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A SITE SPECIFIC STUDY OF A LABYRINTH SPILLWAY

Kathleen L. Houston 1/ and Carol S. DeAngelis 2/

ABSTRACT

The existing structures at Ute Dam do not supply the desired reservoir storage capacity for the future water needs of the area. A laybrinth spillway was selected for the modification of Ute Dam because the labyrinth with a raised crest elevation provides increased reservoir storage and the longer crest length provides greater discharge capability for a fixed spillway width.

Design curves were developed from which a cost effective 14-cycle labyrinth spillway was designed. Hydraulic aspects of the spillway were confirmed by tests with a 1:80 overall scale model and several sectional models. A comparison is made to previously built labyrinth spillways.

Introduction

Ute Dam is located on the Canadian River 2 mi (3.2 km) west of Logan, New Mexico. The dam is a 121-ft (36.9-m) high earthfill structure with crest elevation 3801 ft (1158.5 m). The existing spillway is an 840-ft (256-m) wide ungated overflow structure with crest elevation 3760 ft (1146 m).

Several alternatives for increasing the reservoir storage capacity at Ute Dam were investigated. Gating the existing crest structure was evaluated but the additional load imposed by the increased water surface would cause instability. Therefore, gated alternatives had to include the cost of a new crest structure. The least cost was estimated at $34,000,000. (All estimated costs based on November 1980 unit prices.) Several ungated alternatives were studied. A labyrinth spillway, combined with raising the dam, was the most economical at $10,000,000.

The labyrinth spillway is a series of triangular or trapezoidal shapes in plan view which increase the effective length of the spillway crest within a fixed spillway width. For a given operating head, higher discharges can be passed over the labyrinth spillway crest than a straight crest. The labyrinth spillway was selected as an economical alternative to increase the storage capacity of the reservoir at Ute Dam. The proposed labyrinth structure is shown on Fig. 1.

1/ Hydraulic Engineer, Bureau of Reclamation, Denver, Colorado.
2/ Civil Engineer, Bureau of Reclamation, Denver, Colorado.

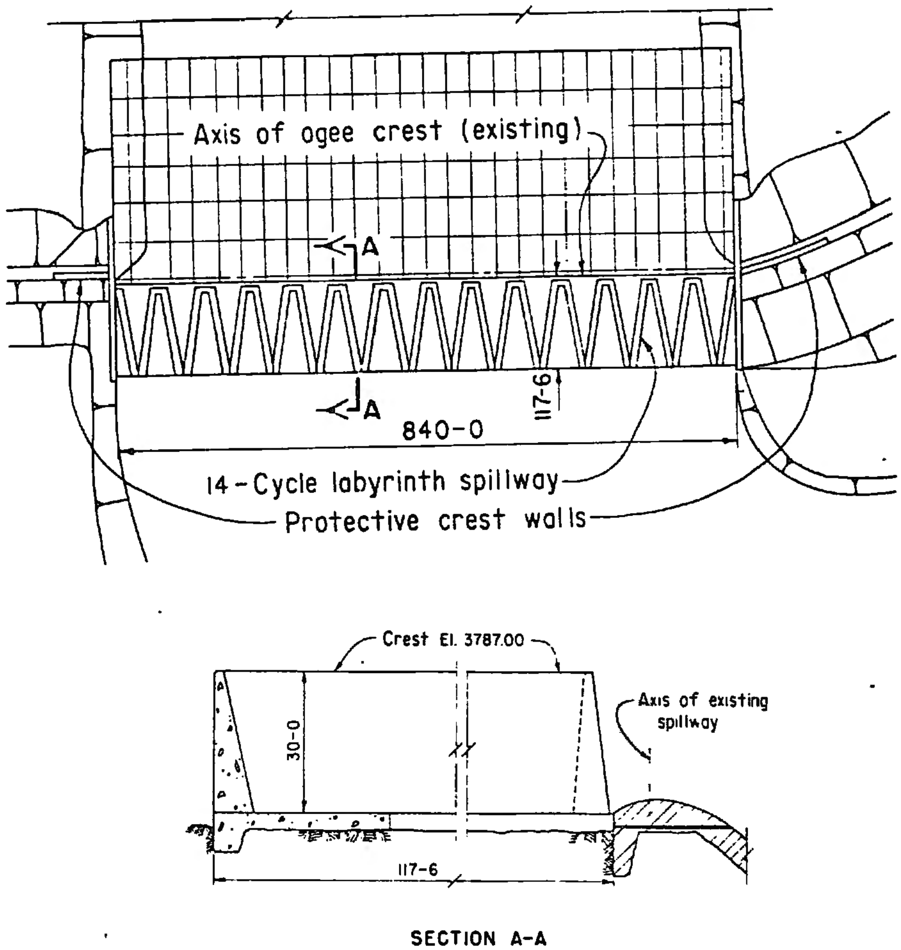


FIG. 1. - Proposed labyrinth spillway structure.

Design Criteria

The IDF (inflow design flood) has a peak of 590 000 ft^3/s (16 707 m^3/s) and a 4-day volume of 2 155 000 acre-feet (2.66 x 10^9 m^3). This flood was also used in the design of the existing structure.

The desired additional reservoir storage of 27 ft (8.2 m) required a crest elevation of 3787 ft (1154.3 m). The maximum reservoir elevation was limited to about 3806 ft (1160 m) to minimize flood damage to private property along the reservoir rim. These criteria are met with a 30-ft (8.2-m) high spillway with a design head, H_o, of 19 ft (5.8 m).

Parameters and Initial Design

The hydraulic design of the labyrinth spillway was originally based on design procedures and curves by Hay and Taylor (5). Parameters which affect the performance of the spillway are discussed below and shown on Fig. 2.

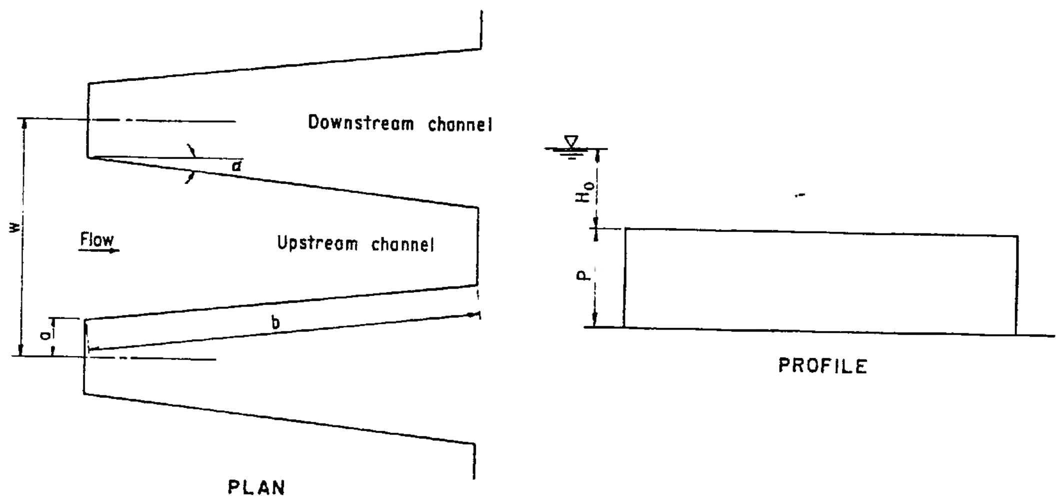
The length magnification, l/w, and the angle α completely define the shape of a plan form with n being the number of cycles forming the spillway. For a given length magnification, the angle α varies from zero for a rectangular plan form to a maximum for a triangular plan form. The vertical geometry of the spillway is defined by the vertical aspect ratio, w/P. The performance of the spillway, Q_L/Q_{NS} is a function of H/P, l/w, w/P, and α. The initial design for the Ute spillway complied with the limits defined by Hay and Taylor [(5) pg. 2342] for each parameter.

Other labyrinth spillways are in use at Quincy Dam, Aurora, Colorado (1); Mercer Dam, Dallas, Oregon (2); Woronora and Avon Dams, Sydney, Australia (4); among others. Hydraulic model studies were done on the Navet Pumped-Storage Project, West Indies (8); Mercer Dam, Oregon (3); and Bartletts Ferry Project, Georgia (7). The ranges of some important design parameters for these labyrinth structures are compared with the Ute laybrinth below (symbols as defined on Fig. 2):

Parameters	Range	Ute labyrinth
l/w	1.9-5.0	4.0
H_0/P	0.40-0.72	0.63
H_0	3-7 ft (0.91-2.13 m)	19 ft (5.79 m)
w/P	1.2-6.0	2.0
n	4-11	14

For the Ute labyrinth, the trapezoidal plan form was chosen for high efficiency and ease of construction. The H_0/P requirement for the Ute labyrinth spillway was beyond the range of the published design curves for performance of labyrinths. The Hay and Taylor curves were extrapolated for the initial design of a 10-cycle labyrinth with an effective crest length of 2322 ft (708 m). The labyrinth would be placed just upstream of the existing ogee crest.

Because the initial design was based on extrapolated design curves, a hydraulic model study was requested. The model would also be used to determine the approach conditions, pressure loadings on the spillway, the effect of the existing downstream ogee crest on the performance of the labyrinth, and an optimum crest shape.



a = half length of labyrinth apex;
b = length of labyrinth side wall;
C_a = discharge coefficient for actual crest section;
C_s = discharge coefficient for the sharp crest;
H = total upstream head over crest, less than H_o;
H_o = design head;
l = developed length of one labyrinth cycle = 4a+2b;
l/w = length magnification;
n = number of spillway cycles in plan;
P = spillway height;
Q_L = discharge over labyrinth spillway;
Q_{Ns} = discharge over corresponding linear sharp crested spillway

$= C_s W H^{3/2}$;

Q_L/Q_{Ns} = flow magnification (measure of spillway performance);
W = width of linear spillway;
w = width of one labyrinth spillway cycle;
w/P = vertical aspect ratio; and
α = angle of side walls to main flow direction.

FIG. 2. - Labyrinth spillway parameters.

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Hydraulic Model Study

The model study was conducted in two phases. The first phase included verification and extrapolation of the Hay and Taylor design curves in a 2.5-ft (0.76-m) wide flume test facility. A 1:80 scale model of the entire labyrinth spillway, reservoir approach area, and downstream channel was studied in the second phase. Tests during this phase also included measuring velocities along the embankment adjacent to the spillway, testing splitter pier locations, and measuring water surface profiles and pressures in the upstream and downstream channels, respectively. These results are described in detail in the hydraulic model study report (6).

Flume Tests

To ensure continuity between the previous and extended range of the design curves, an initial attempt was made to verify the existing curves. Tests began with a sharp-crested triangular-shaped plan form weir of $l/w = 3$. The results of this test did not confirm those of Hay and Taylor which led to further flume testing of triangular-shaped weirs with length magnifications of 2, 4, and 5. The triangular plan form was emphasized as this is the most efficient. The final results were significantly different than the work of Hay and Taylor. The differences were particularly noticeable at high H/P values with the lower values tending towards the ideal case of discharge increasing in exact proportion to length.

The discrepancy between the two sets of design curves [Hay and Taylor (5) and revised (6)] appeared to be the difference in upstream head definition. The discrepancy discovered is attributable to several factors which are currently under study. This paper will not discuss these differences but will emphasize the use of the revised curves that were developed using total head; the measured head plus the velocity head, $V^2/2g$. The total head, H, is used throughout the study and design. H_o is the maximum or design head value which also includes the velocity head. Design curves, shown on Fig. 3, were developed for $n = 2$ (two apexes upstream) and $w/P = 2.5$ with $P = 0.50$ ft (0.15 m), $w = 1.25$ ft (0.38 m), and $0 < H/P \leq 1$.

Ten-cycle Labyrinth Spillway Model

To determine which curves would correctly predict the maximum discharge in a reservoir situation, the 1:80 scale model of Ute Dam was used. The Ute 10-cycle labyrinth spillway, as initially designed from Hay and Taylor's extrapolated curves, was first tested. This test showed that the maximum discharge could not be passed over the spillway within the stipulated design head, H_o, of 19 ft (5.8 m). Therefore, the total developed spillway length required would be greater than that predicted by the Hay and Taylor curves. The design discharge magnification $(Q_L/Q_{NS})_{max}$ and design head to crest height ratio, H_o/P, when plotted on the revised design curves gave a length magnification, l/w, of 4.00 instead of 2.74 as predicted by Hay and Taylor's curves. This result prompted redesign of the spillway based upon the $l/w = 4$ curve shown on Fig. 3.

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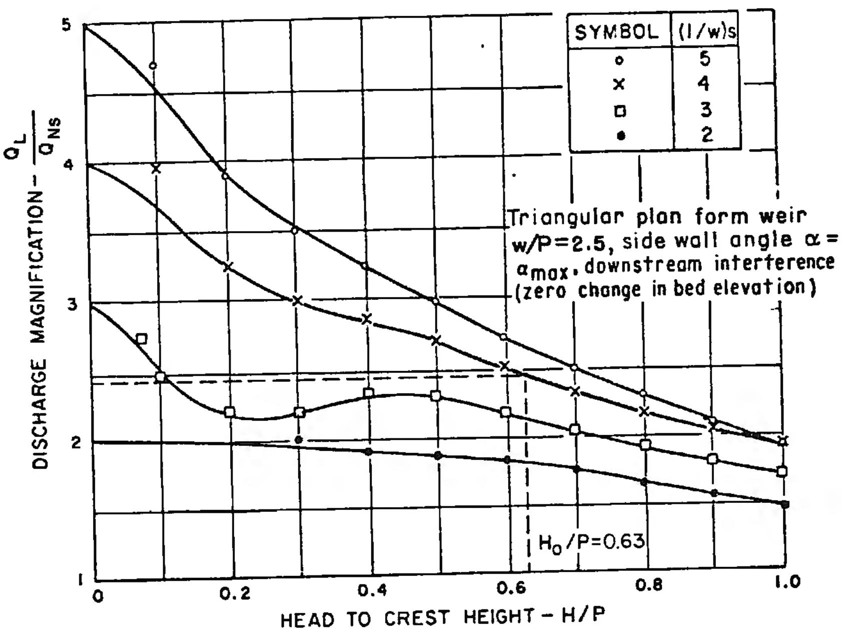

FIG. 3. - Revised design curves.

Design Procedure

The following design method uses a design head, H_0, to size the labyrinth spillway and is based on Hay and Taylor's design procedure with minor modifications:

1. Determine from the site conditions: crest height, P, total channel width, W, and a design head, H_0.

2. Estimate the labyrinth discharge $(Q_L)_{max}$ at the design head by a rough flood routing.

3. Determine the sharp-crested linear weir discharge $(Q_{Ns})_{max}$ by the equation on Fig. 2 using H_0/P to find C_s in Fig. 4. Use either w/P curve as they are very similar and the w/P effect of the final design should actually be determined from a model study.

4. Determine $(Q_L/Q_{Ns})_{max}$ and use H_0/P in the design chart (Fig. 3) to find $(l/w)_s$.

5. Select a crest shape and determine its coefficient, C_a, for the design head, H_0. Fig. 4 shows the curve of experimental data for the Ute crest shape. This curve gives a coefficient of discharge for various values of H/P but this is not to be confused with a discharge coefficient taken in its normal context in the equation: $Q = C_D W H^{3/2}$. The curve on Fig. 4 shows values that have been

derived using this equation with discharge values from the labyrinth rating curve. The equation assumes that the length is constant, but the effective length of the labyrinth spillway is constantly changing with a change in reservoir head. Therefore, the coefficient of discharge shown by this curve reflects this change in length.

6. Modify $(l/w)_s$ from sharp crest to acutal crest section $(l/w)_a$ by $(l/w)_a = \frac{(l/w)_s(C_s)}{C_a}$.

It is now necessary to develop a labyrinth rating curve using the following procedure:

7. Select arbitrary values of H/P between zero and H_o/P and determine C_a and C_s for each value from Fig. 4. (C_a curve on Fig. 4 is specifically for Ute crest shape. Other shapes might require a different curve.)

8. It is necessary to construct an auxiliary curve on Fig. 3 to determine $(Q_L/Q_{Ns})_{equiv}$ for an equivalent sharp-crested labyrinth weir. For each value of H/P compute:

$(l/w)_{equiv} = \frac{C_a}{C_s}(l/w)_a$, then plot $(l/w)_{equiv}$ on Fig. 3 by interpolating between the existing curves.

9. Determine $(Q_L/Q_{Ns})_{equiv}$ for each H/P value from the curve plotted in Fig. 3.

10. Determine the labyrinth rating curve by:

$$Q_L = \left(\frac{Q_L}{Q_{Ns}}\right)_{equiv} \times Q_{Ns} = \left(\frac{Q_L}{Q_{Ns}}\right)_{equiv} \times C_s W H^{3/2}$$

11. Compare the Q_L computed for design head in step 10 with the value of $(Q_L)_{max}$ in step 2. If necessary, adjust the $(Q_L)_{max}$ in step 2 and repeat the procedure. If the $(Q_L)_{max}$ values are very similar, define the geometry of the spillway by selecting the number of cycles, n, and the side wall angle, α. With the spillway geometry designed for the total computed length, check that all parameters are within the acceptable design range. If necessary, redefine the spillway geometry.

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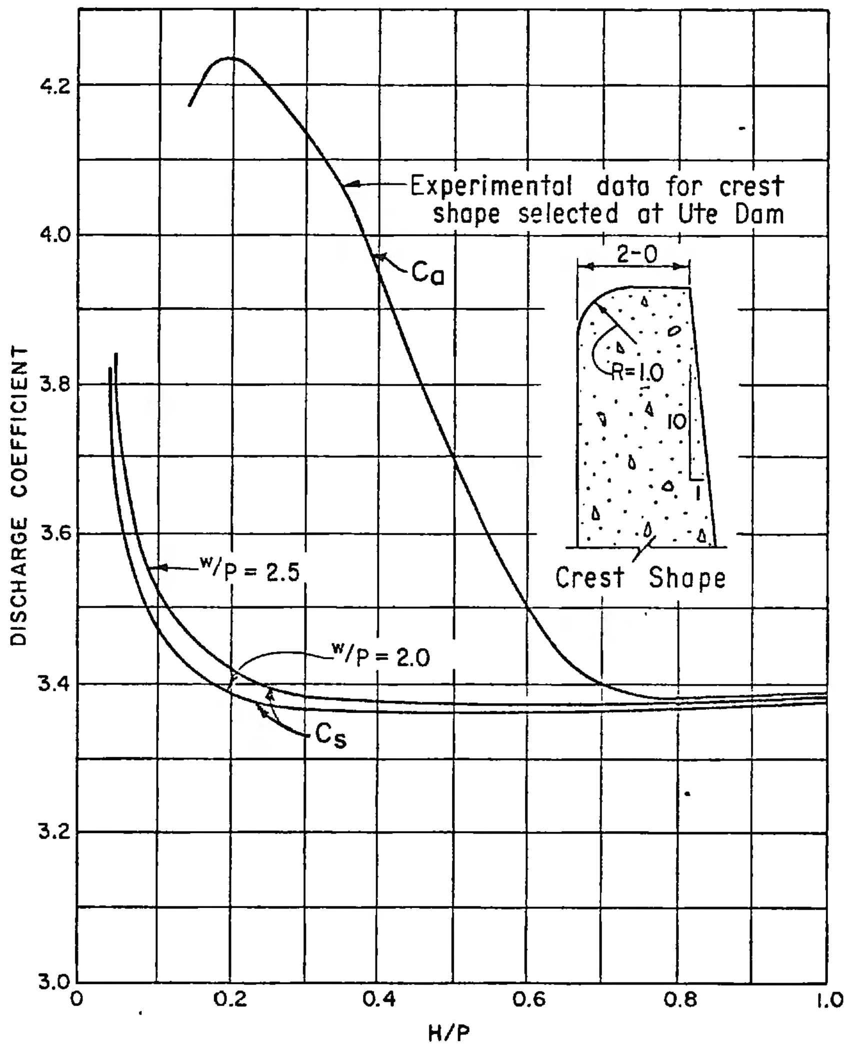

FIG. 4. - Linear weir discharge coefficient curves.

Using this procedure, a 14-cycle spillway was selected for the modification of Ute Dam with an effective crest length of 3360 ft (1024 m) within the 840-ft (256-m) width. Other parameters and dimensions of the 14-cycle spillway are $H_0/P = 0.63$, $Q_L/Q_{Ns} = 2.445$, $1/w = 4$, $w/P = 2$, b = 114 ft (34.75 m), a = 3 ft (0.91 m), and $\alpha = 12.15°$.

Fourteen-cycle Labyrinth Spillway

The labyrinth spillway described previously was installed in the 1:80 scale model (Fig. 5). The discharge curve developed for the spillway showed that more discharge could be passed at lower reservoir elevations than in the 10-cycle spillway.

The high reservoir head caused special hydraulic conditions which warranted study. The lateral flow along the embankment is channeled by a protective crest wall into the spillway chute at the downstream apexes of both end cycles. This lateral flow does not interfere with the flow over the spillway.

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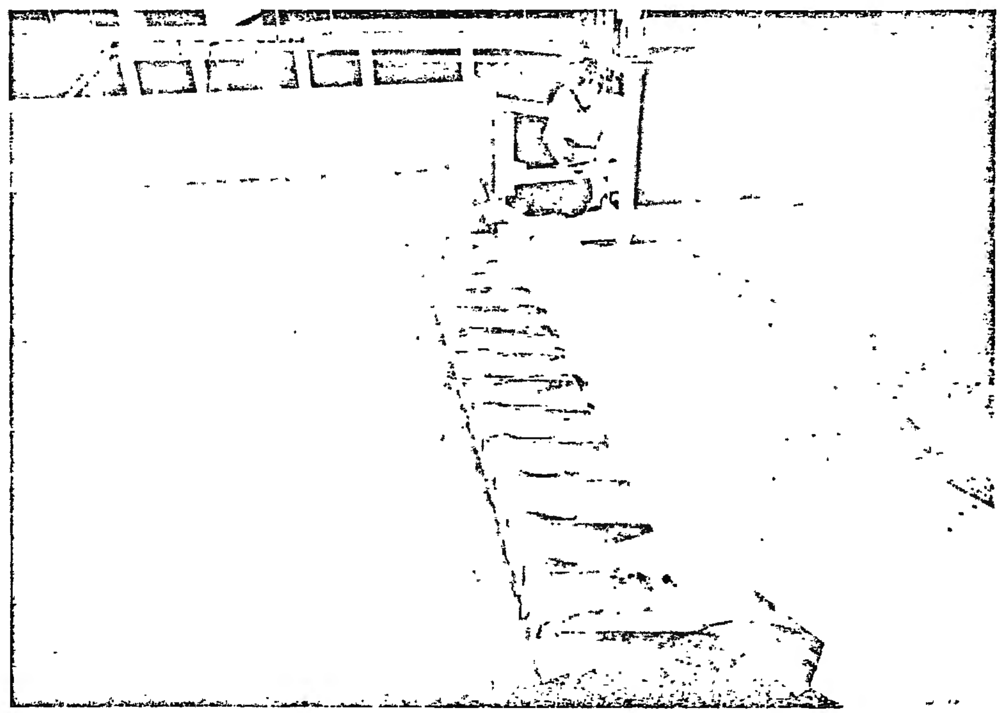

FIG. 5. - Maximum discharge passed by 14-cycle labyrinth spillway model.

Visual observations and water surface profiles showed a significant drop in the water surface immediately upstream of the spillway between cycles. This is attributable to several factors including the area contraction as flow enters the upstream channel, the loss due to the velocity head, and nappe interference. Nappe interference occurs over the upstream apexes of the spillway due to the high reservoir head and small vertical aspect ratio, w/P. As the number of cycles, n, increases for a given overall width, W, w/P is decreased as well as the distance that the labyrinth encroaches into the approach channel. Therefore, by keeping the w/P as small as possible, without lowering the hydraulic efficiency too greatly, the base of the weir will be smaller, which reduces construction costs.

The operating range of low discharges was also of concern. Noise and nappe oscillations have been documented at other sites (9) while operating under low heads. To avoid this problem, a splitter pier will be installed on each spillway side wall 11 ft (3.35 m) upstream of the downstream apexes to supply air and support the nappe. The splitter piers will be 3 ft (0.91 m) tall and become submerged during operation under higher heads.

To assist in the structural design of the labyrinth spillway, pressures were measured on the floor of the downstream channels. The piezometers were located parallel to the side walls and along the centerline. In general, the pressures diminished as the channel width expanded. The pressures were not excessive and ranged from about 6.5 to 17.3 lb/in^2 (44.8 to 119.6 kPa) for the full range of discharges.

Conclusions

The labyrinth spillway has many applications. It can be easily adapted to site constraints of new and existing structures. Tradeoffs between hydraulic, structural, and economic considerations are an important part of the labyrinth spillway selection and design. The hydraulic flume tests resulted in the development of a set of revised design curves and a design method. The accuracy of these curves was verified by the further testing of the site specific scale model which required a much higher length magnification than previously predicted. Splitter piers should be used to prevent nappe oscillations under low flow conditions.

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