to hydroelastic vibrations, and that there is a significant increase in response as the flow passes through about about the 9000 cfs level, which ties quite well to the flows reported on Figure 12 where the pressure head in the spillway shaft turned negative. The sound level readings and the accelerometers showed similar trends except that the effect of ventilating was not apparent on the accelerometer record. Of course, a spectral analysis of similar data should be undertaken to obtain a quantitative measure of the energy-frequency distributions as dependent upon flow rates and changes in the spillway controls.

IV. CONCLUSIONS

Without Ring Gate

The spillway geometry apparently was dimensioned for a flow rate of about 8000 cfs, which it handles very easily; above 10,000 cfs, low pressures develop in the throat. This present study looks at problems arising at flows exceeding the original design levels, and also at the use of the ring gate as an overflow structure, although it was not designed for this function. Today's more stringent hydrologic and management criteria have led to the increased hydraulic loading demands.

The pressure head at the reference point "P" stays positive for the case without piers up to a flow rate of about 9000 cfs, and up to about 8000 cfs with the piers. Above the 8-9000 cfs rates, the pressure head at "P" begins to be negative and reaches a value of -20 feet at about 12,000 cfs. Hydrodynamic instabilities associated with the low pressures at these high flows could lead to structural vibrations. At the 12,000 cfs flow, a separate critical condition is reached, i.e., the reservoir surface reaches the bottom of the ring gate when in its raised position.

The development of the negative pressures in the throat section prevented the flow control from shifting from weir hydraulics to that for an orifice. The piers did not ventilate the flow at any stage, and lowered the spillway discharge coefficient just slightly. At a flow rate of about 18,000 cfs, the weir control gave way to control by the downstream conduit.

With the Ring Gate

When the ring gate is in position on the spillway, it begins to function as an overflow weir at reservoir elevations in excess of the gate crest elevation of 1765 MSL. When the flow rates exceed the 3000-4000 cfs level in the un-vented model, the air pockets that form and break away indicate unsteady hydrodynamic forces, with structural vibrations a probably consequence. An upward lifting force developes due to the shape of the gate crest, with some force contribution from the stiffener rings very probable. The piers alone do not make the gate function as a ventilated weir. Ventilating the gate eliminates the upward force due to the negative pressure field in the vicinity of the crest and lowers the sound level for flows up to about 11,000 cfs. Just one 1/4-inch tube in the model provided adequate ventilation, so one 12-inch pipe behind each pier in the prototype would be sufficient.

The sound levels and vibrations recorded in the model do not, of course, translate directly to the prototype case, but when coupled with other hydraulic phenomena do aid in identifying conditions that would be conducive to hydroelastic vibrations in the prototype. The reduction in the response of the accelerometer on the conduit (gage 2) induced by damping at the supports suggests that a contribution to such "noise" came from the shock waves inevitably present in high-speed free surface flow when there are changes in alignments like those at the two elbows in the spillway-conduit circuit. Some of the vibration recorded at the gage mounted on the elbow flange and the elevated sound levels may have been initiated by the high-velocity flow past the diversion tunnel stub at the base of the elbow.

In summary, the spillway without the ring gate performs very well up to about 120% of the design (8000 cfs) flow. Some hydrodynamic vibration in the spillway shaft may be expected due to low throat pressures for flows higher than about 10,000 cfs. The ring gate is not a suitable overflow device for flows in excess of about 3000 cfs.

V. RECOMMENDATIONS

The following statements are based only upon the hydraulic performance of the model and do not weigh considerations of reservoir management or operational procedures.

The ring gate as now designed should not be used as a flow control structure, either with flow over the top or as an undershot gate because of the inherent unsteady hydrodynamic forces that could lead to structural vibrations, and because of the unsymmetrical pressure loadings caused by variable depths around the spillway.

If the gate must serve as a flow control structure, it should be redesigned. The crest should be re-shaped, full ventilation provided for, and a skin plate should cover the inside stiffener rings and any other projecting surfaces.

The gate height could be reduced to provide more clearance between the reservoir surface and the bottom of the gate when it is in the raised position. A six-foot gate, for example, would provide an extra two feet of clearance when in the raised position. In the lowered position, it would discharge a flow of 10,000 cfs with the pool elevation at 1771 MSL, instead of the presently projected elevation of 1773 MSL.

Although not a direct part of the study and no substantiating data were taken, it is recommended that serious consideration be given to plugging the diversion tunnel stub. This would provide a continuous smooth surface on the outside of the elbow and eliminate hazards associated with misalignments in high-velocity channels.

VI. REFERENCES

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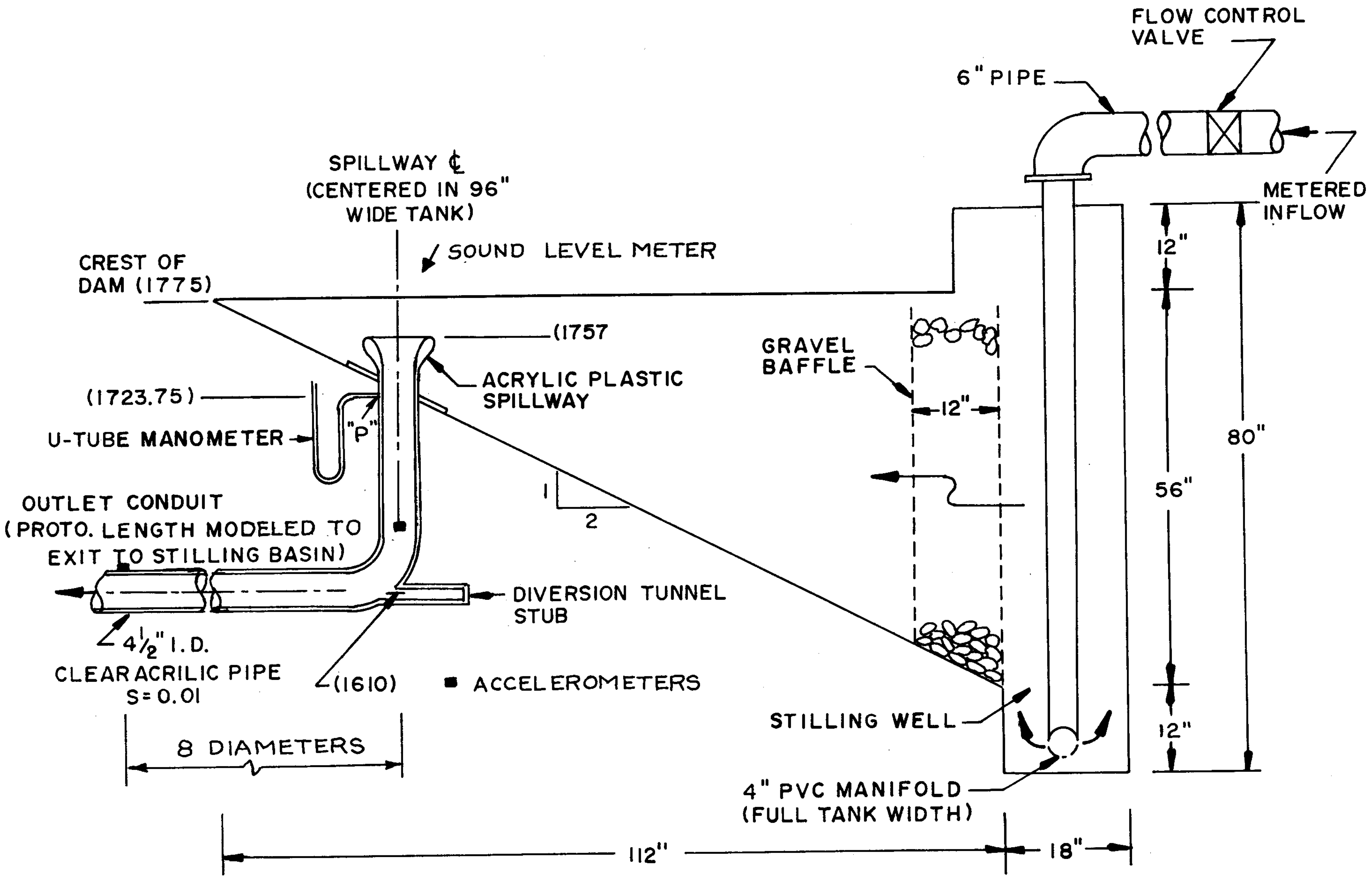


Figure 1. Section Elevation of Model

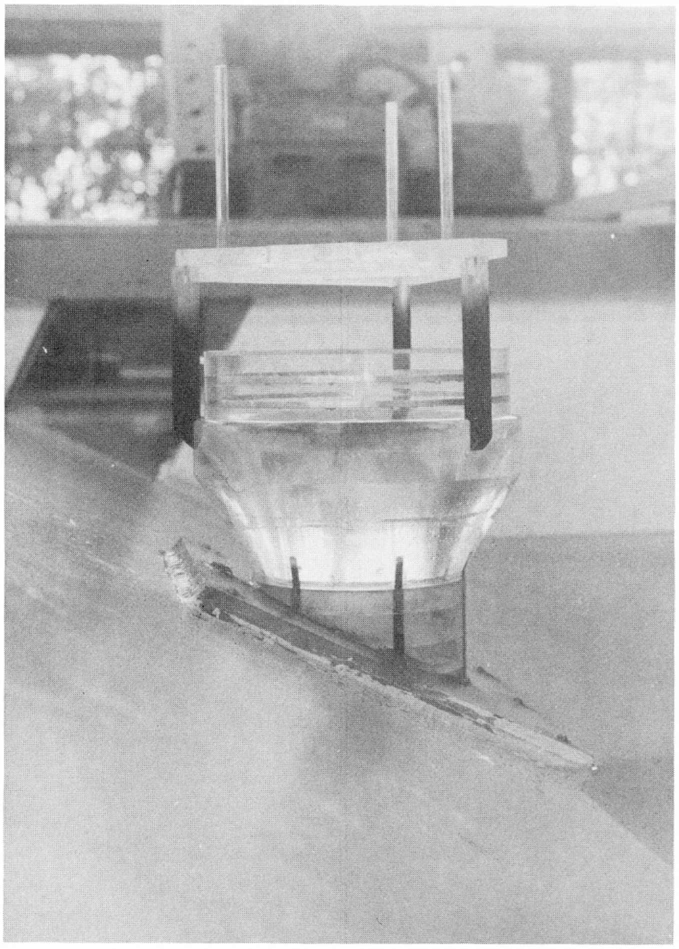


Figure 2. Spillway, Ring Gate in Lowered Position, Q = 10

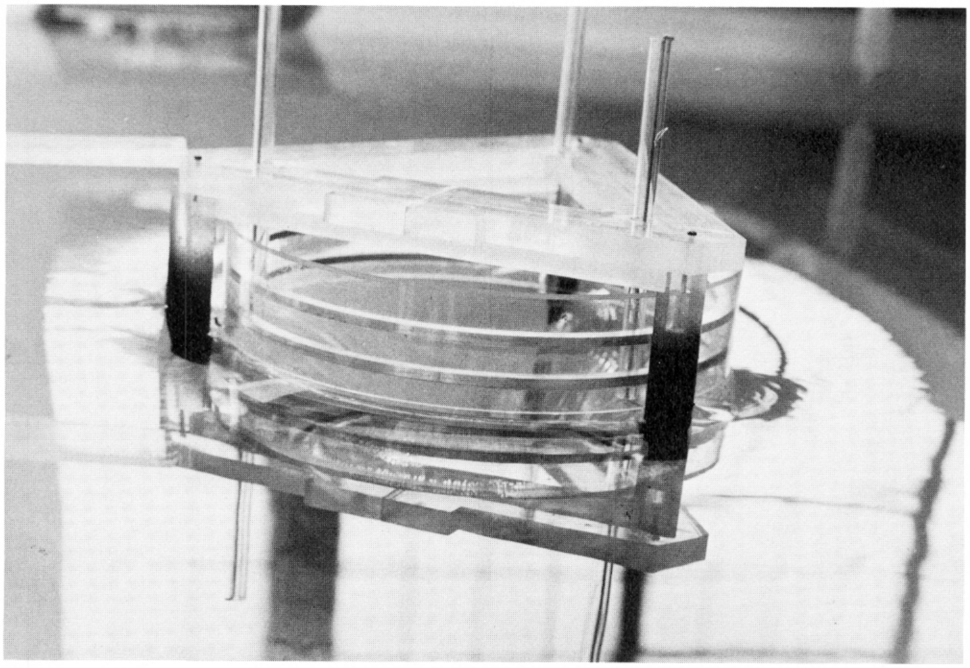


Figure 3. Spillway, Ring Gate in Raised Position, Q = 12,000 cfs

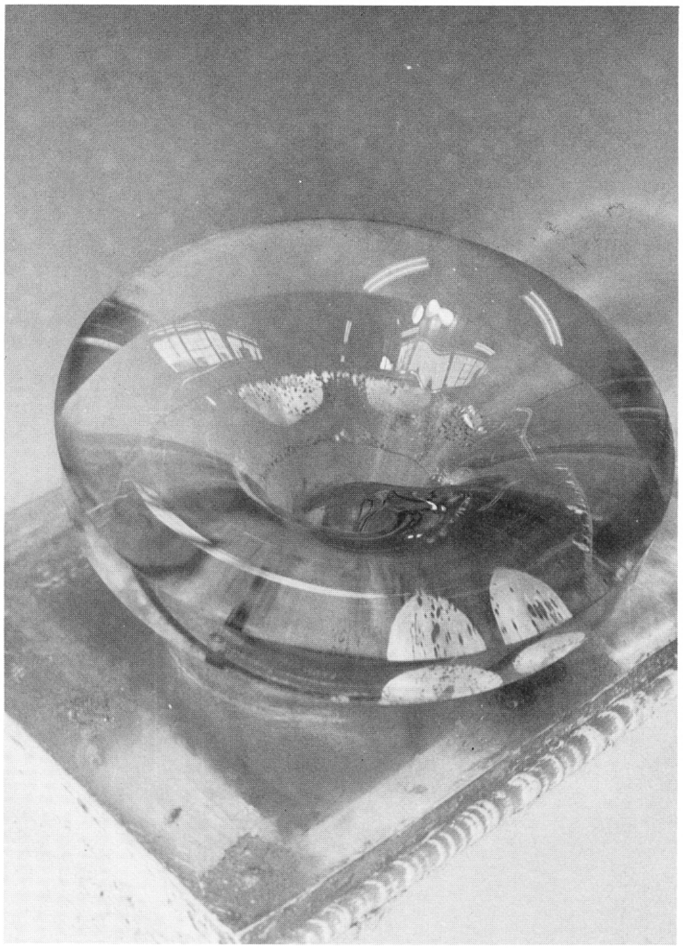


Figure 4. Spillway, No Piers, Rooster-Tail on Dam Axis Side

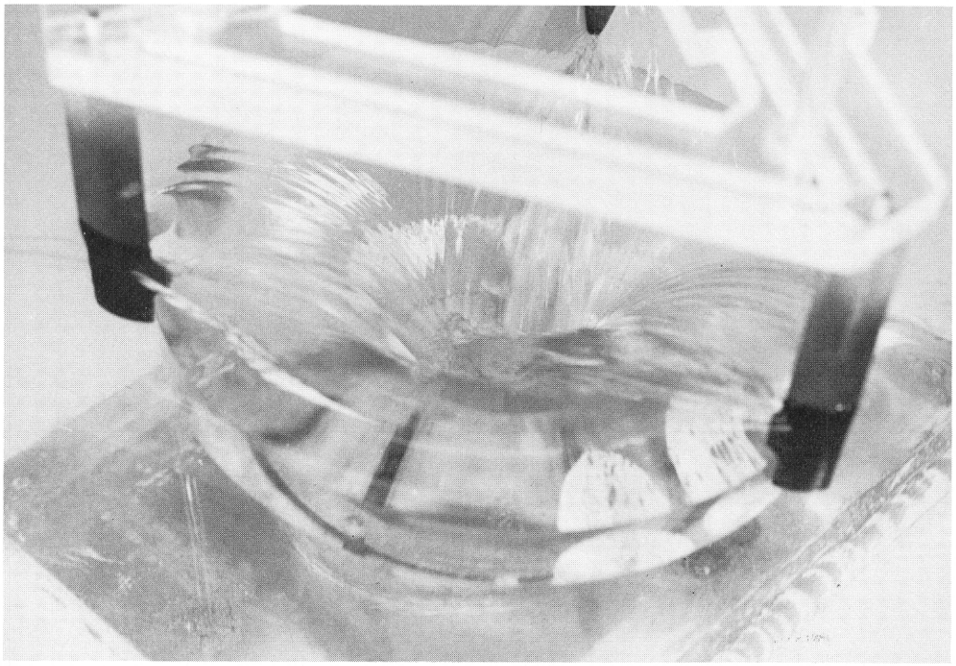


Figure 5. Spillway, Dam Axis Side Pier in Rooster-Tail

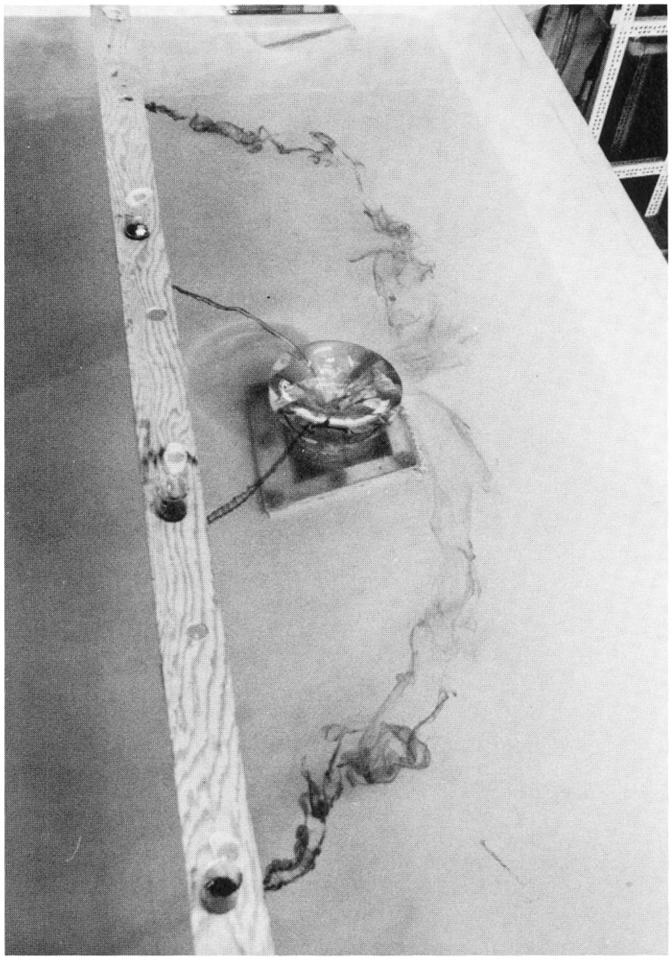


Figure 6. Surface Flow Pathlines

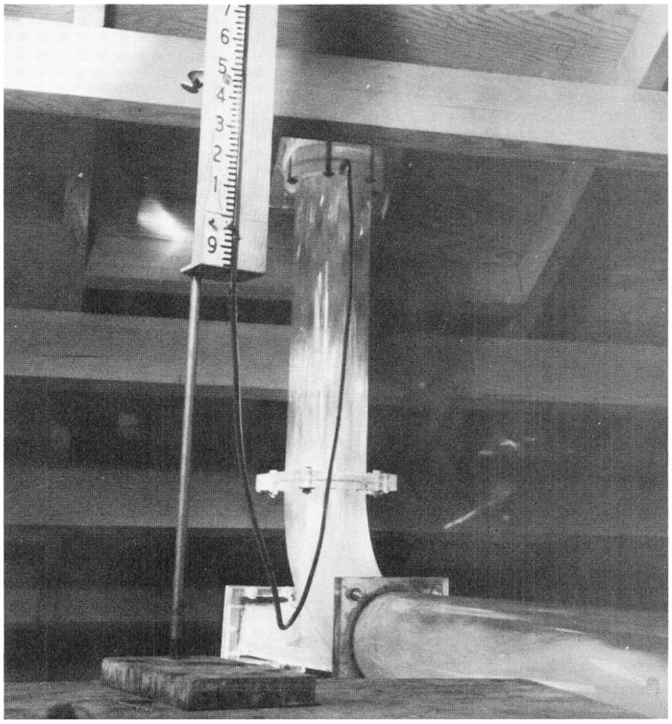


Figure 7. Spillway Shaft Pressure Tap and Piezometer

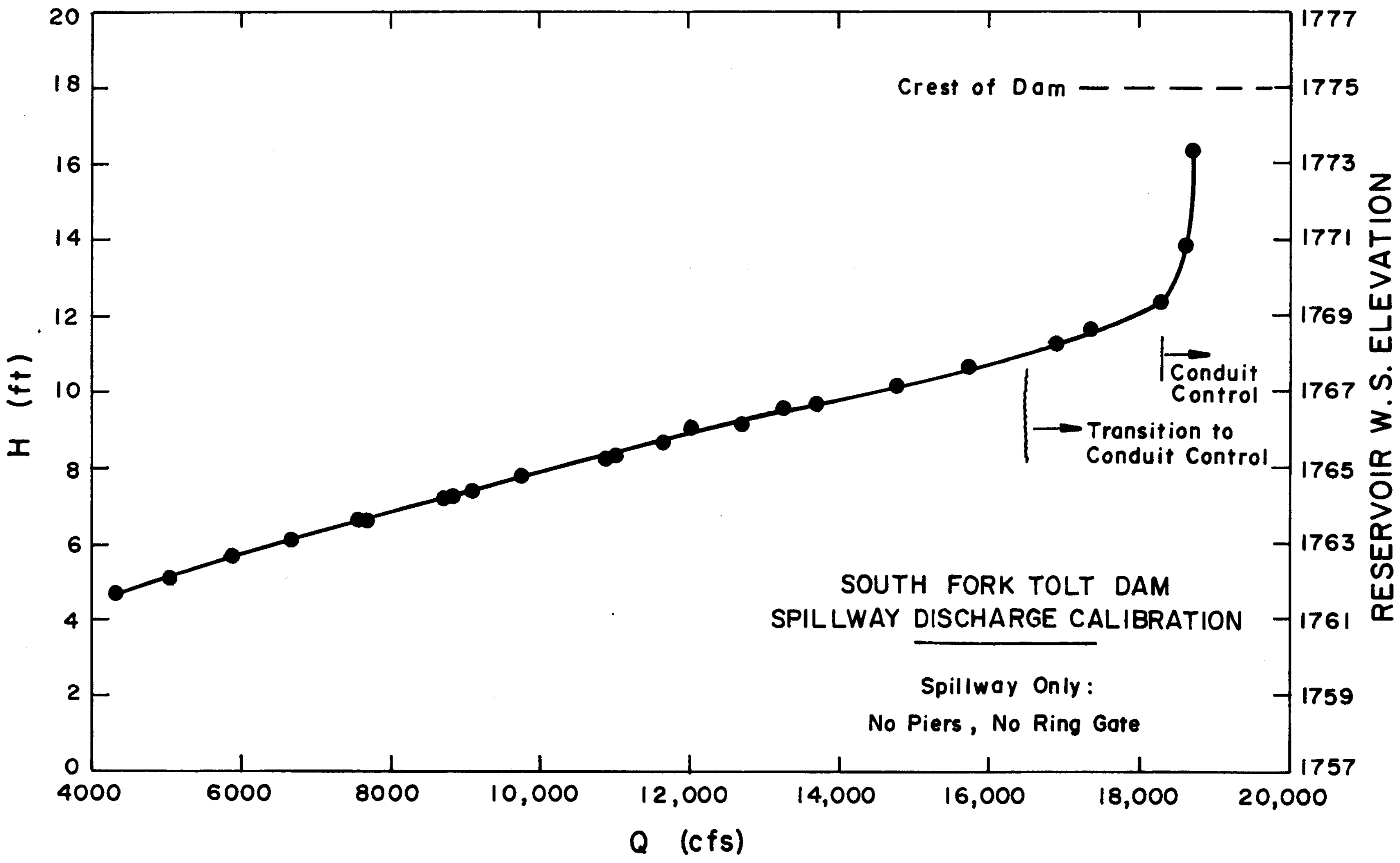


Figure 8. Spillway Rating Curve: No Piers, No Ring Gate

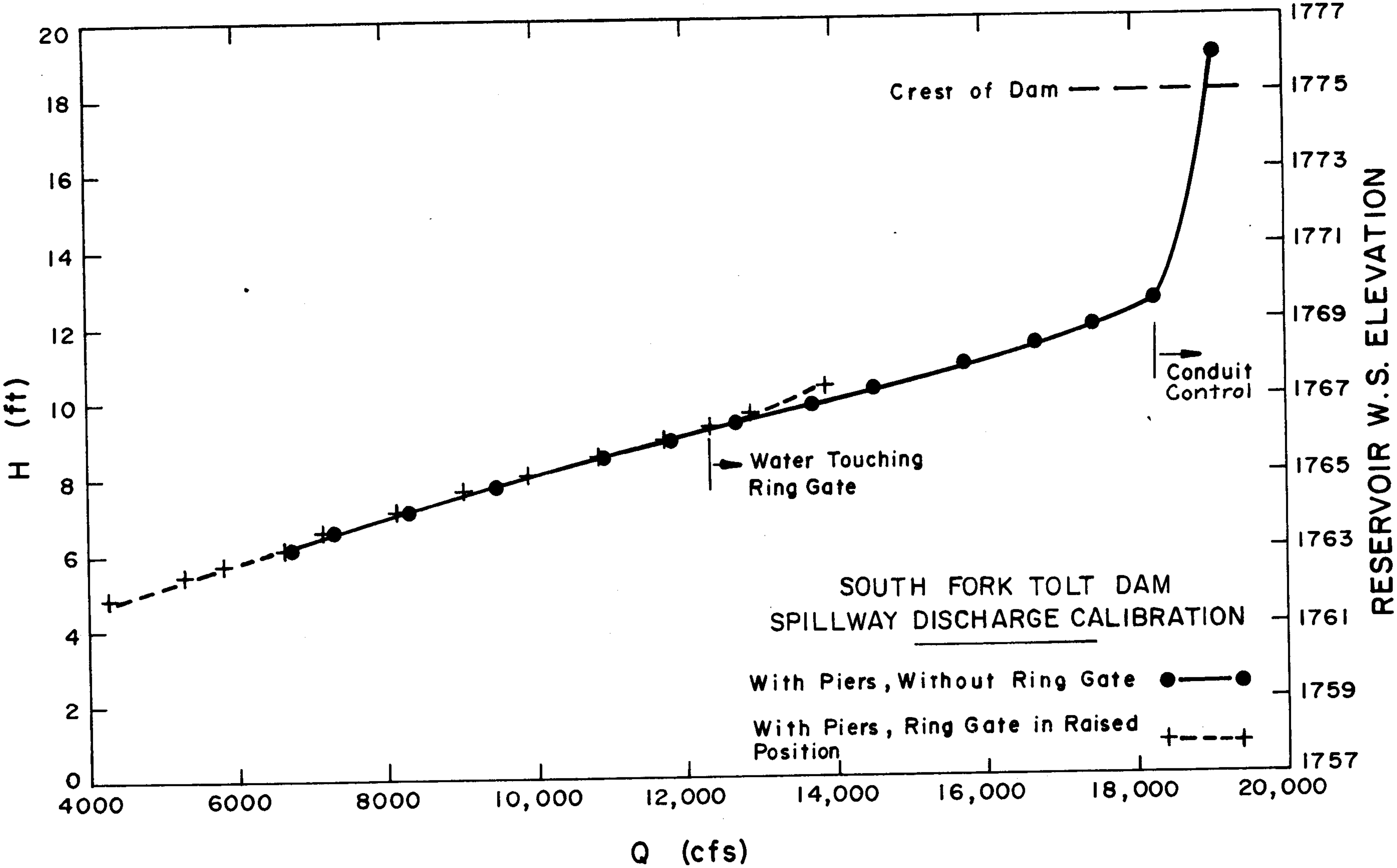


Figure 9. Spillway Rating Curve: With Piers, Ring Gate Absent or in Raised Position

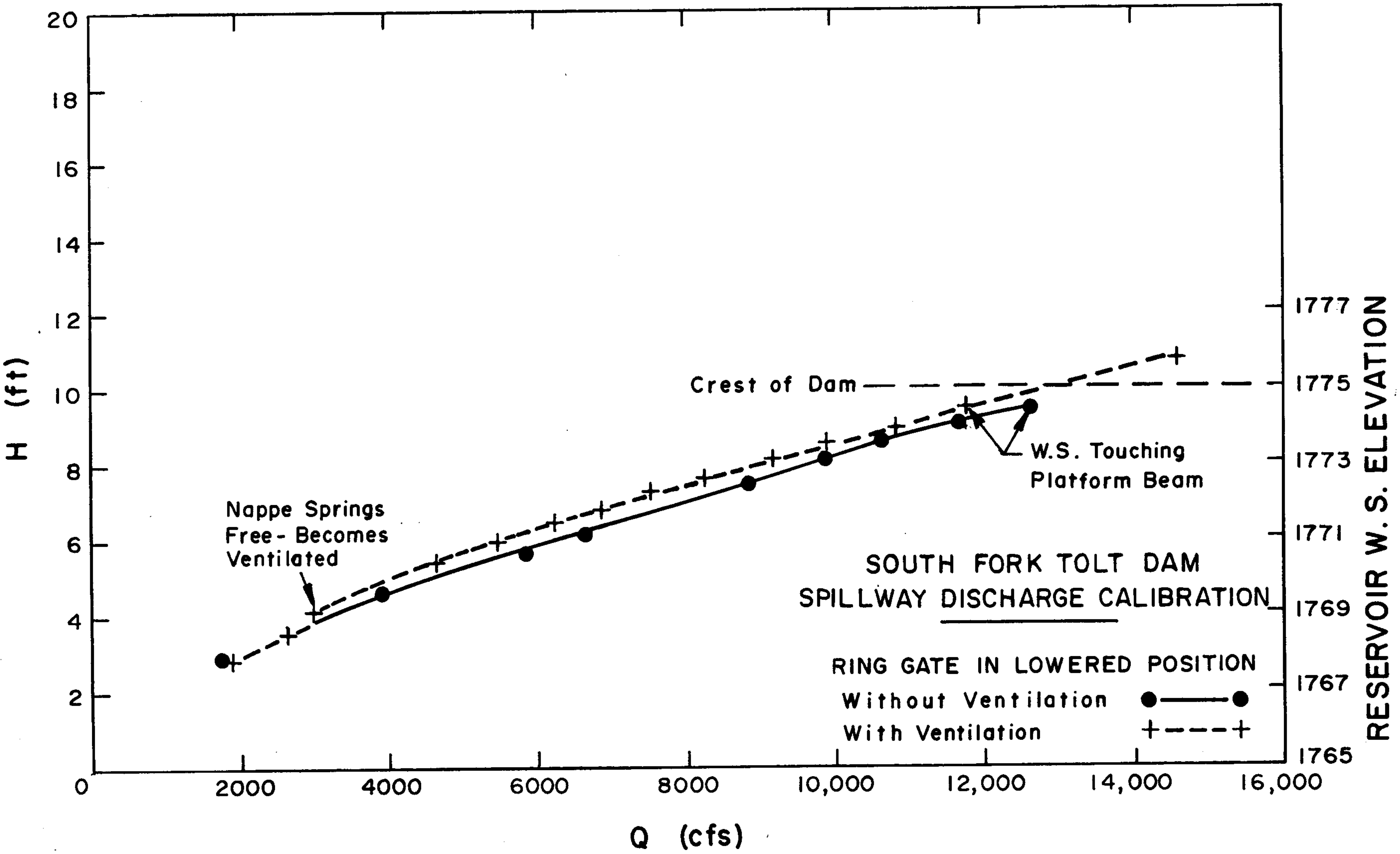


Figure 10. Spillway Rating Curve: Ring Gate in Lowered Position

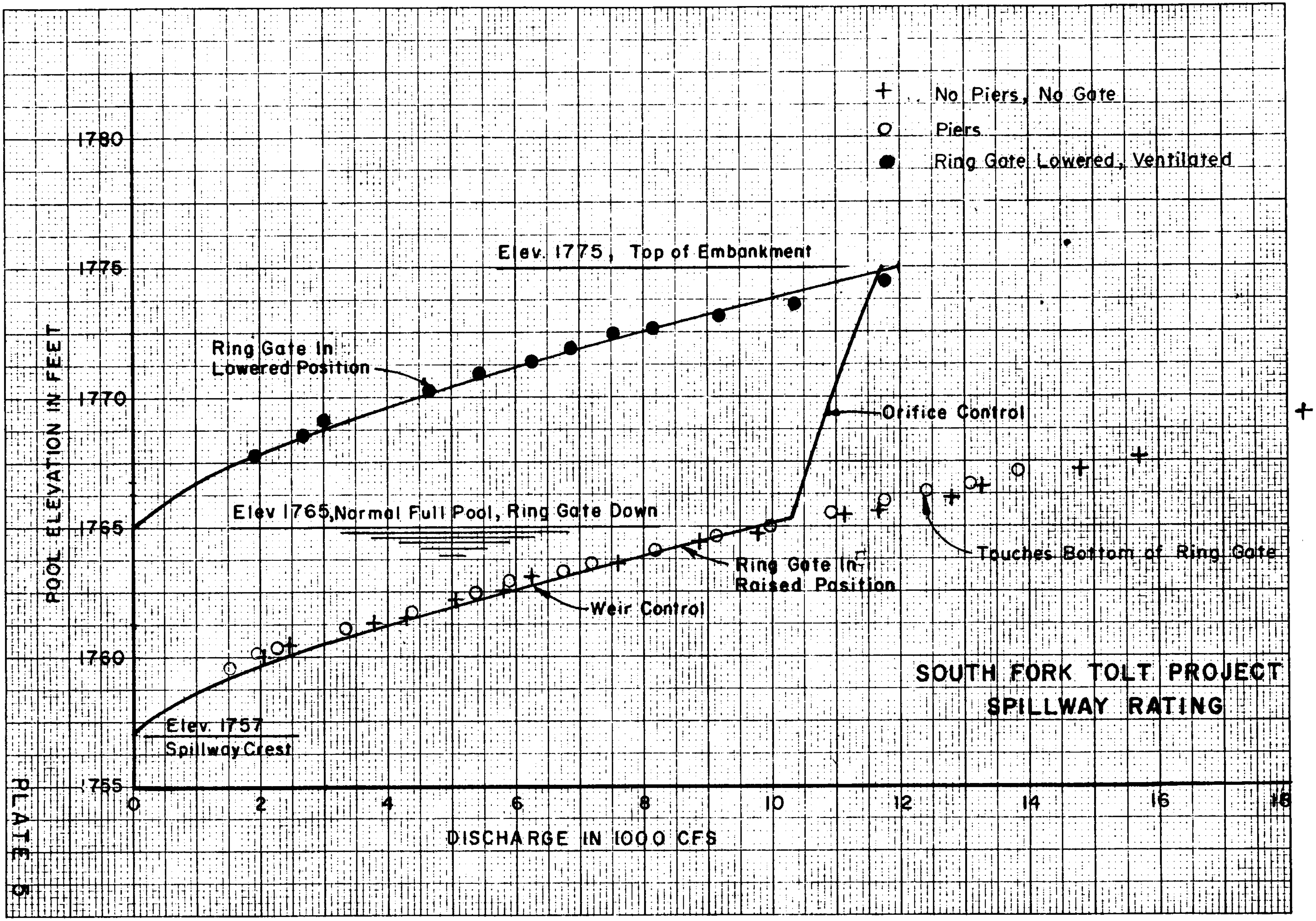


PLATE 5

Figure 11. Comparison of Predicted and Experimental Spillway Rating Curves

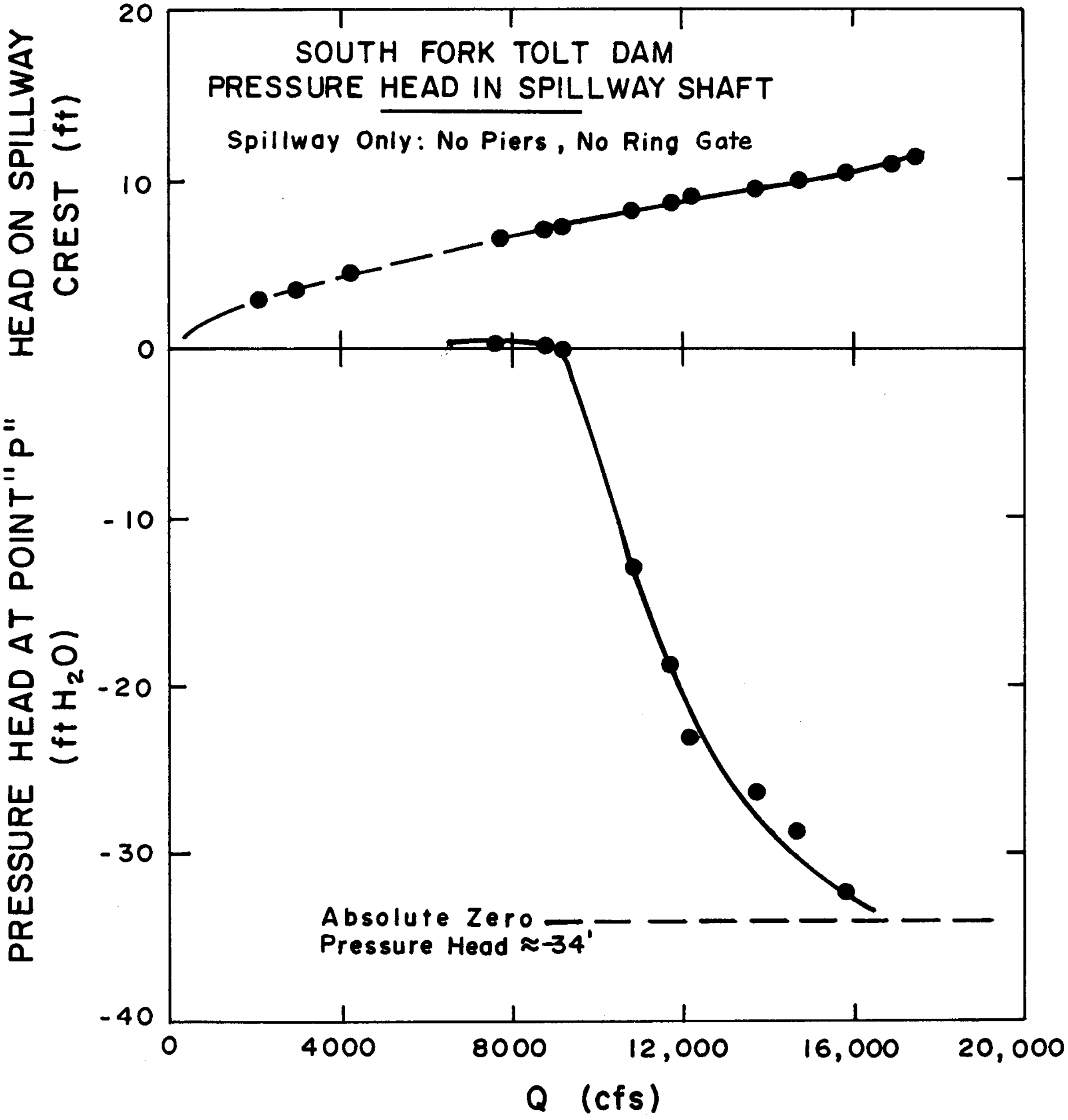


Figure 12. Pressure Head in Spillway Shaft: No Piers

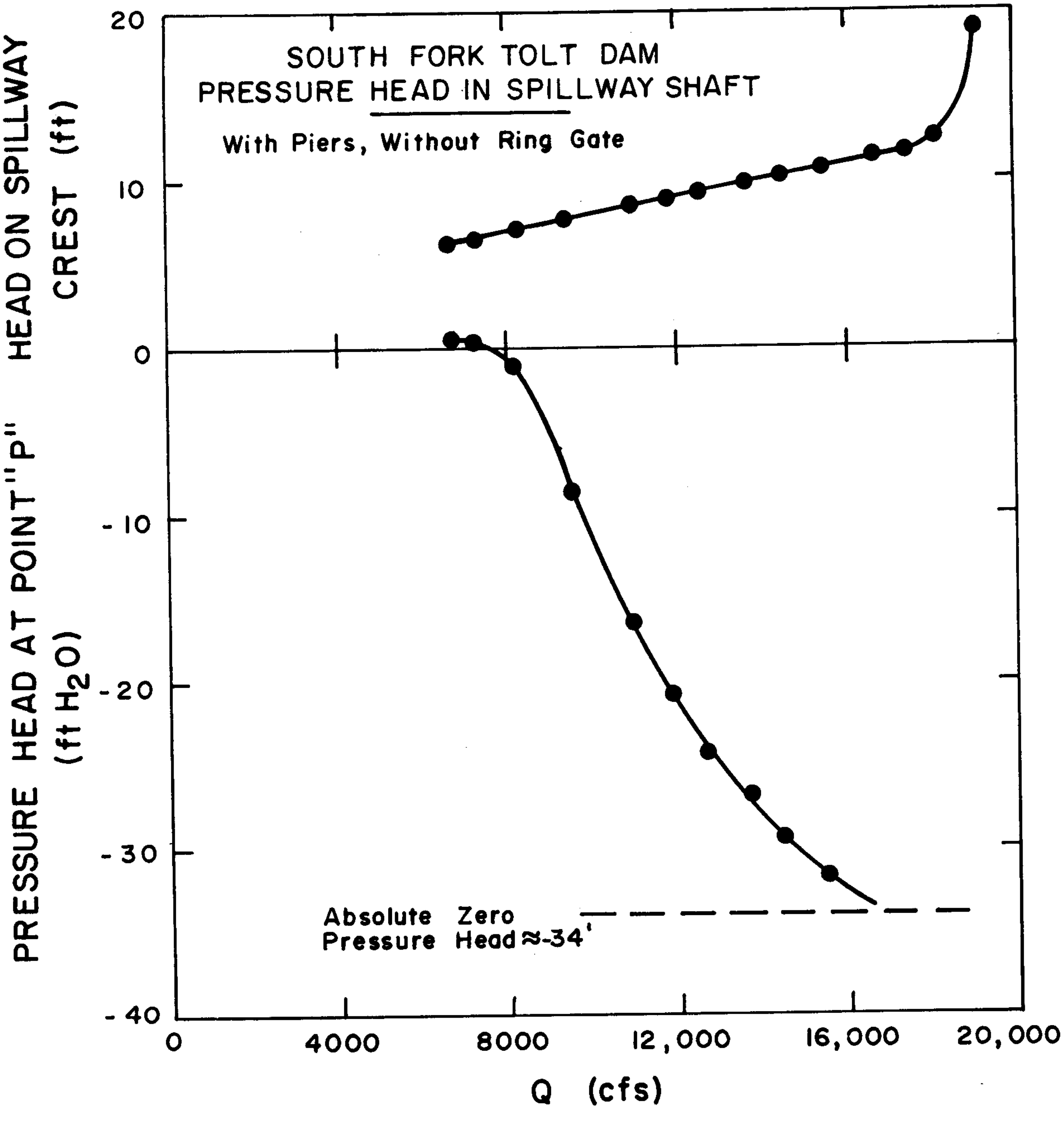


Figure 13. Pressure Head in Spillway Shaft: With Piers

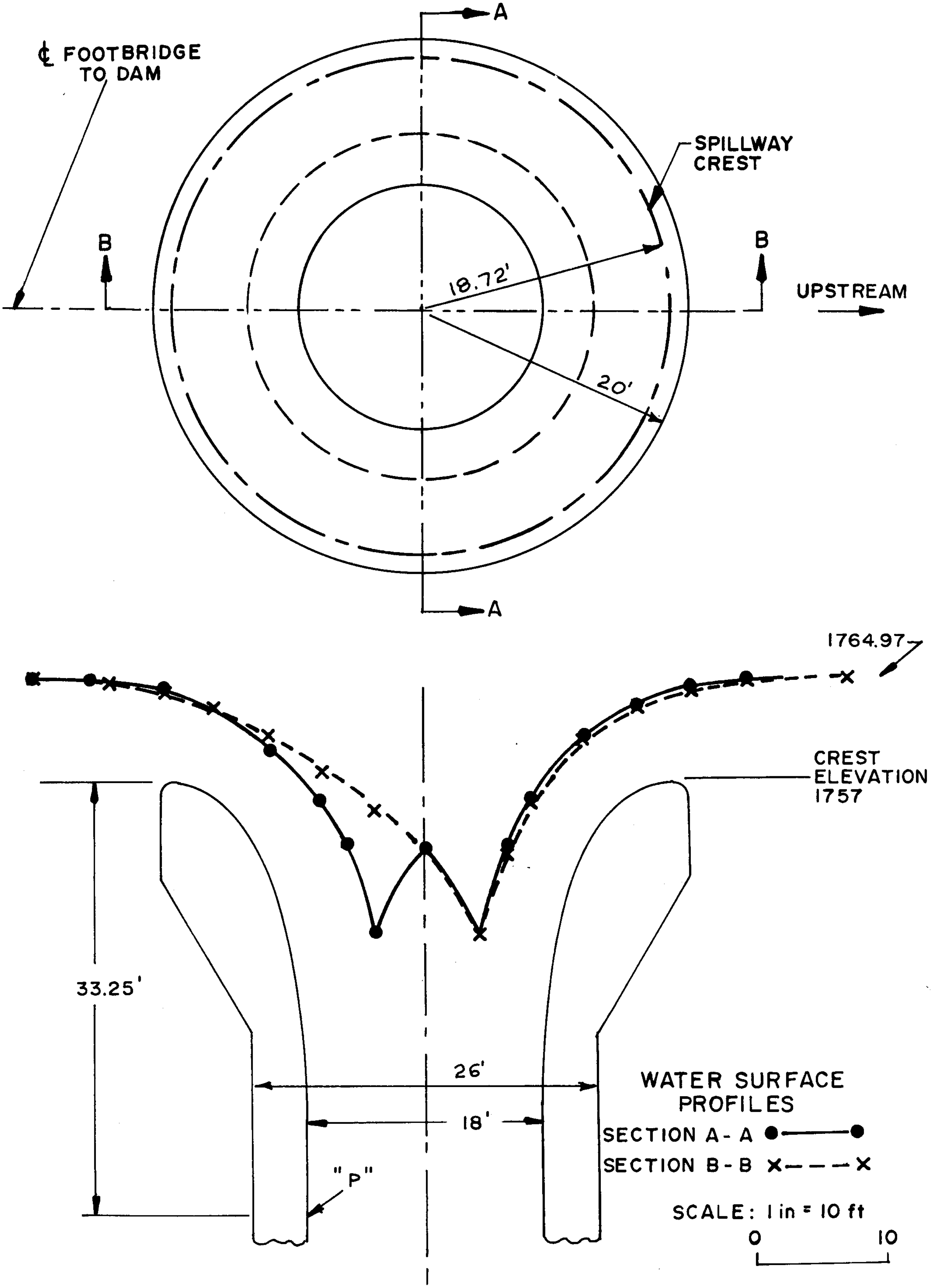


Figure 14. Upper Nappe Profiles: No Piers

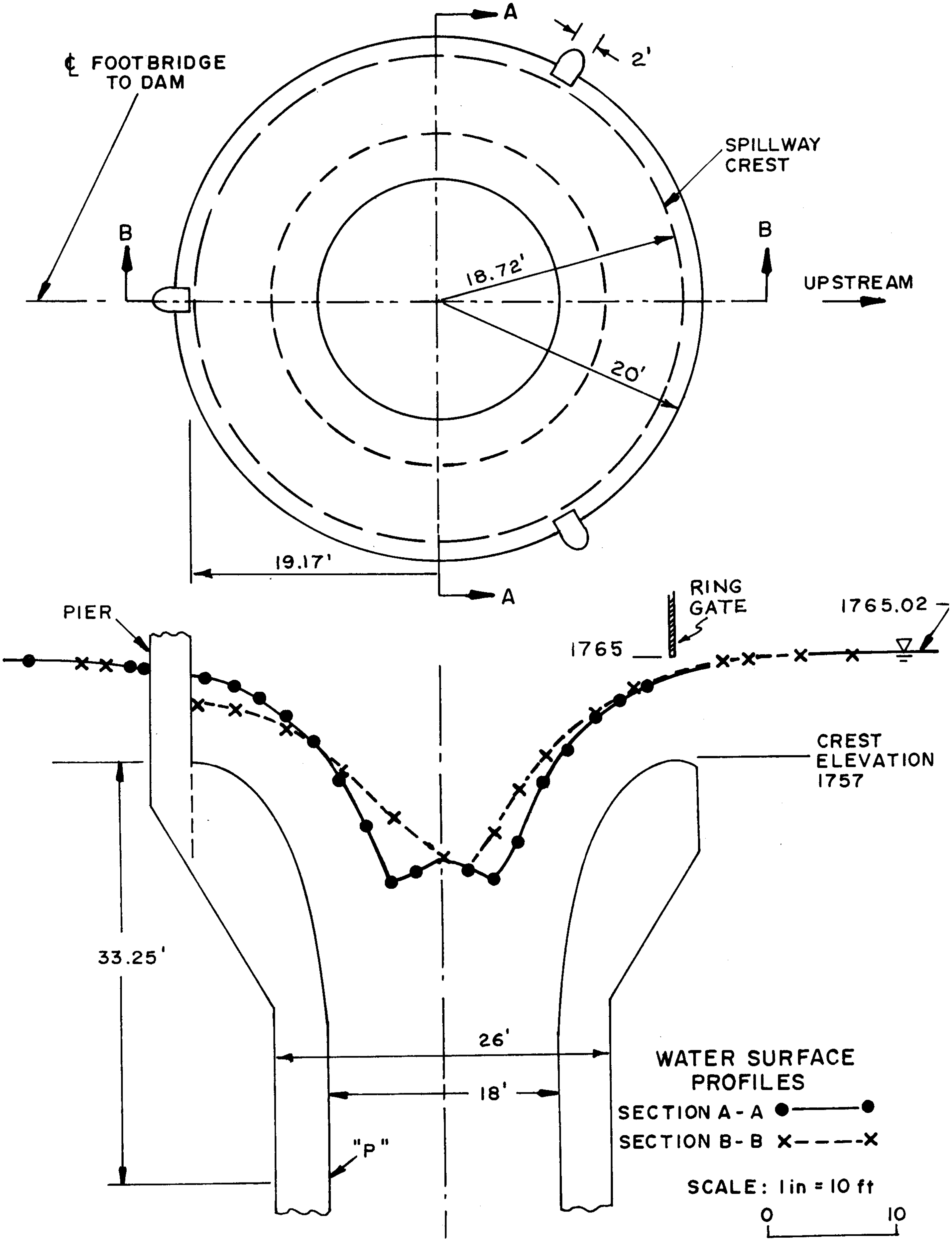
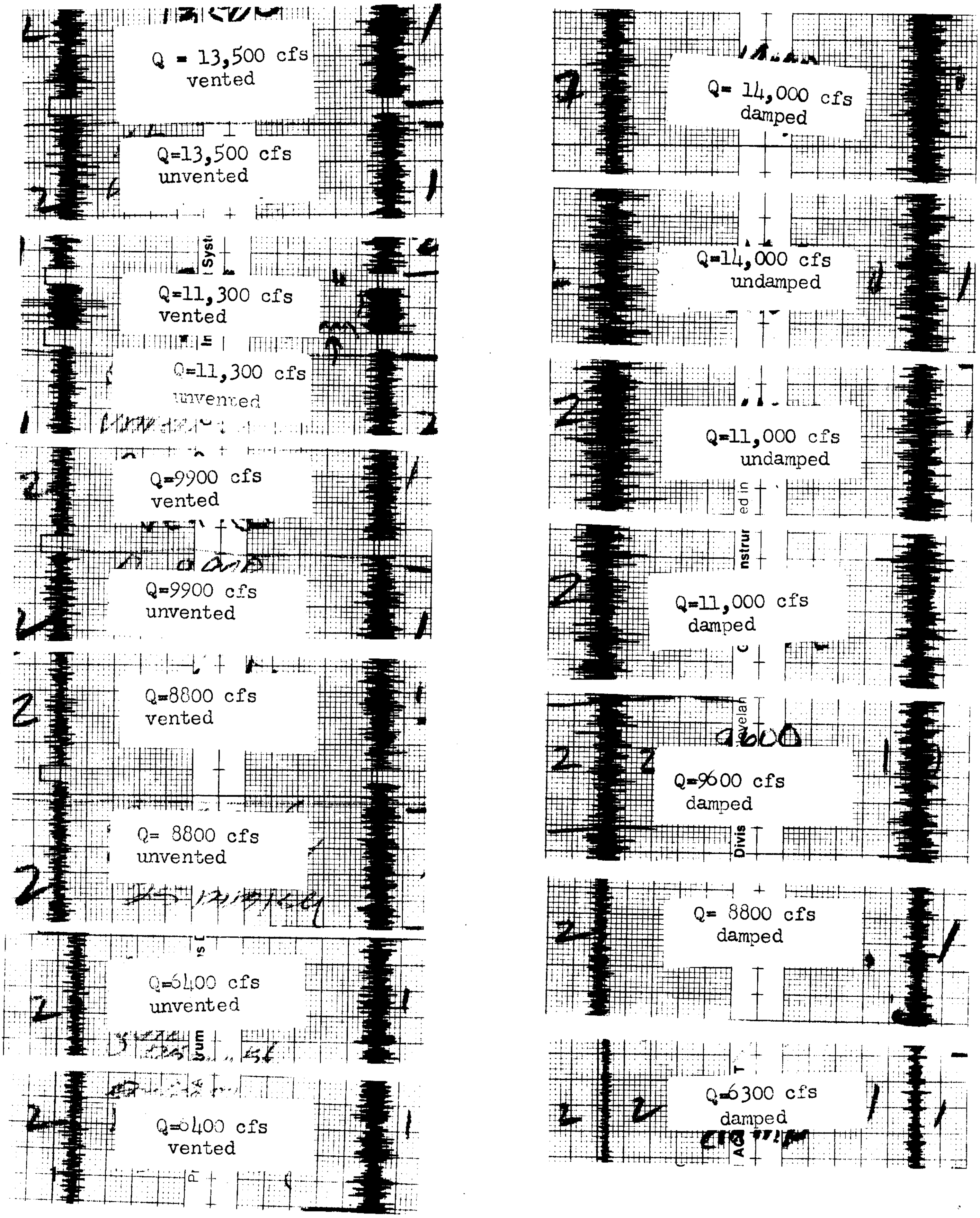


Figure 15. Upper Nappe Profiles: With Piers



WITH GATE

WITHOUT GATE

Figure 16. Accelerometer Track

Table 1

Spillway Discharge Calibration:
Spillway Only - No Piers, No Ring Gate
(from model test data points)

Head on Spillway, ft	Reservoir W.S. Elev.	Q cfs	Comments
0.00	1757	0	Elevation of spillway crest
3.07	1760.07	2050	
3.65	1760.65	2950	
4.22	1761.22	3760	
4.66	1761.66	4310	
5.09	1762.09	5080	
5.62	1762.62	5950	
6.10	1763.10	6710	
6.66	1763.66	7590	
7.25	1764.25	8830	
7.73	1764.73	9770	
8.35	1765.35	11020	
8.64	1765.64	11620	
9.17	1766.17	12730	
9.60	1766.60	13250	
10.18	1767.18	14800	Very little air remaining in spillway shaft
10.66	1767.66	15680	Gulping air - on verge of leaving weir control
12.34	1769.34	18330	Downstream pipe is flowing full
16.32	1773.32	18730	WS over spillway calm, small vortex, almost no air
13.87	1770.87	18650	Unstable, intermittent air gulping

Table 2

Spillway Discharge Calibration:
With Piers; but without Ring Gate
(from model test data points)

Head on Spillway, ft	Reservoir W.S. Elev.	Q cfs	Comments
0.00	1757	0	Elevation of spillway crest
6.10	1763.10	6770	
6.58	1763.58	7270	
7.06	1764.06	8310	
7.73	1764.73	9490	
8.50	1765.50	10950	
8.93	1765.93	11820	
9.36	1766.36	12680	
9.84	1766.84	13700	
10.27	1767.27	14530	On verge of leaving weir control
10.90	1767.90	15790	
11.47	1768.47	16680	
11.86	1768.86	17450	
12.53	1769.53	18290	
18.97	1775.97	19070	W.S. elevation is above crest of dam

Table 3

Spillway Discharge Calibration: With Piers, Ring Gate in Raised Position (from model test data points)

Head on Spillway, ft	Reservoir W.S. Elev.	Q cfs	Comments
0.00	1757	0	Elevation of spillway crest
2.59	1759.59	1550	
3.07	1760.07	1980	
3.41	1760.41	2260	
4.08	1761.08	3330	
4.80	1761.80	4310	
5.42	1762.42	5310	
5.71	1762.71	5822	
6.24	1763.24	6710	
6.53	1763.53	7140	
7.06	1764.06	8160	
7.58	1764.58	9050	
8.02	1765.02	9920	
8.54	1765.54	10910	
8.93	1765.93	11750	
9.26	1766.26	12370	Maximum flow before water touches bottom of ring gate
9.62	1766.62	13080	Intermittent filling of shaft, region of unstable flow
10.37	1767.37	13860	

Table 4

Spillway Discharge Calibration:
Ring Gate in Lowered Position; No Ventilation
(from model test data points)

Head on Spillway, ft	Reservoir W.S. Elev.	Q cfs	Comments
0.00	1765	0	Elevation of top of ring gate
2.83	1767.83	1730	Air trapped above spillway
4.03	1769.03	3240	Air pocket is above top stiffener ring on inside of gate; all other air is gone
4.64	1769.64	3950	Transient air pockets
5.66	1770.66	5850	Air pockets have gone; bubbles move up from bottom of gate, near piers
6.14	1761.14	6640	
6.82	1761.82	7750	Transient small bubbles inside gate; some gulping in spillway shaft
7.44	1772.44	8830	
8.02	1773.02	9920	
8.54	1773.54	10680	
8.98	1773.98	11640	Flow in spillway shaft is noisier
9.45	1774.45	12610	Increase in number of bubbles rising on inside of gate, greatest number at pier nearest dam; W.S. touches bottom of deck beam, at end closest to dam, and is just below crest of dam

Table 5

Spillway Discharge Calibration: Ring Gate in Lowered Position; With Ventilation (from model test data points)

Head on Gate ft	Reservoir W.S. Elev.	Q cfs	Comments
0.00	1765	0	Elevation of top of ring gate
2.78	1767.78	1900	Air pocket trapped above top stiffener ring. Nappe hits on spillway.
3.50	1768.50	2630	
4.08	1769.08	3000	Air pocket at top of gate vanishes, nappe becomes aerated; flow in conduit is more aerated, and overflow is less noisy
5.33	1770.33	4650	
5.86	1770.86	5480	
6.38	1771.38	6240	
6.77	1771.77	6860	
7.25	1772.25	7550	
7.63	1772.63	8230	Flow still fully aerated, quiet
8.06	1773.06	9160	
8.50	1773.50	9920	
8.93	1773.93	10820	Some 'gurgling' noise in shaft, but visible flow in shaft is still steady
9.51	1774.51	11780	W.S. almost touching bottom of deck beam
10.80	1775.80	14590	W.S. touches bottom of deck slab, and beam near dam-side pier. W.S. above dam crest

Table 6

Pressure Head in Spillway Shaft
Spillway Only - No Piers, No Ring Gate
(from model test data points)

Head on Spillway, ft	Q cfs	Pressure Head at Point "P"* ft	Comments
0.00	0	0	No flow
6.58	7710	0.38	
7.10	8750	0.09	
7.30	9100	0	
8.21	10860	-12.96	
8.74	11770	-18.72	
9.12	12050	-23.04	
9.65	13690	-26.40	
10.03	14690	-28.80	
10.51	15780	-32.40	Leaving weir control. Near cavitation in prototype.
11.09	16910	<-34	Cavitation in prototype
11.62	17390	<-34	Cavitation in prototype

* Point "P": Elevation 1723.75, or 33.25 ft below spillway crest elevation. On inside wall of spillway shaft, at point on shaft circumference closest to dam face.

Table 7

Pressure Head in Spillway Shaft
With Piers, but Without Ring Gate
(from model test data points)

Head on Spillway, ft	Q cfs	Pressure Head at Point "P"* ft	Comments
0.00	0	0	No flow
6.10	6770	0.48	
6.58	7270	0.24	
7.06	8310	-1.44	
7.73	9490	-8.64	
8.50	10950	-16.32	
8.93	11820	-20.88	
9.36	12680	-24.48	
9.84	13700	-26.88	
10.27	14530	-29.52	On verge of leaving weir control
10.90	15790	-31.68	Near cavitation in prototype
11.47	16680	<-34	Cavitation in prototype
11.86	17450	<-34	Cavitation in prototype
12.53	18290	<-34	Cavitation in prototype
18.97	19070	<-34	Cavitation in prototype

* Point "P": Elevation 1723.75, or 33.25 ft below spillway crest elevation. On inside wall of spillway shaft, at point on shaft circumference closest to dam face.

Table 8

Spillway Noise Sound Level, db

Q cfs	No Gate	Ring Gate on Crest vented	Ring Gate on Crest unvented
6300	86-87	84-85	---
6400	---	83-85	88-89
8800	83-84	84-85	88-90
9600	88-89	---	---
9900	---	84-86	89-91
11,300	---	90-94	87-89
11,600	92-93	---	---
13,500	---	95-98	98-100
14,000*	91-92	---	---

*gulping, conduit full