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HYDRAULIC MODEL STUDIES OF O'SULLIVAN DAM

Columbia Basin Project

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16. ABSTRACT

Hydraulic model studies were made to verify the design of the spillway, approach channel, and spillway chute for O'Sullivan Dam. Discharge rating curves are presented relating spillway discharge capacity to pier location upstream of the crest, at the crest, and downstream from the crest. The preliminary approach channel design was modified to improve the entrance flow conditions. Operating criteria for the spillway gates are recommended to assure acceptable flow conditions in the spillway chute.

Of particular interest were the tests relating spillway discharge capacity to pier location. Relocation of the pier nose from upstream of the spillway crest, to the crest, and to two downstream locations, resulted in an increase in the effective spillway width of 38, 67, and 91 percent of the total pier width, respectively.

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by

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PURPOSE

The studies were made to verify the hydraulic design of the spillway, the approach channel and the spillway chute. Also included were tests to relate discharge capacity to pier location along the spillway profile.

RESULTS

1. The turbulence created at the entrance to the initial spillway approach channel was significantly reduced by rounding the entrance. An entrance radius of 50 feet (15.2 meters) at the bottom of the side slope (elevation 1024) yielded good model results.

2. Although the wide-flange (12 WF 31) pier nose created more flow disturbance than the elliptical pier nose, identical design discharges were recorded for both shapes.

3. Free-flow and uniform (all gates equally open) gate-controlled flow were smooth through the spillway chute without tendency to overtop the training walls.

4. Free-flow discharges with the spillway head, H = 18.5 feet (5.6 meters) through the two center bays or three adjacent bays produced flow conditions in the spillway chute which resulted in overtopping of the training wall. For these gate operations and a training wall elevation of 1030, the spillway head should not exceed 17.65 feet (5.38 meters) and 15.90 feet (4.85 meters) respectively.

5. With alternate free-flow bays operating at H = 18.5 feet (5.6 meters), the 12 WF 31 pier nose produced a stable flow separation at the pier nose. The same gate operation with the elliptical pier nose yielded a relatively unstable but minor flow separation at the pier nose. However, either pier nose would serve adequately.

6. Relocation of the pier nose from 7 feet (2.13 meters) upstream of the spillway crest, to the crest, to 6 feet (1.83 meters) and 13 feet (3.96 meters) downstream from the crest, resulted in an increase in the effective spillway width of 38, 67, and 91 percent of the total pier width [9 ft (2.74 meters)], respectively. The respective design discharges were 29,750 cfs (842.4 cms), 30,800 cfs (872.2 cms), 31,620 cfs (895.4 cms), and 32,300 cfs (914.6 cms) for a design head, H = 20 feet (6.10 meters). Tests without piers yielded a spillway discharge of 32,580 cfs (922.6 cms) for the design head.

APPLICATION

The results of this study can be applied qualitatively to the hydraulic design of similar low head, gated structures.

INTRODUCTION

O'Sullivan Dam is a feature of the Columbia Basin Project, located 25 miles (40.2 km) southeast of Ephrata, Washington, on Crab Creek (Figure 1). The 29,000 acre (117.4 km^2) Potholes Reservoir formed by O'Sullivan Dam collects return flows from all irrigation in the northern portion of the project for reuse in the southern portion. The dam was constructed in 1949. The present spillway has an uncontrolled crest which also serves as a highway crossing at elevation 1052. A rock cut extends downstream from the crest and terminates in a dry coulee.

Modifications to the original plan of operation for O'Sullivan Dam resulted in the need for a gate controlled spillway structure which will pass the design flood without exceeding a reservoir elevation of 1048 [Design head = 20 feet (6.1 meters)]. The structure will consist of four bays controlled by four 24- by 19-foot, 4-1/2-inch (7.3- by 5.9-meter) radial gates. The new spillway structure will support a 32-foot (9.8-meter) wide highway bridge.

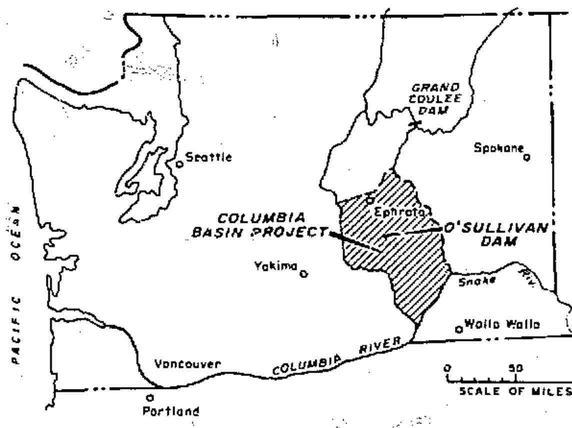
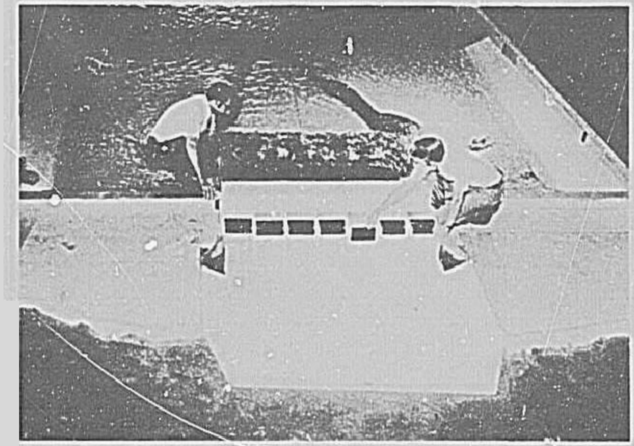


Figure 1. Location map.

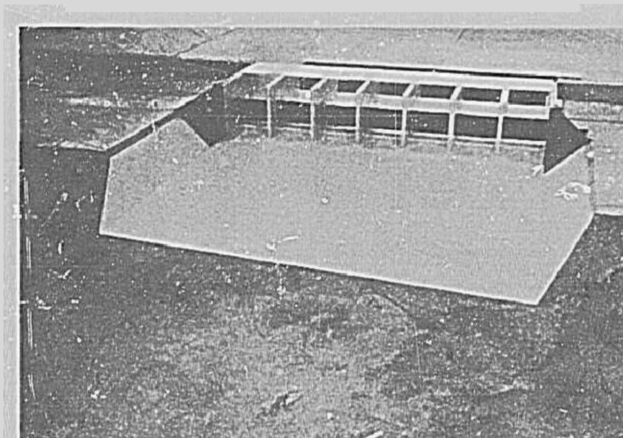
THE MODEL

The model, constructed to a scale ratio of 1:36, included a portion of the upstream reservoir, the intake channel, the spillway and 460 feet (140 meters) of the downstream channel (Figure 2a). The model spillway was constructed of urethane plastic. The existing 500-foot (152.4-meter) wide rock excavated channel downstream of the spillway was modeled and a gravel basin was placed immediately downstream of the spillway chute to observe the erosion tendencies of the flow. Field geological data later indicated that the fractured granite in the downstream channel would adequately resist the spillway flows thus eliminating the need for the erosion study.

Water was supplied to the model through the permanent laboratory system and was measured by one of a bank of Venturi meters installed in the laboratory.



a. Flow through seven-bay spillway. P222-D-73810



b. No flow. P222-D-73811

Figure 2. Initial design.

THE INVESTIGATION

Initial Design

Early during the model study the basic spillway design was changed from seven to four bays resulting in an increase in design head from 14 feet (4.3 meters) to 20 feet (6.1 meters). Preliminary studies with the seven-bay model spillway (Figure 2) indicated two problem areas which were eliminated while modifying the model spillway. Turbulence resulting from the abrupt drawdown at the entrance to the spillway approach channel was significantly reduced by rounding the entrance. The preliminary design also had a transitional warp from the 1:1 approach channel side slope to the vertical spillway wall in 28 feet (8.5 meters). This warp was replaced in the modified model with a curved transition from the 1:1 side slope to the vertical sidewall of the spillway in the same length, Figure 3b. These design modifications are shown on the detailed plans included in the appendix.

The four-bay modified spillway was also constructed of urethane plastic. Slots in the spillway surface permitted pier sections to be added to the fixed model piers which were located 13 feet (4.0 meters) downstream from the crest (Figure 3b). Provision was made to place the radial gates on the structure once the piers were extended to the crest. The study results discussed in this report refer to the four-bay spillway design (Figure 3).

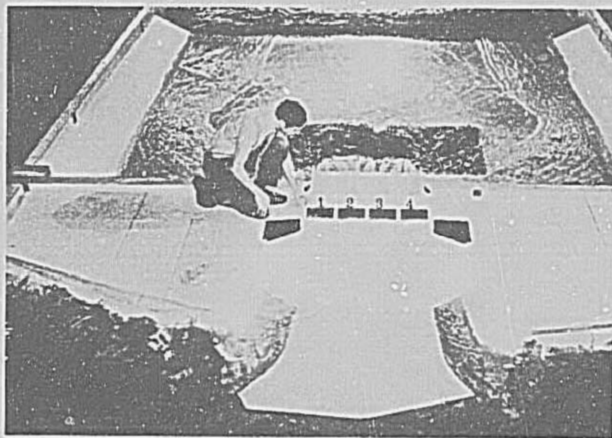
Spillway Flow Characteristics

The prototype spillway will have the pier nose located at the crest. The radial gates will thus seat 0.88 foot (0.27 meter) below the crest. Various gate operations were tested during the investigation to determine the flow characteristics in the approach channel, at the piers, and in the spillway chute.

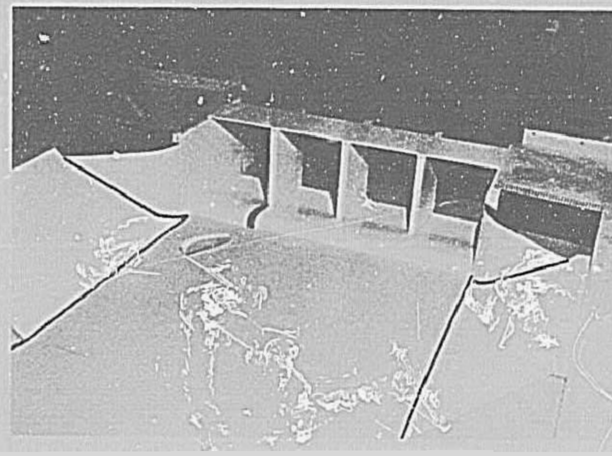
Approach channel. The tendency for an eddy along the 1:1 side slopes of the approach channel progressively increased as the gate operation changed from two outside gates (1 and 4), to the inside gates (2 and 3), to one outside gate (1 or 4), Figure 4.

With uniform gate-controlled operation, a standing wave appeared in the approach channel upstream of the spillway gates but it did not create surging in the approach channel (Figure 5). The size of the wave depended on the gate opening and reservoir head.

Spillway piers. Tests were conducted to determine discharge coefficients for a wide-flange pier nose and an elliptical pier nose placed at the crest. The test of a 6-1/2- by 12-inch (165 x 305 mm) wide flange is shown in Figure 6a. The two pier configurations yielded the same model discharge. Figure 6b illustrates the flow patterns around the elliptical and wide-flange pier noses (elliptical pier nose on right).



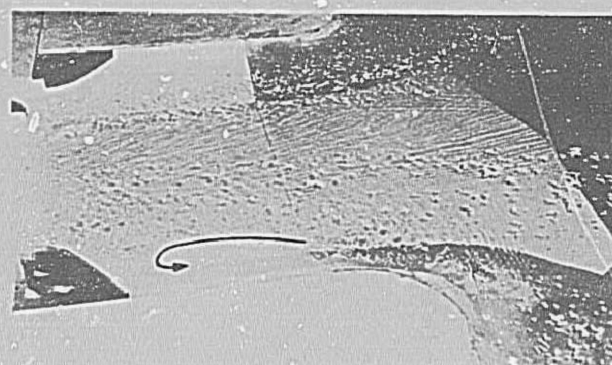
a. O'Sullivan Dam model. P222-D-73813



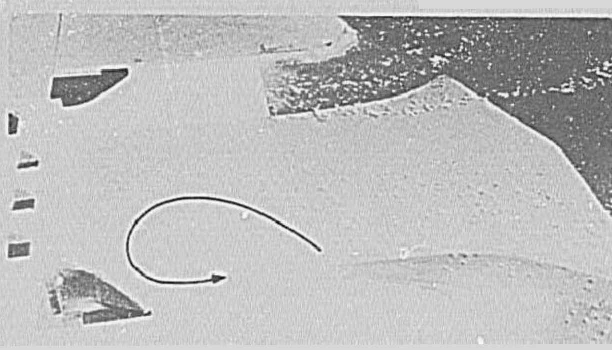
b. Spillway pier slots. P222-D-73812

Figure 3. 1:36 scale model layout.

a. Outside gates—1 and 4 open. P222-D-73814

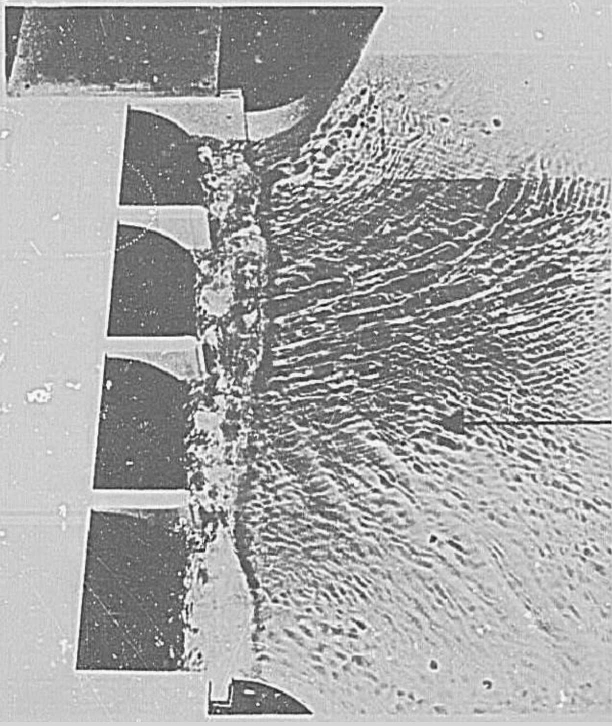


b. Inside gates—2 and 3 open. P222-D-73815



c Gate 4 open. P222-D-73816

Figure 4. Flow in spillway approach channel.



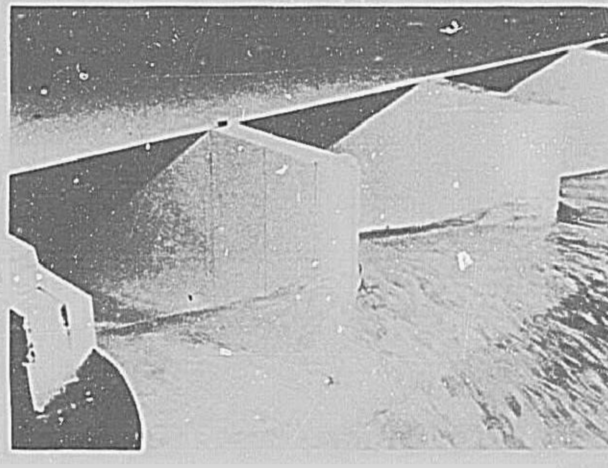
Head = 20 ft.
Gate lip 12 ft. above crest

Figure 5. Wave at spillway gates. P222-D-73817

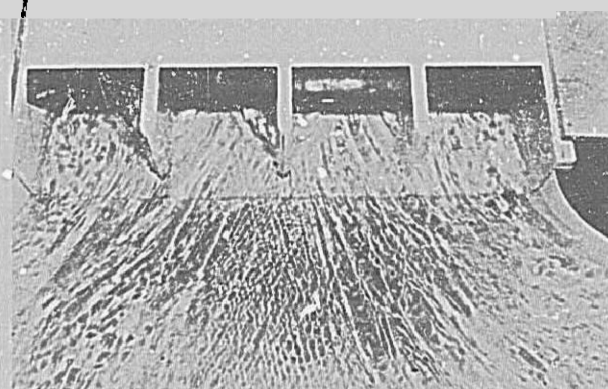
With free-flow or gate-controlled operation, the wide-flange and elliptical pier performances were essentially the same. A drawdown occurred around the piers when gates were fully opened adjacent to closed gates. At H = 18.5 feet (5.64 meters) (reservoir at the top of the closed gates), the flow separated along the full height of the wide-flange pier. The contracted flow rejoined the parallel pier wall downstream from the pier nose. Under the same conditions the flow alternately separated and rejoined the elliptical pier nose.

Figure 7 illustrates flow around the two pier nose shapes when adjacent gates are closed. The wide-flange pier nose yielded a more stable flow condition at the pier than the elliptical pier nose under the above operating conditions. However, the flow instability related to the elliptical pier nose did not create a surge in the approach channel and the fluctuation was too random to create structural vibrations.

The wide-flange pier nose could serve a dual capacity of stoplog slot as well as pier in this particular design where the pier will not extend upstream of the spillway crest. However, it is envisioned that the reservoir elevation will recede below the spillway crest each year which should provide for normal gate maintenance without the use of stoplogs. Therefore the elliptical

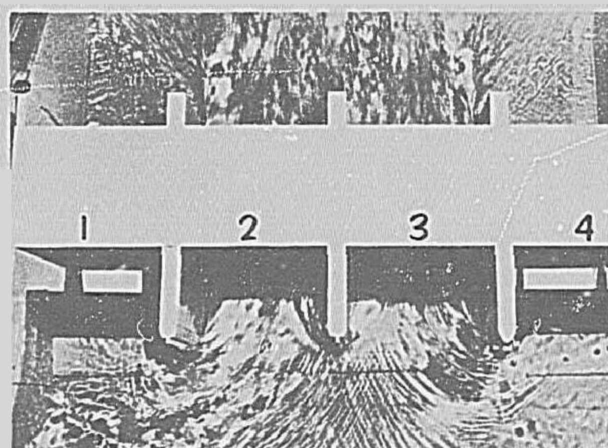


a. Wide-flange pier nose. P222-D-73818



b. Design flow through spillway. Note less flow contraction around elliptical pier nose on right side. P222-D-73819

Figure 6. Wide-flange pier nose.
Q = 30,800 cfs



H = 18.5 ft.

Figure 7. Wide-flange and elliptical pier noses. P222-D-73820

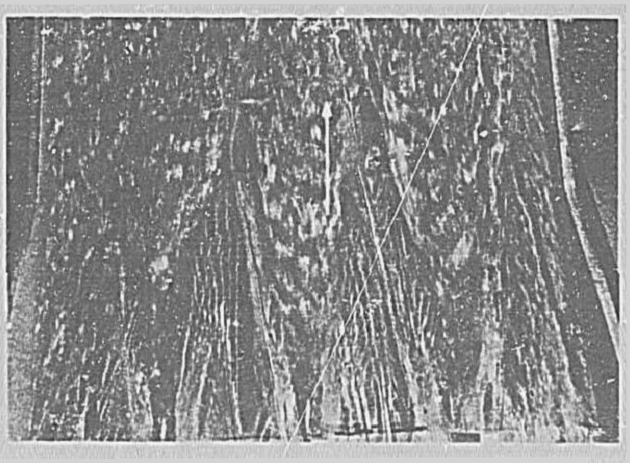
pier design will be utilized for this spillway. Stoplog slots will be provided in the spillway training walls at the crest. If needed, long stoplogs could be placed across the spillway and rest against the nose of the elliptical piers.

Spillway chute. For free-flow spillway releases and gate-controlled releases with four gates equally open (uniform), a typical diamond-shape pattern appeared in the spillway chute and there was no tendency toward overtopping the downstream training walls, Figure 8.

Tests were also conducted using various free-flow gate combinations with H = 18.5 feet (5.64 meters). Flow through one or both (Figure 9a) of the outside gates (1 and 4) yielded quite satisfactory hydraulic conditions in the spillway chute. Flow through one of the inside gates alone also produced satisfactory hydraulic conditions in the spillway chute, Figure 9b. Spillway operation with flow through the two center gates (2 and 3) resulted in a flow condition which overtopped the training walls, Figure 9c. The designed training walls were adequate for H = 17.65 feet (5.38 meters) or less with the two center gates operating under a free-flow condition. When three adjacent gates operated under free-flow conditions, the flow in the spillway chute overtopped the opposite training walls, Figure 9d. The designed training walls were adequate for H = 15.90 feet (4.85 meters) or less under this operating condition.

Pier Location Studies

In a study reported by Thompson[1*] an increase in effective spillway length of 40 percent of the total pier width was realized by moving the pier nose from the upstream face of the spillway to the crest. To determine the effect of pier location in the O'Sullivan model, tests were conducted locating the pier nose at various stations along the spillway profile.



Q = 30,000 cfs, pier nose at crest

Figure 8. Spillway chute (all gates open). P222-D-73821

*Numbers designate references at end of text.

The spillway profile is described by the equation:

$$x^2 = 80\ y$$

where: x = the horizontal distance downstream from the crest

y = the vertical distance below the crest elevation

The basic equation to describe flow over a weir or spillway is

$$Q = C\ L(H)^{3/2} \qquad \text{Equation 1}$$

where: Q = discharge

C = coefficient of discharge

L = length of weir

H = total head

Utilizing methods described by Bradley[2] the coefficient of discharge was estimated to be 3.49. (The O'Sullivan spillway profile coincided with the Tiber spillway profile.) The spillway length, L, was 96 feet (29.3 meters) for the case where the piers extended upstream from the crest and 105 feet (32.0 meters) for the case where the piers were located downstream from the crest. This difference in spillway length was due to the total pier width. The design head, H, was 20 feet (6.10 meters).

For the normal pier nose location, upstream from the crest:

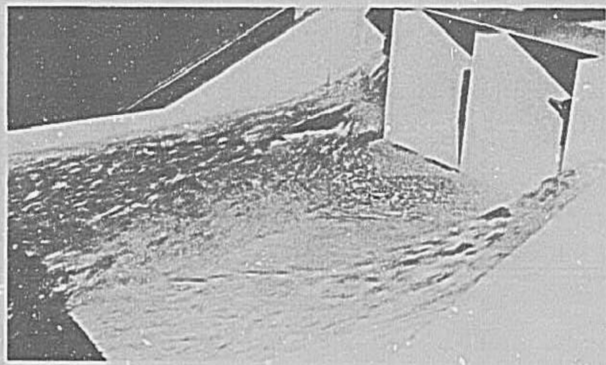
$$\text{Design discharge} = Q = 3.49\ (96)\ (20)^{3/2} = 29{,}966 \text{ cfs}$$

For the case where the pier is located downstream from the spillway crest:

$$Q = 3.49\ (105)\ (20)^{3/2} = 32{,}775 \text{ cfs}$$

However, with the pier nose located near the crest, the flow contraction around the pier nose resulted in an effective spillway length less than the 105 feet (32.0 meters) and a discharge less than the theoretical quantity computed above. It is possible to locate the piers at some distance downstream from the crest such that they no longer affect the spillway discharge.

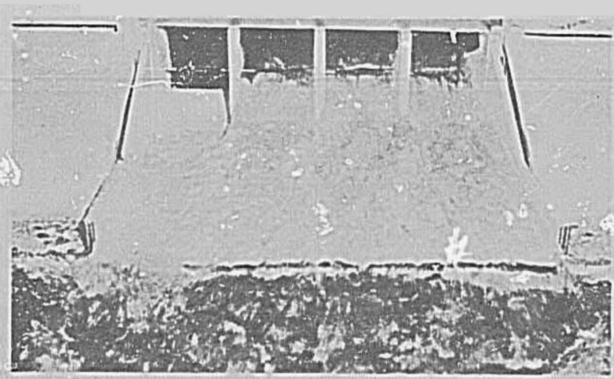
Pier nose located 13 feet (3.96 meters) downstream from the crest. The fixed section of the model pier with the elliptical nose was placed 13 feet (3.96 meters) downstream from the crest, Figure 10. The flow impinging on the pier nose climbed approximately 4.5 feet (1.37 meters). Figure 11 illustrates half cross sections of the symmetrical approach channel in the zone 4 feet (1.22 meters) upstream to 11 feet (3.35



a. H = 18.5 feet, Gates 1 and 4 open. P222-D-73822

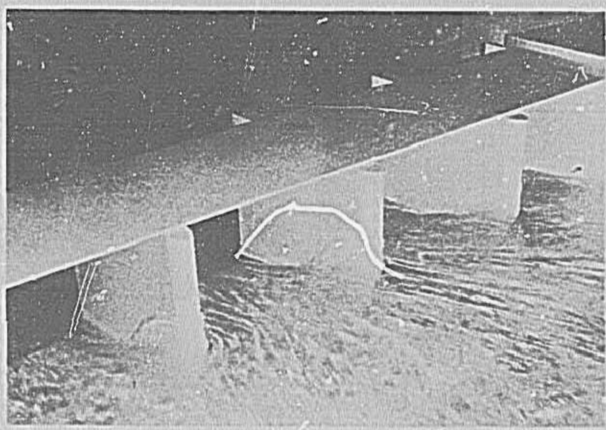
b. H = 18.5 feet, Gate 2 open. P222-D-73823

c. H = 18.5 feet, Gates 2 and 3 open. P222-D-73824



d. H = 18.5 feet, Gates 1, 2, and 3 open. P222-D-73825

Figure 9. Spillway chute (gate combinations).



Q = 32,300 cfs.

Figure 10. Pier nose 13 feet downstream from crest. P222-D-73826

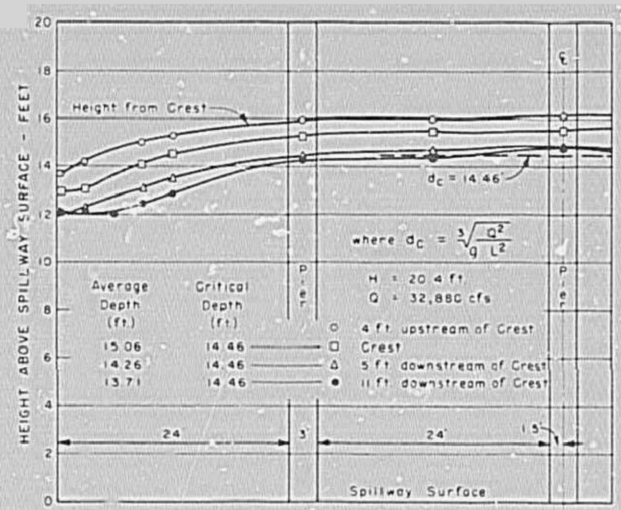
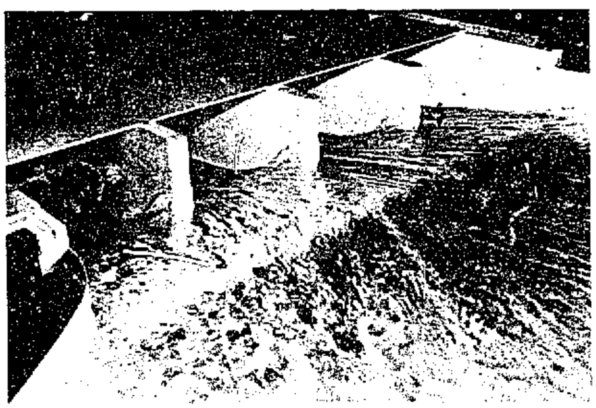


Figure 11. Spillway flow cross sections (piers 13 feet downstream).

meters) downstream of the spillway crest. Due to the transition from the 1:1 side slope to the vertical training wall a larger portion of the discharge passed through the center bays than the outside bays. The discharge for a design head of 20 feet (6.10 meters) was 32,300 cfs (915 cms).

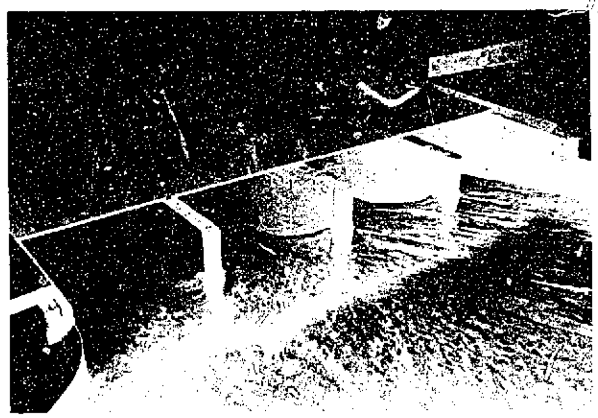
Pier nose located 6 feet (1.83 meters) downstream from the crest. A section of pier representing 7 feet (2.13 meters) was fastened to the upstream end of the fixed section with the elliptical nose fastened to the end of the addition. The pier nose was therefore located 6 feet (1.83 meters) downstream from the crest, Figure 12. The flow impinging on the elliptical nose climbed approximately 3.4 feet (1.04 meters). Figure 13 illustrates half cross sections of the flow as it passed over the crest. The water surface profiles again indicate a larger discharge through the two center bays. The discharge for the design head, H = 20 feet (6.10 meters) was 31,620 cfs (895 cms).

Pier nose located on the crest. A section of pier representing 6 feet (1.83 meters) was fastened to the earlier addition with the elliptical nose fastened to the upstream end; the pier now extended to the crest, Figure 14. The flow impinging on the nose climbed 2.0 feet (0.61 meter). Figure 15 shows half cross sections of the flow in the same area as mentioned previously. The discharge for the design head, H = 20 feet (6.10 meters) was 30,800 cfs (872 cms).



Q = 31,620 cfs.

Figure 12. Pier nose 6 feet downstream from crest. P222-D-73827



Q = 30,800 cfs.

Figure 14. Pier nose on crest. P222-D-73828

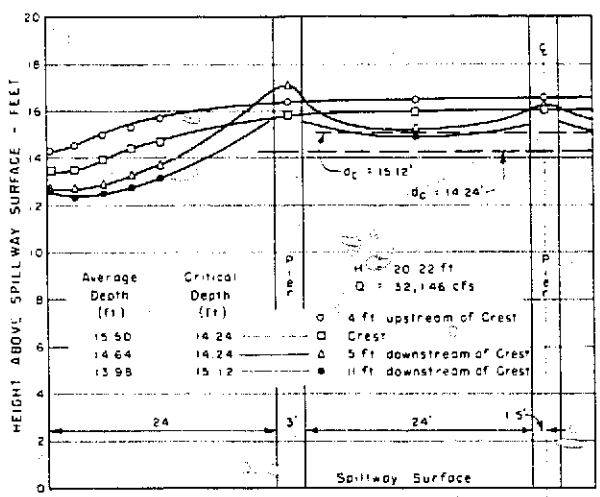


Figure 13. Spillway flow cross sections (piers 6 feet downstream).

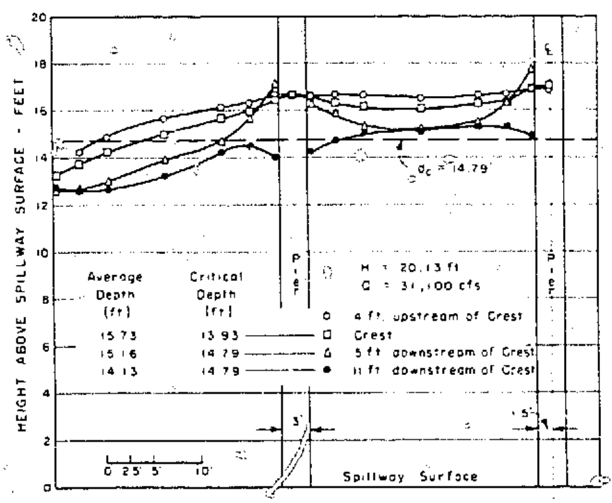


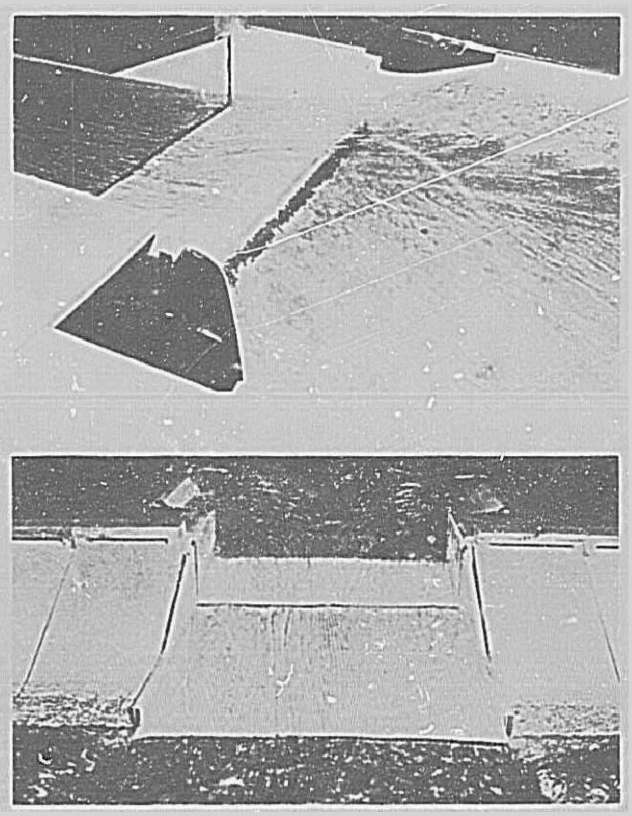
Figure 15. Spillway flow cross sections (piers at crest).

Pier nose located 7 feet (2.13 meters) upstream from crest. A section of pier representing 7 feet (2.13 meters) was fastened to the earlier additions. With the elliptical nose attached, the pier extended 7 feet (2.13 meters) upstream from the crest, Figure 16. Figure 17 illustrates half cross sections of the flow in the area 4 feet (1.22 meters) upstream to 11 feet (3.35 meters) downstream from the crest. The discharge for the design head, H = 20 feet (6.10 meters), was 29,750 cfs (842 cms).

Spillway without piers. The piers were removed from the model crest and tests conducted to determine the spillway capacity without piers, Figure 18. Figure 19 illustrates half cross sections of the flow in the same area as mentioned previously. The discharge for the design head, H = 20 feet (6.10 meters) was 32,580 cfs (922.6 cms). This would yield a coefficient of discharge of 3.47 in Equation 1.

Q = 29,750 cfs

Figure 16. Pier nose 7 feet upstream from crest. P222-D-73829



Q = 32,580 cfs.

Figure 18. Spillway without piers. Top Photo P222-D-73830, bottom Photo P222-D-73831

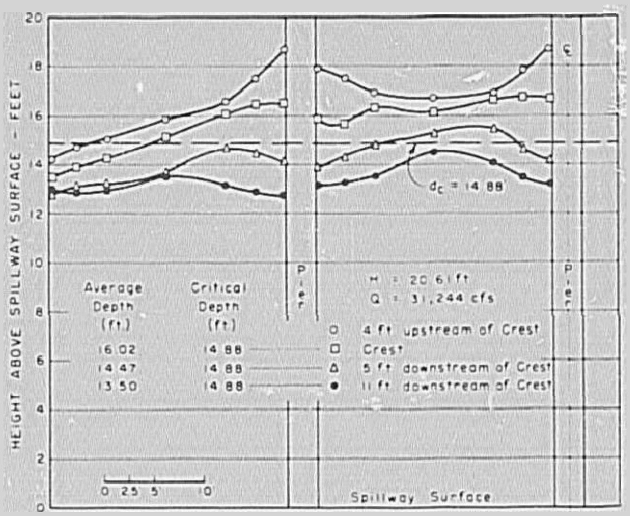


Figure 17. Spillway flow cross sections (piers 7 feet upstream).

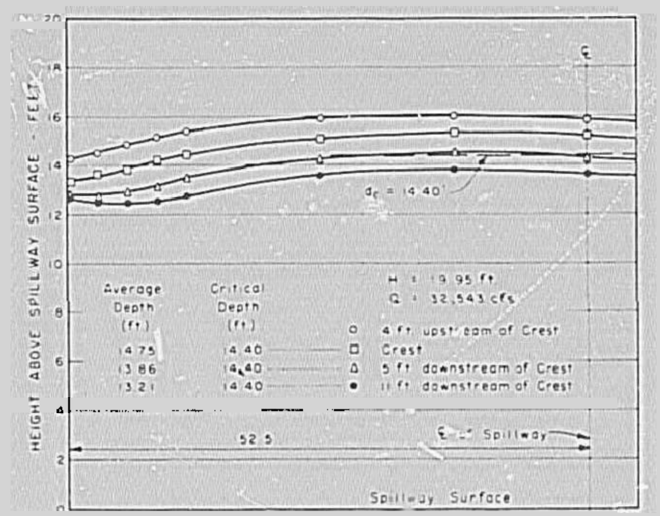


Figure 19. Spillway flow cross sections (without piers).

Discharge Capacity Rating

The discharge rating curves for the four pier locations are illustrated in Figure 20. It was originally assumed that the pier location 13 feet (3.96 meters) downstream from the crest was also downstream of the critical section. However, Figure 11 indicates a slight disturbance in the water surface 2 feet (0.61 meter) upstream from the center pier. Although the average depth was below critical, the depth near the center pier and therefore the flow in this zone was slightly above the critical condition. This result was further verified by a plot of design discharge [H = 20 feet (6.10 meters)] versus pier nose location, Figure 21. With the pier nose located 13 feet (3.96 meters) downstream from the crest, the design discharge is very close to the no-pier discharge.

A decrease in discharge is noted as the pier nose is moved up through the crest to a location 7 feet (2.13 meters) upstream from the crest. At some location upstream from the crest the lower end of the curve will level off to a constant discharge where the location of the pier nose will no longer affect the discharge rating.

As the pier nose was moved progressively downstream from the position 7 feet (2.13 meters) upstream of the crest, to the crest, to 6 feet (1.83 meters) downstream from the crest and to 13 feet (3.96 meters) downstream from the crest, the effective spillway length was increased by 38, 67, and 91 percent of the total pier width, respectively.

A model study of Horseshoe Dam spillway[3] showed an increase in the effective spillway length of 59 percent of the total pier width, by moving the pier nose 20 feet (6.10 meters) downstream from the crest. The O'Sullivan crest yielded a greater increase in the effective length in a shorter distance [91 percent in 13 feet (3.96 meters)]. This was due to the relatively steep spillway profile of the O'Sullivan spillway compared to the broad crested horizontal weir profile of the Horseshoe spillway.

Discharge measurements were made for uniform controlled flow at gate openings of 4, 8, and 12 feet (1.22, 2.44, and 3.67 meters), Figure 22. The gate openings were measured vertically from the spillway crest elevation to the bottom of the gate. Although these dis-

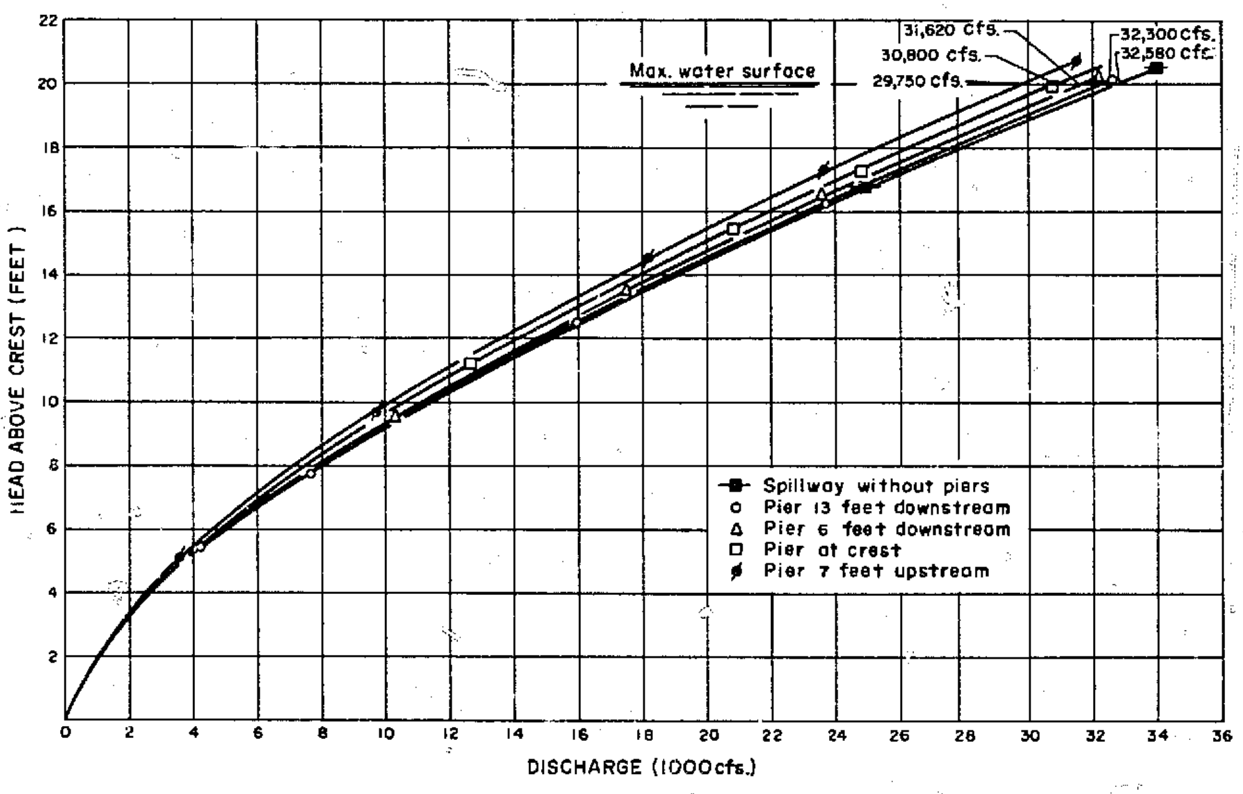


Figure 20. Discharge capacity (various pier locations).

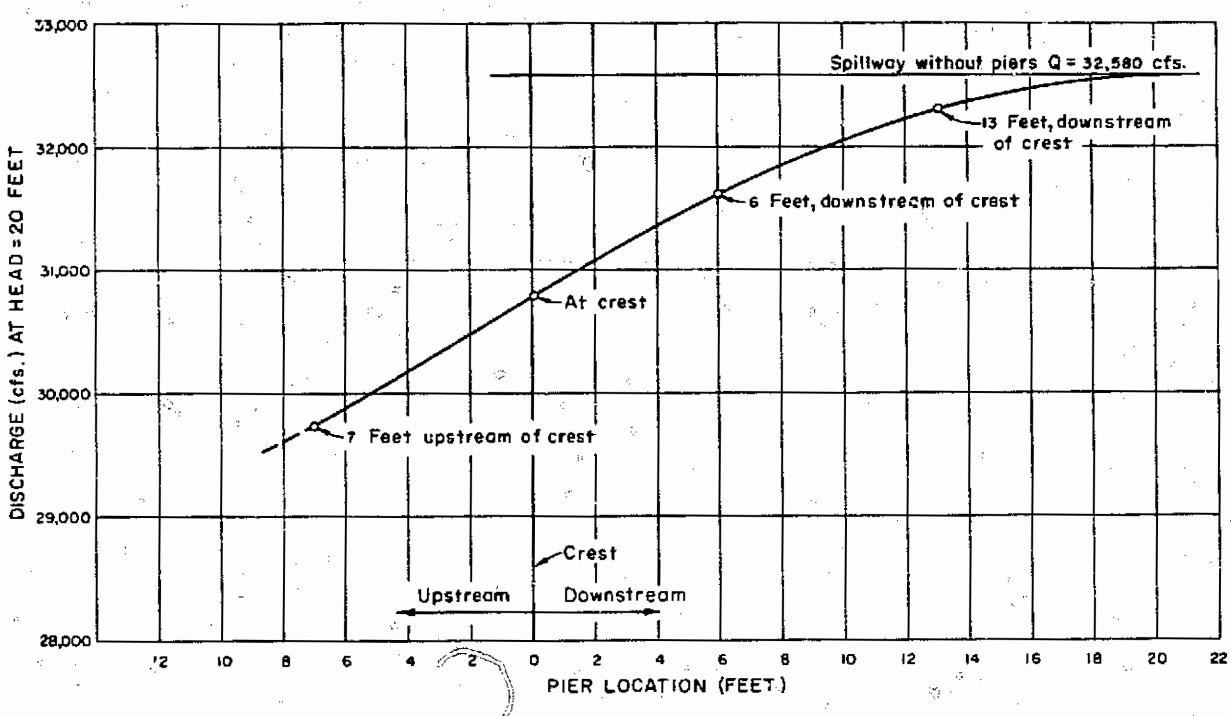


Figure 21. Spillway design discharge (various pier locations).

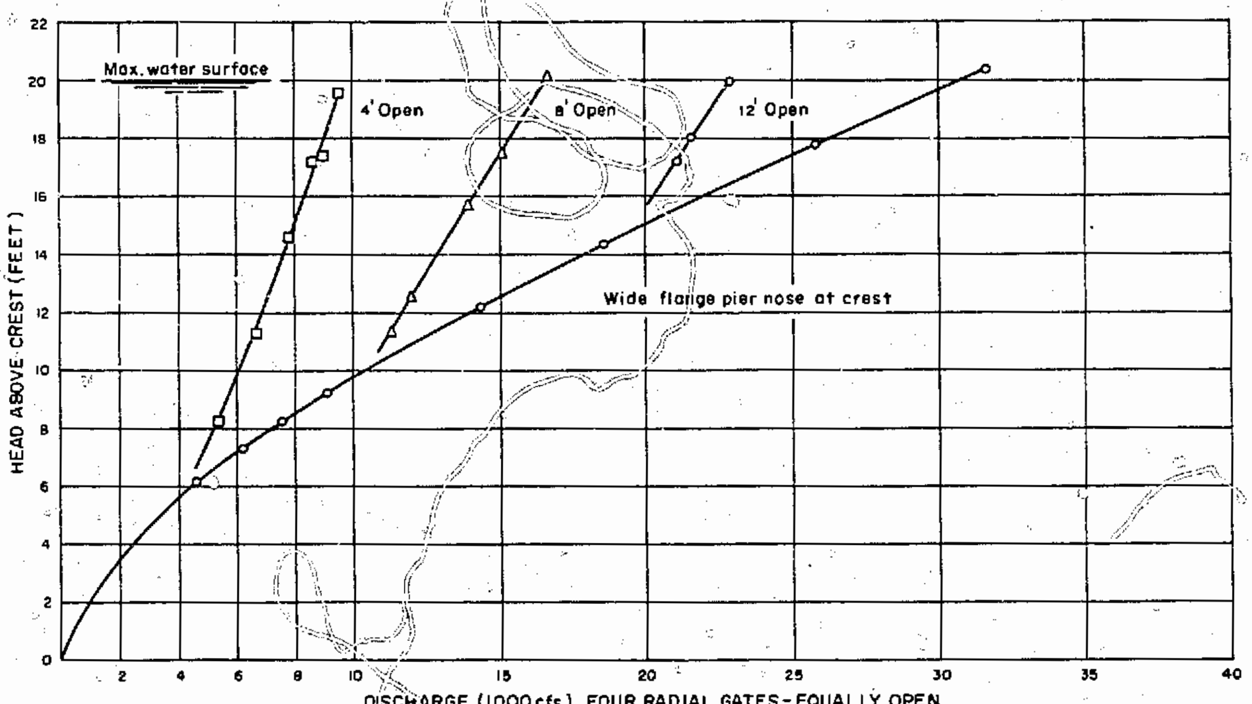


Figure 22. Discharge capacity (gate-controlled flow).

charge measurements were made with the wide-flange pier nose placed on the spillway crest, the elliptical pier nose would yield identical results.

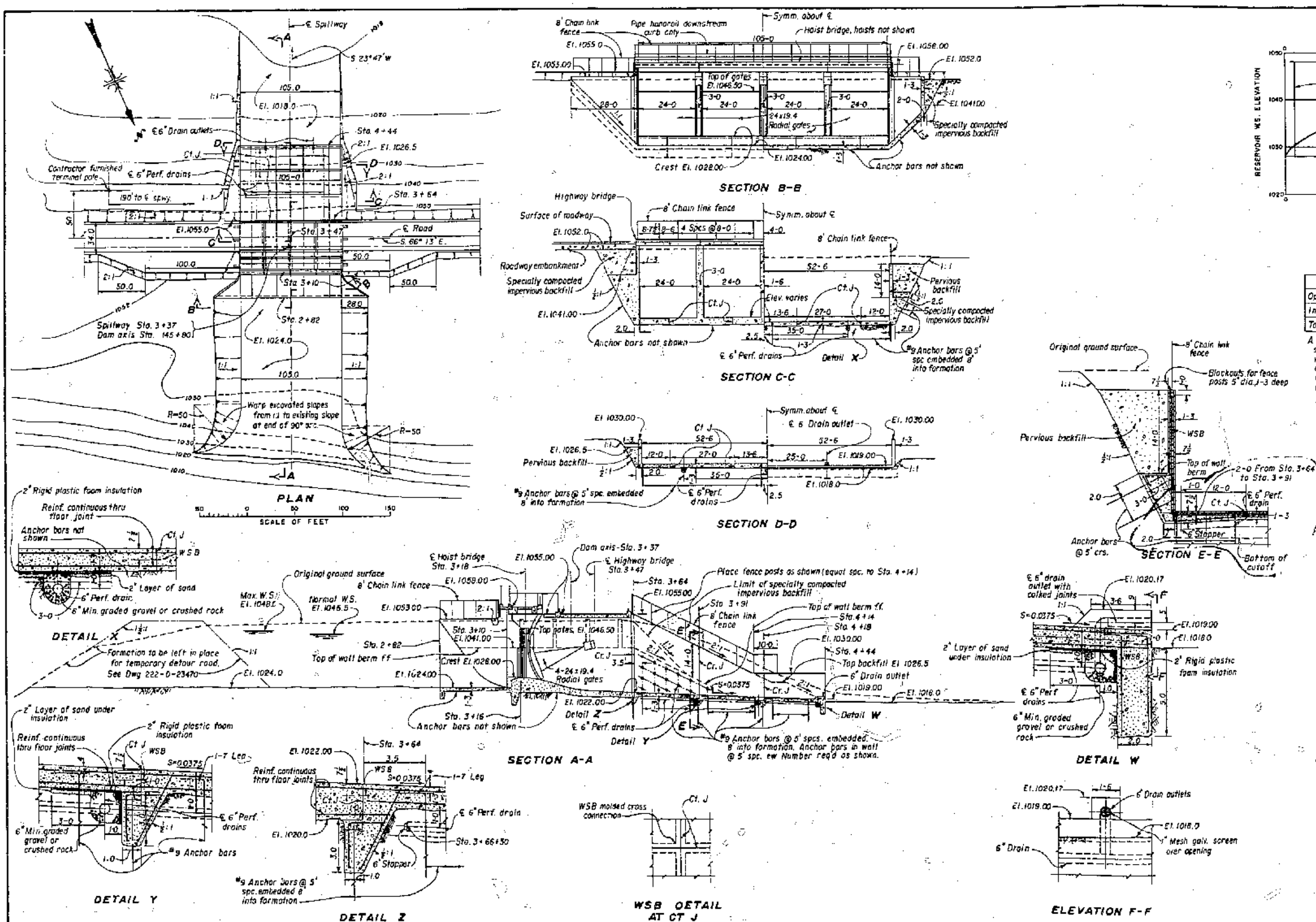
It is interesting to note the required height of the spillway gate as the piers are moved through the range from upstream to downstream of the crest. When the pier nose is located some distance upstream from the crest the gate seat is usually placed on the crest or immediately downstream from the crest. For the O'Sullivan Dam spillway with the pier nose located at the crest, the gate seat is 8.5 feet (2.59 meters) downstream from the crest and approximately 0.9 foot (0.27 meter) below the crest elevation. If the pier nose were located 6 feet (1.83 meters) downstream from the crest, the gate seat would be approximately 15 feet (4.57 meters) downstream from the crest and approximately 2.8 feet (0.85 meter) below the crest. It is obvious that the greatest improvement in discharge for a given increase in gate height occurs as the piers are moved from the position 7 feet (2.13 meters) upstream to the crest. Once past the crest, any more shortening of the piers results in an accelerated increase in gate height which quickly leads to a point of diminishing economic returns.

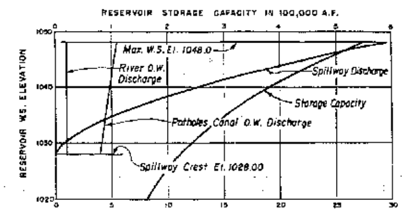
REFERENCES

1. Thompson, Major H., "Wallace Dam," A paper presented at the ASCE National Meeting on Water Resources Engineering, Atlanta, Georgia, January 24-28, 1972.

2. Bradley, J. N., "Discharge Coefficients for Irregular Overfall Spillways," Engineering Monograph No. 9, USBR, March 1952.

3. Peterka, A. J., "Hydraulic Model Studies for the Modification of Horseshoe Dam Spillway," Hydraulic Report No. Hyd-248, USBR, October 4, 1948.





DISCHARGE AND CAPACITY CURVES

RESERVOIR ALLOCATIONS

PURPOSE	ELEVATIONS	CAPACITY-A.F.
Operating Levels	1021.0 – 1046.5	341,500
Inactive	Up to 1021.0	168,300
Total		509,800

A surcharge of 42,600 A.F. (Max. W.S. El. 1048.0) with a spillway discharge of 29,600 c.f.s., a Potholes Canal outlet works discharge of 5,570 c.f.s., and a river outlet works discharge of 1,000 c.f.s. is provided to protect against an inflow design flood having a peak of 51,000 c.f.s. and a 15-day volume of 473,000 A.F.

NOTE

For general notes, see Dwgs. 40-D-7006 and 40-D-6263.
The design is based on an f'c of 4000 psi and fy of 60,000 psi.

REFERENCE DRAWINGS

INLET AND GATE STRUCTURE
STA. 2+82 TO STA. 3+64 .... 222-D-23458
BRIDGES - PLAN, SECTIONS AND DETAILS 222-D-23459
RUBBER WATERSTOPS - TYPES A, B, G, AND H 40-D-2867

A 4-30-73	REVISED CONCRETE THICKNESS ON SECTION E-E

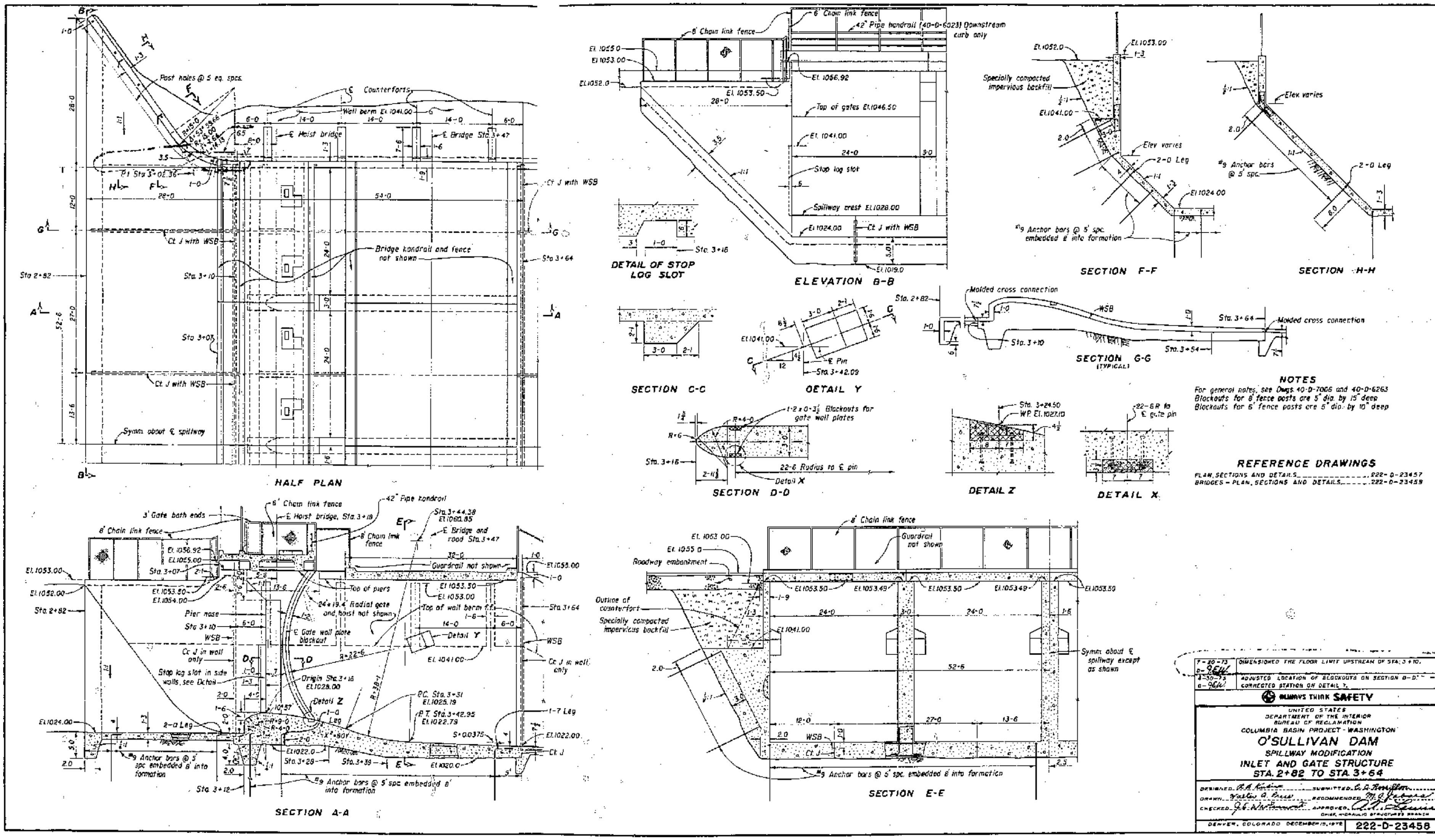
ALWAYS THINK SAFETY

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT - WASHINGTON

O'SULLIVAN DAM
SPILLWAY MODIFICATION
PLAN, SECTIONS, AND DETAILS

DESIGNED .... SUBMITTED ....
DRAWN .... RECOMMENDED ....
CHECKED .... APPROVED ....
C. C. [illegible] CHIEF, DIVISION OF DESIGN

DENVER, COLORADO DECEMBER 18, 1972 | 222-D-23457


HALF PLAN
SECTION A-A
DETAIL OF STOP LOG SLOT
ELEVATION B-B
SECTION F-F
SECTION H-H
SECTION C-C
DETAIL Y
SECTION G-G (TYPICAL)
SECTION D-D
DETAIL Z
DETAIL X
SECTION E-E
NOTES
For general notes, see Dwgs. 40-D-7006 and 40-D-6263
Blockouts for 8' fence posts are 5" dia. by 15" deep
Blockouts for 6' fence posts are 5" dia. by 10" deep
REFERENCE DRAWINGS
PLAN, SECTIONS AND DETAILS 222-D-23457
BRIDGES – PLAN, SECTIONS AND DETAILS 222-D-23459
DIMENSIONED THE FLOOR LIMIT UPSTREAM OF STA. 3+10.
ADJUSTED LOCATION OF BLOCKOUTS ON SECTION D-D". CORRECTED STATION ON DETAIL Y.
ALWAYS THINK SAFETY
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT – WASHINGTON
O'SULLIVAN DAM
SPILLWAY MODIFICATION
INLET AND GATE STRUCTURE
STA. 2+82 TO STA. 3+64
DENVER, COLORADO
222-D-23458

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
LENGTH		
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
AREA		
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
VOLUME		
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
CAPACITY		
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985 x 10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582 x 10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	*0.965873 x 10^{-6}	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	*4.4482 x 10^5	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

ABSTRACT

Hydraulic model studies were made to verify the design of the spillway, approach channel, and spillway chute for O'Sullivan Dam. Discharge rating curves are presented relating spillway discharge capacity to pier location upstream of the crest, at the crest, and downstream from the crest. The preliminary approach channel design was modified to improve the entrance flow conditions. Operating criteria for the spillway gates are recommended to assure acceptable flow conditions in the spillway chute.

Of particular interest were the tests relating spillway discharge capacity to pier location. Relocation of the pier nose from upstream of the spillway crest, to the crest, and to two downstream locations, resulted in an increase in the effective spillway width of 38, 67, and 91 percent of the total pier width, respectively.

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REC-ERC-73-15
Burgi, P H
HYDRAULIC MODEL STUDIES OF O'SULLIVAN DAM, COLUMBIA BASIN PROJECT
Bur Reclam Rep REC-ERC-73-15, Div Gen Res, Sept 1973. Bureau of Reclamation, Denver, 17 p, 22 fig, 3 ref, append

DESCRIPTORS—/ hydraulic structures/ *discharge coefficients/ discharge measurement/ *hydraulic models/ spillway crests/ water surface profiles/ radial gates/ approach channels/ critical flow/ gate control/ *spillway piers/ hydraulic design
IDENTIFIERS—/ O'Sullivan Dam, WA/ Columbia River Basin Proj/ Potholes Reservoir, WA/ pier noses

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