INVESTIGATIONS OF VARIOUS SHAPES OF THE UPSTREAM QUADRANT OF THE CREST OF A HIGH SPILLWAY

Hydraulic Laboratory Investigation

by

E. S. Melsheimer, T. E. Murphy

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Sponsored by Office, Chief of Engineers, U. S. Army

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi
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FOREWORD

The study described herein was performed at the U. S. Army Engineer Waterways Experiment Station, during the period May 1968 to May 1969, for the Office, Chief of Engineers, as part of the Engineering Studies Program. Funds utilized were allotted under ES 801, "General Spillway Investigations."

Engineers actively involved in the study were Mr. E. S. Melsheimer, Hydraulic Research Engineer, Mr. J. L. Grace, Jr., Chief, Spillways and Conduits Section, and Mr. T. E. Murphy, Chief, Structures Branch. The work was performed under the general supervision of Mr. E. P. Fortson, Jr., Chief, Hydraulics Division. This report was prepared by Messrs. Melsheimer and Murphy.

Director of the Waterways Experiment Station during the conduct of this study and preparation and publication of this report was COL Levi A. Brown, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.
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SUMMARY

This investigation was concerned with the shape of the upstream quadrant of the crest of a high spillway. Tests involved determination of pressures and discharge coefficients, with and without crest piers, at heads varying from one-fourth the design head to one and one-half times the design head. Limiting conditions for cavitation on the crest are defined.
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INTRODUCTION

1. Discharge coefficients and crest pressures, with and without crest piers, were observed on four shapes for the upstream quadrant of the crest of a high spillway. Data were collected at heads (H) from about one-fourth the design head to one and one-half times the design head (0.25Hd to 1.5Hd).

CREST SHAPES

2. Four shapes for the upstream quadrant (shown in plate 1) were studied:
   a. Type 1. A compound curve formed by two radii, 0.2Hd and 0.5Hd, with the 0.2Hd radius curve intersecting but not tangent to the upstream face of the spillway and the 0.5Hd radius curve having a zero slope at the crest. This alignment was set forth in circular letter No. 3281, dated 2 September 1944, by the Office, Chief of Engineers.
   b. Type 2. An elliptical curve of the equation
      \[ \frac{x^2}{(0.280Hd)^2} + \frac{y^2}{(0.167Hd)^2} = 1 \]
      This curve was developed at the U. S. Army Engineer Waterways Experiment Station by fitting an elliptical curve, tangent to the upstream face of the spillway and having a zero slope at the crest, to lower nappe profile data contained in the Bureau of Reclamation report on the Boulder Canyon Project, Part IV: Hydraulic Investigations, Bulletin 3, “Studies of Crests for Overfall Dams,” 1948.
   c. Type 3. A curve of the equation
      \[ \frac{Y_w}{H_w} = 0.413 \left( \frac{X_w}{H_w} \right)^{0.625} - 0.801 \left( \frac{X_w}{H_w} \right)^{1.85} \]
      Like the type 2 curve, this curve also is tangent to the upstream face and has a zero slope at the crest. Coordinates computed by McNown, Hsu, and Yih employing relaxation techniques to determine the path of the jet in the region close to a sharp-crested weir were used in development of the first X_w/H_w term. The second X_w/H_w term is required to account for the effect of gravity as the flow approaches the crest and to bring the equation into agreement with experimental data. The complexity of the equation shown in plate 1 results when the dimensionless parameters (X_w/H_w) and (Y_w/H_w) are changed from the head on the weir (H_w) to the head on the crest (H_d) and when the coordinate origin is transferred from the weir lip to the crest.
   d. Type 4. A compound curve formed by three radii, 0.2Hd and 0.5Hd (same as in type 1) plus 0.04H_d, with the last radius making the curve tangent to the
face of the dam. This shape is recommended by Mr. F. M. Manzanares Abecasis in “Spillways, Some Special Problems,” Memorandum No. 175 of the National Laboratory of Civil Engineering, Lisbon, Portugal, 1961.

In all tests the upstream face of the spillway was vertical and the downstream quadrant was shaped to the equation $X^{1.85} = 2.0H_d^{0.85} Y$.

TEST FACILITIES

3. The test spillway was designed for a head of 1.0 ft* ($H_d$) and was installed in a flume 2.4 ft wide. The crest piers (plate 1) were 0.2 ft wide, had ogival noses, and were installed with the noses on the same vertical plane as the upstream face of the spillway. With the two crest piers installed, the spillway was divided into a 1.0-ft-wide gate bay flanked by 0.5-ft-wide sections representing half gate bays. For the types 1, 2, and 3 crest shapes, the crest of the spillway was 3.4 ft above the floor of the flume; for the type 4 crest shape, the crest of the spillway was 2.5 ft above the floor of the flume.

4. The spillway was fabricated, for the most part, of sheet metal mounted on a steel frame set in concrete. A section of the crest containing the piezometers was accurately machined in plastic to ensure the exactness of the crest shape; extreme care was taken to set the piezometers precisely at right angles to the spillway surface. The crest piers were fabricated of sheet metal.

5. Two rows of piezometers were installed in each spillway crest with approximately 45 piezometers in each row, of which about 25 were in the upstream quadrant. The rows of piezometers were spaced so that when crest piers were installed, one row of piezometers was on the center line of the gate bay and the other row was parallel to and 0.01 ft from the side of a crest pier. However, only in the type 4 crest were piezometers installed 0.01 ft from the ogival nose of the crest pier.

CALIBRATION

6. In all calibration data, the velocity head for the average velocity of flow in the approach flume has been added to the pool elevation to obtain the head ($H$) on the spillway crest. Differences in capacity for the four spillway crests tested, either without or with crest piers, were considered insignificant. Discharge coefficients ($C$) in the usual weir formula $Q = CLH^{3/2}$ are plotted in plate 2. Also plotted in this plate are pier contraction coefficients ($K_p$) in the formula $Q = C(L - K_pNH)H^{3/2}$ where $N$ is the total number of contractions, two per pier.

PRESSURES

7. Pressures (as ratios to the design head) on the spillway crests without piers, on the center line of a gate bay, and along a pier are plotted in plates 3-14. Minimum pressures on the upstream quadrant of the crests for heads equal to or greater than the design head are tabulated on the following page:

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* Multiply feet by 0.3048 to obtain meters.
8. The minimum pressure on the type 4 crest along the pier was observed adjacent to the point where the pier nose became tangent to the side of the pier. Pressures were obtained at corresponding points on the other three crests, and it is probable that the pressures at these points were the minimum pressures although this was not established since data were not taken along the pier nose.

### DISCUSSION

9. The weir discharge coefficient curve (plate 2) developed from these tests closely follows the curve in Hydraulic Design Chart (HDC) 111-3 (revised 1-64) at heads equal to and less than the design head. At heads greater than the design head the present series of tests indicates more favorable discharge coefficients. Since the HDC 111-3 (revised 1-64) curve was based on limited data at heads greater than the design head, the data presented herewith are considered more reliable and should be used in future computations.

10. The rather wide variations in minimum pressures on the crest with undetectable variations in discharge coefficients may appear unreasonable. However, for all crests the pressures at the crest line were essentially the same for equal discharges. The variations in minimum pressures occurred in dips in the pressure gradients on the upstream quadrant and thus apparently had no effect on the discharge coefficients.

11. Pier contraction coefficients are sensitive to direction of approach flow, width of pier, and position of pier nose with respect to crest as well as pier-nose shape; thus it is hard to develop generalized data applicable to any particular set of conditions. However, pier contraction coefficient values developed from these tests are in good agreement with those plotted in HDC 111-5 (WES 4-1-53) and serve to confirm previously developed data.

12. The sharp dip in the pressure grade line on the type 1 crest immediately downstream from the intersection of the crest and the upstream face of the dam confirms the opinion that the...
discontinuity should be eliminated and the crest made tangent to the upstream face of the dam as was done in the types 2, 3, and 4 crests.

13. In general, minimum pressure conditions were more favorable with the types 2 and 4 crests than with the types 1 and 3 crests. The minimum pressure that can be tolerated on a spillway crest without cavitation has not been established. However, Abecasis (see subparagraph 2d) conducted tests in a vacuum tank and established a curve for incipient cavitation on a graph with $H_d$ as ordinate and $H/H_d$ as abscissa. From current data on the type 4 crests, plots for minimum pressures of -20 and -25 ft have been made on a similar graph in plate 15; Abecasis' incipient cavitation curve closely follows the curve for a minimum pressure of -25 ft. However, spillway crests seldom are constructed in the field to the close tolerance observed in these model tests and thus it is recommended that, in design, conditions be limited to those that will result in pressures no lower than -20 ft. Curves for minimum pressures of -20 and -25 ft on the types 2 and 4 crests with piers installed are plotted in plate 16.

14. It has been the practice in the Corps of Engineers to design certain spillway crests for a ratio of $H/H_d = 1.33$ regardless of the value of $H_d$. It is suggested that in the future consideration be given to the data in plates 15 and 16 and that ratios of $H/H_d$ be selected for design so that the minimum pressure will not be less than -20 ft.

15. Usually, structural considerations will result in crest piers sufficiently long to extend downstream of the subatmospheric pressure zone on the spillway crest; however, care should be taken to see that this always is true. If the downstream end of the pier is located within the subatmospheric zone, aeration of the spillway nappe is a possibility. This could result in a loss of capacity or, worse still, in an unstable nappe. A pier that extends a horizontal distance of $1.2H_d$ downstream from the axis of the crest should be sufficiently long in most cases.
PLAN OF TYPICAL PIER

UPSTREAM NOSE OF PIER

AXIS OF CREST

TYPE 1 CREST

Y = 0.724 \( \frac{(X + 0.270 H_d)^{0.85}}{H_d^{0.85}} + 0.126 H_d - 0.4315 H_d^{0.375} (X + 0.270 H_d)^{0.625} \)

TYPE 2 CREST

\( \frac{X^2}{(0.280 H_d)^2} + \frac{Y^2}{(0.167 H_d)^2} = 1 \)

TYPE 3 CREST

\( X^{0.85} = 2 H_d \)

TYPE 4 CREST

DETAILS OF CRESTS AND PIER

SCALE IN FEET

PLATE 1


**Legend**
- ○ Type 1 Crest
- △ Type 3 Crest
- □ Type 2 Crest
- ▽ Type 4 Crest

**Equation**
- \( C = \frac{Q}{LH^{1/2}} \)

**Graph**
- Total Head on Crest = \( H_H \)
- Design Head

**Notes**
- Pier nose shape located in the same plane as upstream face of spillway.
CREST PRESSURES
WITHOUT PIERS
TYPE 1 CREST
CREST Pressures at Center Line of Gate Bay
Type 1 Crest

PLATE 4
CREST PRESSURES ALONG PIER
TYPE 1 CREST

PLATE 5
CREST PRESSURES
WITHOUT PIERS
TYPE 2 CREST

PLATE 6
CREST PRESSURES AT CENTER LINE OF GATE BAY
TYPE 2 CREST

PLATE 7
CREST PRESSURES
WITHOUT PIERS
TYPE 3 CREST

PLATE 9
CREST PRESSURES AT CENTER LINE OF GATE BAY
TYPE 3 CREST
CREST PRESSURES ALONG PIER
TYPE 3 CREST

PLATE II
CREST PRESSURES
WITHOUT PIERS
TYPE 4 CREST

PLATE 12
CREST PRESSURES AT CENTER LINE OF GATE BAY
TYPE 4 CREST

PLATE 13
CREST PRESSURES ALONG PIER
TYPE 4 CREST

PLATE 14
PREDICTED MINIMUM PRESSURES
TYPE 4 CREST—WITHOUT PIERS

PLATE 15
Predicted minimum pressures
Types 2 and 4 crests with piers

Plate 16
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Final report

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Final report

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Research Report H-70-1

This investigation was concerned with the shape of the upstream quadrant of the crest of a high spillway. Tests involved determination of pressures and discharge coefficients, with and without crest piers, at heads varying from one-fourth the design head to one and one-half times the design head. Limiting conditions for cavitation on the crest are defined.
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