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HYDRAULIC DESIGN AND APPLICATION OF LABYRINTH SPILLWAYS

by

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ABSTRACT

A significant portion of the work performed by the Bureau of Reclamation deals with dam safety and rehabilitation. Inadequate spillway capacity is one of the primary reasons some Bureau dams require rehabilitation and modification. With advances in the fields of hydrology and meteorology and an increased streamflow and runoff data base, the probable maximum flood a dam must safely withstand may increase substantially over the original design flood. This is especially true for older dams. If design analysis indicates that a spillway may not be adequate to safely pass the updated flood, resulting in overtopping the dam and possible failure, modifications to the spillway must be made.

The Bureau is also involved in enlarging dams and reservoirs to meet increasing downstream water demands, to provide additional flood control capacity in reservoirs, and to develop greater hydroelectric generation capabilities. One of the major difficulties in raising a dam is modifying the spillway to function adequately at higher reservoir levels.

An alternative that should be considered for these modification needs is the use of a labyrinth spillway. The Bureau and other engineering organizations are finding that labyrinth spillways are particularly well suited for rehabilitation of existing spillway structures because the developed crest length can be greatly increased for a given width. This increased crest length allows passage of a greater design flood than the existing structure. A free overflow labyrinth spillway provides reservoir storage capacity equal to the traditional gated structure, which requires manual or mechanical operation. In addition, labyrinth structures may be built economically provided an adequate foundation is available and the structure does not exceed certain established limitations.

LABYRINTH SPILLWAY PARAMETERS AND FLOW DESCRIPTION

The labyrinth spillway is defined by the parameters shown on figure 1-1. The values of these parameters are chosen to accommodate site geometry and to provide optimum hydraulic performance. The plan geometry is defined by the parameters of length, l, width per cycle, w, sidewall angle, α, and the number of cycles, n. The length and width per cycle may be combined to form the dimensionless length magnification, l/w. The vertical geometry of the labyrinth is described by the spillway height, P, and the vertical aspect ratio, w/P.

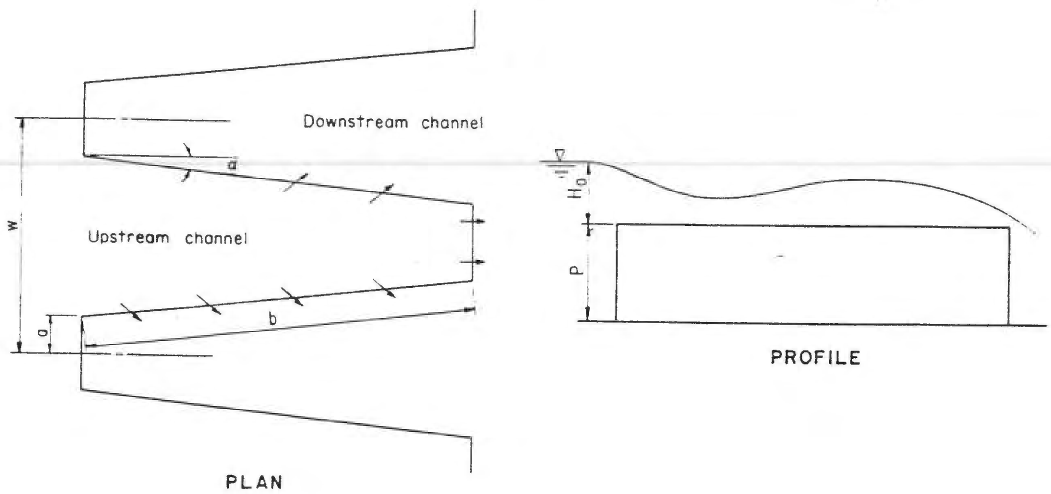
The performance of the labyrinth spillway is directly related to the discharge, Q_N, passed by a linear weir of width, W, equal to the total width occupied by all the labyrinth spillway cycles. Therefore, two analyses must be performed - one for the linear weir discharge and one for the labyrinth weir discharge. The labyrinth length required to pass the design discharge is then determined from design curves that show the labyrinth to linear discharge ratio, Q_L/Q_N, and the head to crest height ratio, H/P.

Ideally, the discharge passing over the labyrinth spillway should increase in direct proportion to an increase in the crest length. For instance, a length magnification of three should allow passage of a discharge three times as great. However, this is only the case for spillways with low head to crest height ratios, because the spillway efficiency decreases as the head increases. In addition, this efficiency loss is greater and occurs more rapidly with greater length magnifications.

Description of the flow over a labyrinth spillway is complicated and will be explained in terms of the reservoir head, the local head present in the upstream channels, flow over the weir, and the tailwater depth in the downstream channels. The flow over a labyrinth spillway passes through three basic phases: subatmospheric pressure under the nappe, an aerated nappe, and a nonaerated solid water nappe. These flow phases occur as the head to crest height ratio increases from very low values (less than 0.15) to the maximum design value. These changes in the flow conditions are clearly seen in the behavior of the discharge coefficient and a discontinuity, or "hump," in the length magnification curve.

With small heads over the spillway, the flow behaves almost ideally with an almost negligible head difference between the upstream reservoir and the spillway channels. However, with low flows, subatmospheric pressures under the nappe cause the nappe to cling to the downstream face of the spillway. This low flow condition (fig. 1-2) produces an increase in the discharge coefficient, but may also cause structural problems.

Median range discharges and head to crest height ratios produce a noticeable drop in head as the flow from the reservoir enters the upstream channels. Farther into the channels the water surface rises again, but



LEGEND

a	=	Half length of labyrinth apex
b	=	Length of labyrinth wall
H	=	Total upstream head over crest (less than H_0)
H_0	=	Design head
l	=	Developed length of one labyrinth cycle = 4a + 2b
L	=	Total developed length of spillway
l/w	=	Length magnification
n	=	Number of spillway cycles in plan
P	=	Spillway height (crest height)
Q_L	=	Discharge over labyrinth spillway
Q_N	=	Discharge over linear spillway
Q_L/Q_N	=	Flow magnification (measure of spillway performance)
W	=	Width of linear spillway
w	=	Width of one labyrinth spillway cycle
w/P	=	Vertical aspect ratio
α	=	Angle of sidewalls to main flow direction

Figure 1-1. - General plan and section of labyrinth spillway with definition of parameters.

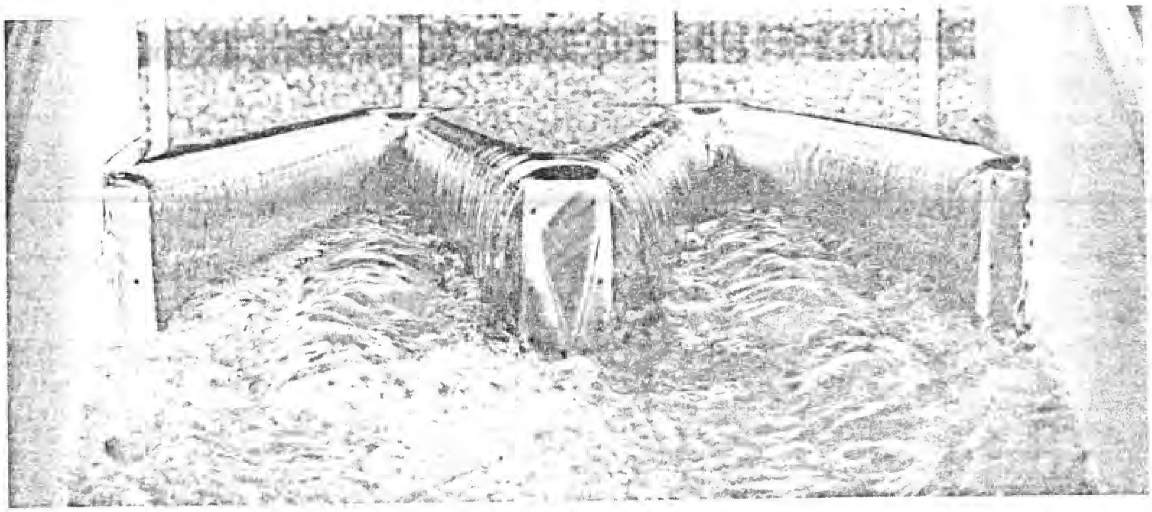


Figure 1-2. - Labyrinth low flow condition.

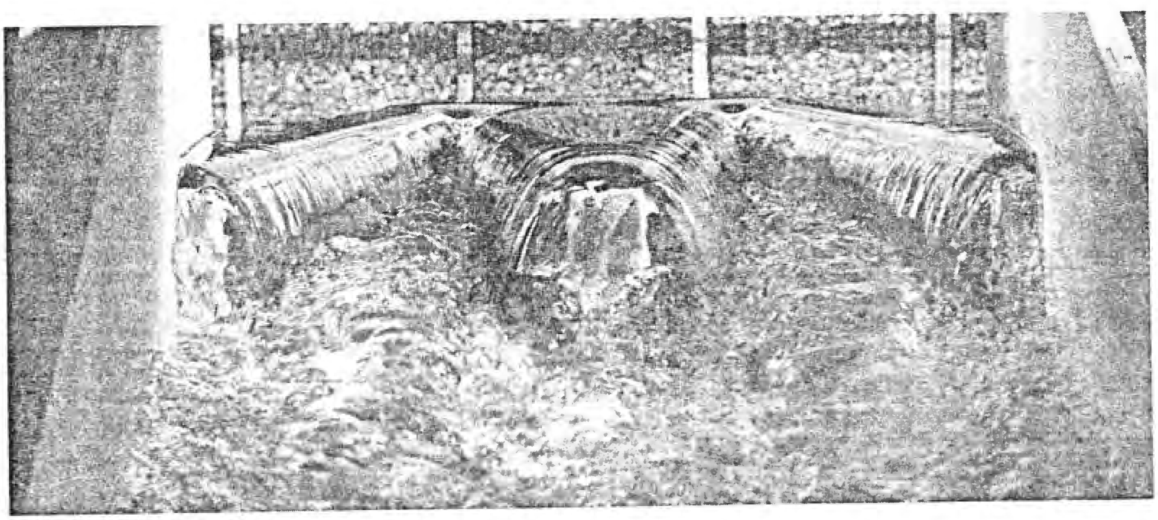


Figure 1-3. - Labyrinth medium flow condition.

never returns to the original reservoir level. In this median head to crest height range the spillway nappe alternates between being aerated and nonaerated. As the head increases, the nappe becomes aerated and springs free of the downstream face, producing the most desired operating condition. However, with a further increase in head, the nappe thickens and begins closing off the area between the nappe and the downstream spillway face. At this point, the flow alternates between being aerated and nonaerated, with air being drawn under the nappe at the downstream apexes of the spillway and intermittently moving upstream (fig. 1-3). This unstable flow condition produces a discontinuity in the discharge coefficient curve.

The final flow condition consists of the higher head to crest height ratios ($H/P \leq 0.4$) and produces an even greater upstream head loss as the flow enters the spillway channels. Flow over the spillway is in the form of a solid nonaerated nappe. The thickness of the nappe and the tailwater height do not permit air to be drawn under the nappe (fig. 1-4). Eventually, as the head increases, the spillway becomes submerged producing extremely inefficient spillway operation.

CASE STUDY - UTE DAM

To illustrate the design and construction considerations involved with labyrinth spillways, the Bureau's experiences with the modifications to Ute Dam in New Mexico are discussed in the following sections.

Ute Dam, completed in 1963, is owned and operated by the NMISC (New Mexico Interstate Stream Commission). The dam is located on the Canadian River in east-central New Mexico, near the community of Logan. The existing facility consists of a zoned embankment main dam with a maximum height of approximately 120 feet; an ungated ogee-type concrete spillway located to the left of the main dam with a crest length, W, of 840 feet; and an embankment dike located to the left of the spillway with a maximum height of approximately 25 feet (fig. 1-5).

The dam as originally constructed did not provide sufficient reservoir capacity to permit the State to use its full storage allotment, as agreed in the Canadian River Compact. The NMISC requested that the Bureau undertake the investigation, design, specifications, and construction of the addition of 27-foot-high spillway gates, which would increase the reservoir to its desired capacity. The Bureau prepared appraisal designs and estimates for several types of gated structures having a minimum field cost of approximately $34 million (based on November 1980 unit prices). This cost was unacceptable to the NMISC. The Bureau then prepared several designs and estimates for ungated alternatives that provided the necessary normal reservoir capacity and limited the maximum water surface elevation during floods to prevent the inundation of homes around the reservoir. The most economical alternative was a labyrinth spillway combined with raising the dam for an estimated cost of $10 million. In 1981, the NMISC accepted the

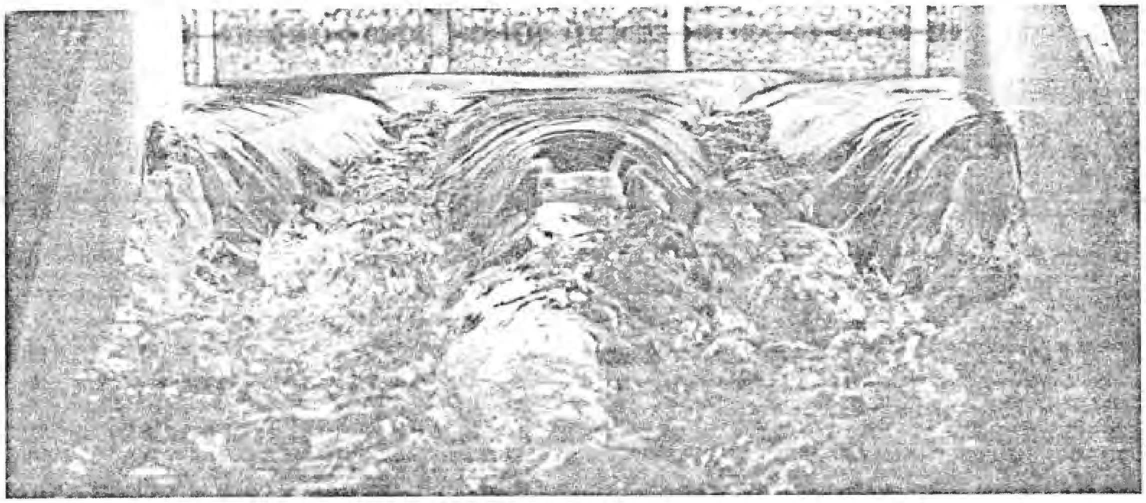


Figure 1-4. - Labyrinth high flow condition.

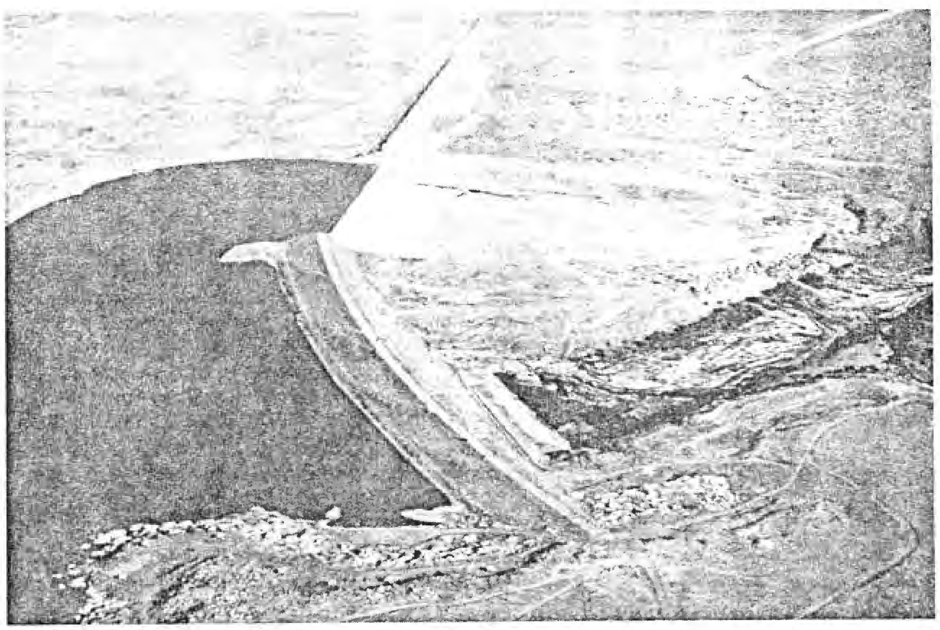


Figure 1-5. - Ute Dam near Logan, New Mexico, before modification.

labyrinth spillway concept and provided funds for laboratory investigations and the preparation of the final design and specifications.

Hydraulic Model Studies

Hydraulic model studies were initiated to extrapolate existing design curves [5]* for application to the Ute Dam labyrinth spillway. These tests included flume testing of two-cycle labyrinth weir sectional models and two 1:80 scale models of the proposed Ute spillway designs [6, 7].

The design criteria for the Ute labyrinth spillway were:

H_o = 19 feet	W = 840 feet
P = 30 feet	H_o/P = 0.63
Q_L = 590,000 ft^3/s	

These criteria were based on the existing site geometry and the IDF (inflow design flood). The remaining parameters were determined during the design process and investigated during the model study. For the initial 10-cycle labyrinth spillway model, these parameters were:

w = 84 feet	a = 3 feet
l/w = 2.74	b = 109.1 feet
w/P = 2.8	L = 2,300 feet
α = 19°15'55"	

Model testing of this labyrinth spillway - based on design curves published by Hay and Taylor [5] - showed the design discharge could not be passed by the spillway within the stipulated design head of 19 feet. The reservoir head reached 22.6 feet before passing the required maximum discharge. This was a result of the large head to crest height ratio and an inadequate labyrinth crest length. The crest length was inadequate because of the characteristics of the flow over the labyrinth. Further details of this 10-cycle labyrinth spillway may be found in [6].

Because the 10-cycle spillway did not pass the required discharge within the reservoir head limitation, another model spillway of longer crest length was designed and tested. This spillway design was based on the results of the 10-cycle spillway tests and additional flume testing. The most economical design, given the new longer crest length, required 14 cycles. The other labyrinth spillway parameters for this design were:

w = 60 feet	a = 3 feet
l/w = 4.0	b = 114 feet
w/P = 2.0	L = 3,360 feet
α = 12°8'15"	

* Numbers in brackets refer to entries in the Bibliography.

Comparing these parameters with those of the 10-cycle spillway shows the difference between the crest lengths and length magnifications in the two designs.

The 14-cycle spillway passed the required maximum discharge at 19 feet of head (fig. 1-6). In addition to the labyrinth spillway shape, other aspects of labyrinth spillway operation determined with this model included the effect of nappe interference, impact pressures in the downstream channels, water surface profiles in the upstream channels, and low flow conditions. These aspects will be discussed in the section dealing with general design guidelines.

Structural Analysis and Design

Once the hydraulic design and model studies were completed, the Ute Dam labyrinth spillway was analyzed for stability and structural integrity. The labyrinth spillway was analyzed as a series of 14 V-shaped cycles. Thirteen of the cycles are monolithic and separated by contraction joints. The remaining cycle consists of two monolithic half cycles - one at each end of the spillway.

The stability analysis of a typical labyrinth cycle included the investigation of overturning, sliding, and foundation bearing pressures when the cycle was subjected to the following loads:

Normal load - normal water surface (elevation 3787), no tailwater, uplift assumed to be full head under area of base upstream of the wall.

Extreme load - maximum water surface (elevation 3806), tailwater height of 15 feet, uplift varying from full head at the upstream edge of the labyrinth to tailwater head at the downstream edge.

Analyses showed that a typical full cycle was stable against overturning, but required a 5-foot-deep key trench to provide an adequate factor of safety against sliding, when subjected to the extreme load. The foundation bearing pressure was acceptable for both loading conditions. The analysis on an end half cycle of the labyrinth showed that it was not stable against overturning. To make the half cycle stable, an anchor block was attached to the existing spillway end wall. The anchor block resisted upward movement of the labyrinth base slab and transferred the load to the existing wall. However, this additional upward load on the existing wall lowered the wall's factor of safety against sliding, which made it unstable when subjected to the load from the maximum reservoir water surface elevation. Therefore, to make the existing wall and the labyrinth half cycle stable against sliding, a key trench, parallel to the existing wall, was added to the base of the half cycle. The anchor block and key trench allowed the existing end wall and the labyrinth half cycle to act as a unit. A contraction joint was placed between the two to ensure that compressive loads would be transmitted from the existing wall to the labyrinth, and to prevent tensile loads from being transmitted from the labyrinth to the wall.

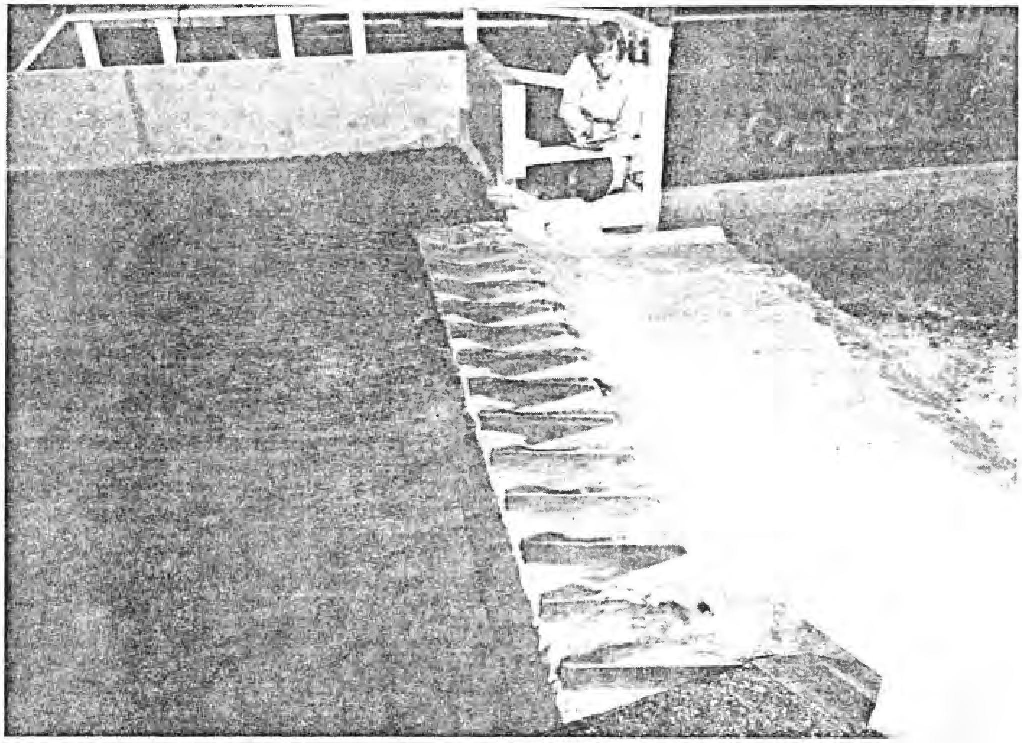


Figure 1-6. - 1:80 scale model of Ute Dam labyrinth spillway.

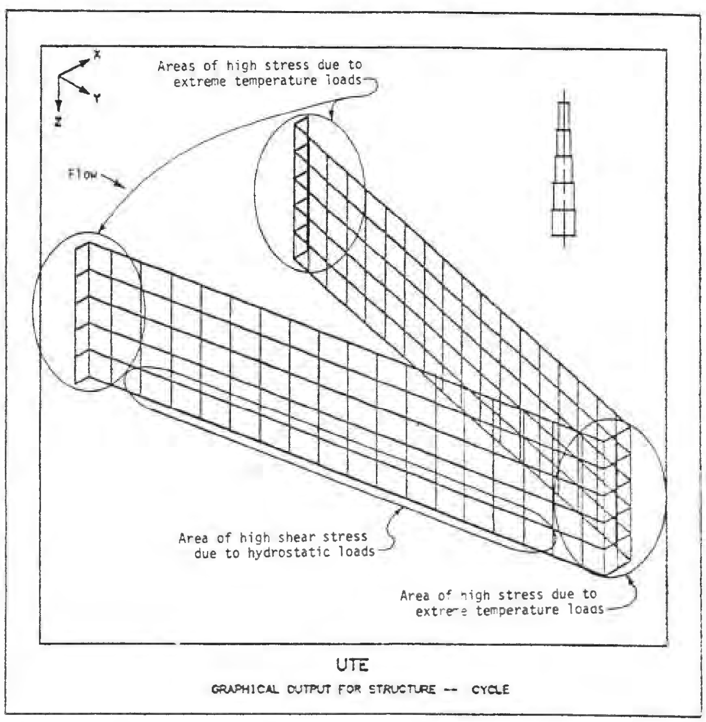


Figure 1-7. - Finite element model of the wall for the Ute labyrinth spillway.

Once the stability of the spillway was ensured, the individual components were sized and the reinforcement designed. The structural analysis was made on both a typical full and half cycle using a finite element indeterminate structural analysis computer program. Separate analyses were made for the labyrinth wall and base slab because of limitations in the program's ability to determine the number of unknowns. Sixteen different factored load combinations were applied to the wall of the labyrinth using various boundary conditions. The maximum stresses computed for the various elements of the computer model were used for determining the reinforcement required for that element.

The structural analysis showed that the high stresses were located in areas around the apexes of the labyrinth (fig. 1-7). These high stresses were primarily caused by the extreme temperature loads that developed from the large seasonal temperature variations typical for this vicinity. The apexes had to be stiffened by increasing the thickness of the concrete, and heavily reinforced to resist the high bending moments, tensile stresses, and shear stresses that developed. The large hydrostatic loads caused by the height of the wall and the depth of overtopping of the labyrinth required significant amounts of reinforcement for all other areas of the labyrinth wall as well.

The analysis of the half cycle wall indicated deflections at the downstream apex where the labyrinth meets the existing spillway end wall were too large to ensure watertightness. To keep the wall watertight without having to depend on the bond between the labyrinth and the existing wall, an anchor block was placed on the existing wall downstream of the labyrinth. A waterstop was installed between the labyrinth and the anchor block, and an expansion joint was installed to allow the labyrinth wall to deflect without transferring shear and tensile loads to the existing wall.

For the base slab analysis, loads from the wall were applied along a set of points where the centerline of the wall meets the base. These loads were determined by analyzing the wall, which was assumed to be fixed at the base. This produced a set of reactions that was then changed into loads to be applied to the base slab. Along with loads from the wall, additional loads such as the weight of the slab, the weight of water on the slab, temperature loads and uplift were applied to the base of the labyrinth under various boundary conditions and load combinations.

For the typical cycle, areas near the center of the base showed upward deflections as high as three-fourths of an inch when subjected to extreme load combinations (fig. 1-8). While the deflections did not seem excessive, a check was made to determine if anchor bars could be used to hold down the base. The results showed that the restraint of the anchor bars caused higher stresses in the concrete and that stresses in the different anchor patterns were usually concentrated on a few bars. This indicated that a progressive failure of anchor bars could occur. It was decided to let the base deflect and redistribute the stresses. As with the wall, the base slab was heavily reinforced to resist the high

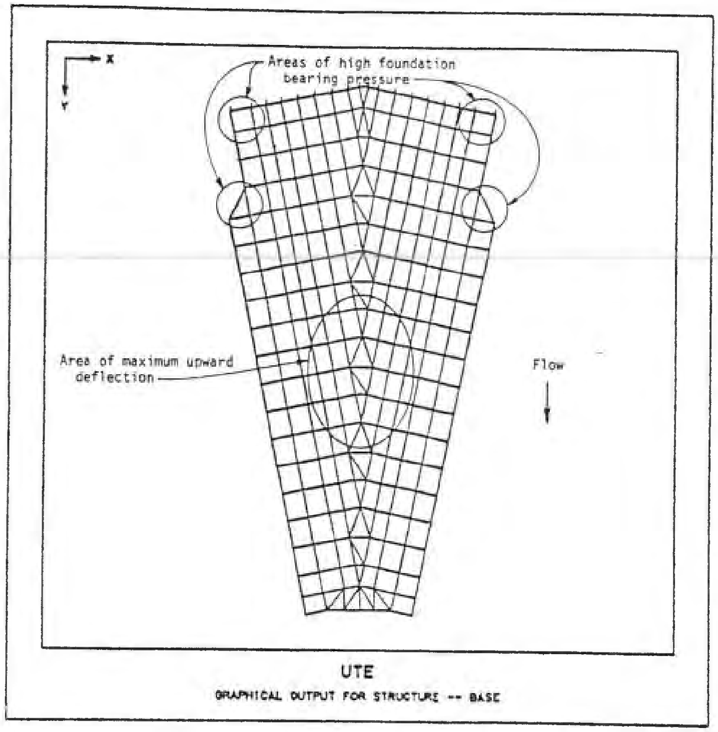
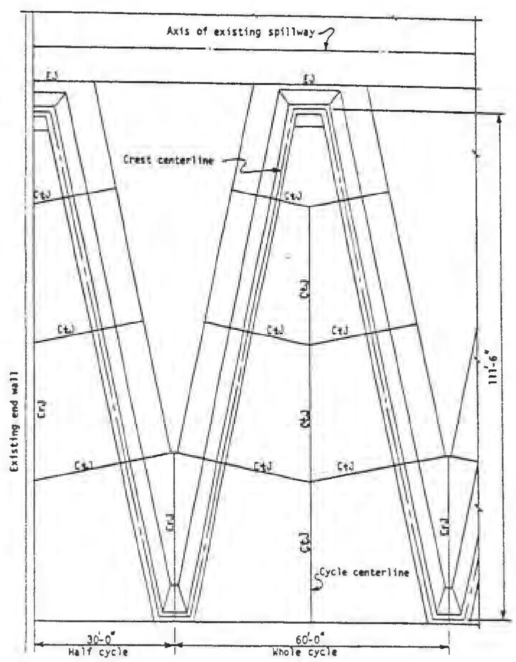


Figure 1-8. - Finite element model of the base slab for the Ute labyrinth spillway.



CtJ = Control joint (no bond, fully reinforced)
CrJ = Contraction joint (no bond, no reinforcement)
EJ = Expansion joint (no bond, joint filler)

Figure 1-9. - Joint layout for labyrinth spillway.

bending moments, tensile stresses, and shear stresses that developed from the various load combinations applied to the computer model.

In the design of the labyrinth spillway, four types of joints were used: contraction joints, control joints, construction joints, and expansion joints (fig. 1-9). The configuration of the labyrinth base slab permitted placement of contraction joints at the narrowest sections of the slab. This allowed each cycle of the spillway to act monolithically, with the contraction joints having unbonded surfaces and no reinforcement. The location of the contraction joints at the downstream apexes of the wall ensured that hydrostatic forces would tend to hold the wall joints closed.

Although the walls and base slabs were heavily reinforced, random cracking was possible throughout the structure due to its large size and the high stresses involved. Therefore, control joints were provided to concentrate cracking at predetermined locations. The joints were designed to have surfaces that were unbonded but fully reinforced. In addition, chamfers were provided at the surface of each joint. To keep each joint watertight after a crack had formed, waterstop was installed and a polysulfide sealant was applied to the upstream face of the joint.

Horizontal construction joints were placed in the wall of the labyrinth to allow for the placement of concrete in three 10-foot-high lifts. Because these joints were designed to be fully bonded and reinforced, they were not a factor in the design of the structure. Construction joints were not included in the base slab because the control joints provided satisfactory concrete placement dimensions.

To prevent the labyrinth spillway from transferring loads to the existing ogee crest structure, a 1-inch sponge-rubber-filled expansion joint was placed between the base slab and the existing crest structure.

Construction

Construction on the labyrinth spillway at Ute Dam began in November 1982. After a short period of mobilization, the contractor, KNC, Inc., of Albuquerque, New Mexico, began excavation for the labyrinth spillway foundation. A Roto-Mill profiler was used for excavating the sandstone to a uniform elevation of 3753.0 (fig. 1-10). The machine, used mainly in highway construction, had a rotating drum with carbide cutting teeth capable of removing approximately 3 inches per pass. A power broom was then driven over the excavated area to remove loose sand and clean the foundation surface producing a smooth, clean surface at the desired grade (fig. 1-11). A few areas of clay seams and fractured sandstone were encountered. These required overexcavation and backfilling with concrete. The 5-foot-wide key trench for the labyrinth base slab was excavated in two passes - each 2 feet wide - by a trenching machine. A backhoe excavated the remaining rock left in the trench (fig. 1-12).

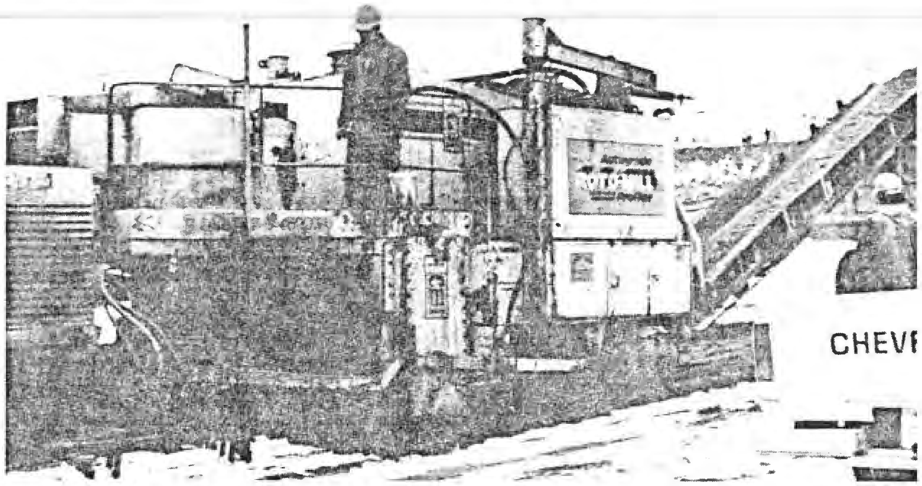


Figure 1-10. - Roto-Mill profiler used for excavation of the foundation for the labyrinth spillway.

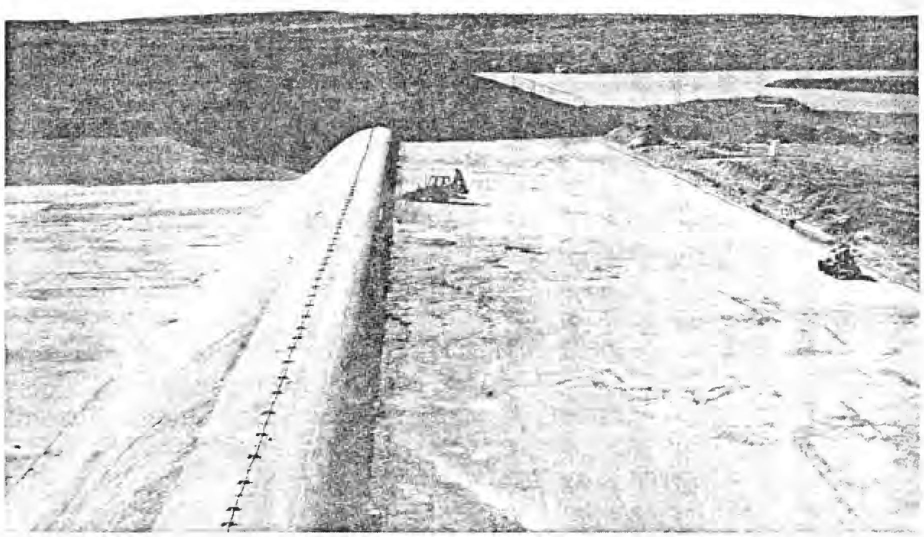


Figure 1-11. - Excavated surface for labyrinth spillway.

Figure 1-12. - Excavation of key trench.

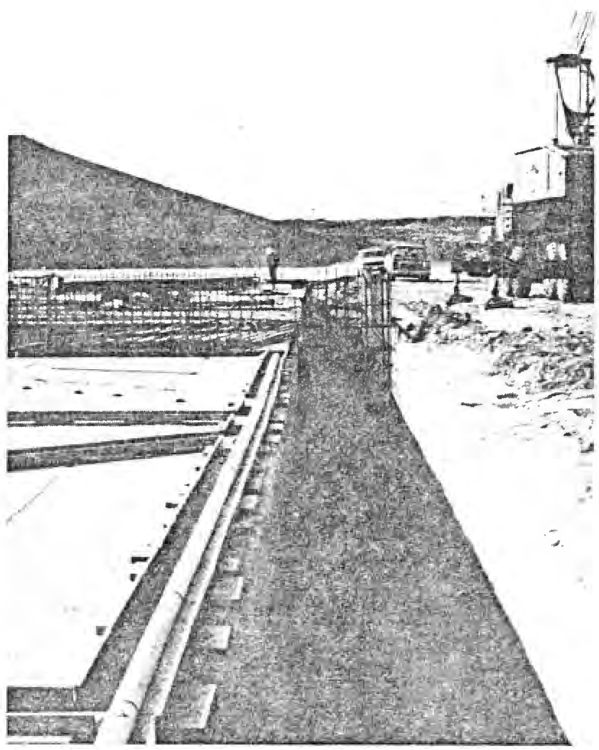


Figure 1-13. - Four-inch-diameter split drains placed on excavated surface before concrete encasement.

After excavation was completed, a series of 4-inch-diameter split drain pipes was installed on the foundation surface to intercept seepage and reduce uplift pressures on the base of the labyrinth (fig. 1-13). These split drains were encased in concrete to prevent them from being damaged during construction of the base slabs. Water collected by the split drains is carried downstream of the labyrinth and passes through the existing ogee in a series of holes drilled horizontally through the crest. To prevent excessive uplift pressures from developing beneath the existing crest structure, a line of 70-foot-deep relief wells was drilled immediately upstream of the crest. These wells were cased with slotted PVC (polyvinyl chloride) pipe and capped with a flap valve to prevent debris from plugging the hole.

Forms for the base slab were then constructed and reinforcement installed. Because the labyrinth is a cantilever-type structure, most of the reinforcement for the wall had to be embedded in the base slab before the concrete for the base was placed. This created difficulties in placing the large amounts of reinforcement required and in supporting the steel for the walls of the labyrinth. Forming the control joints within the base slab was also difficult because of the number of reinforcing bars that had to pass through the joint and the installation of PVC waterstops along the joint.

The center cycle of the labyrinth was the first to be constructed. Initially, work proceeded slowly as the contractor developed efficient methods of building forms and installing and supporting reinforcement, and as the steel supplier improved the steel cutting and bending operations. The pace of construction increased rapidly as additional cycles were constructed. Figures 1-14 and 1-15 show how construction of the cycles progressed.

Concrete, with a design strength of 5,000 lb/in^2 at 90 days, was placed for the base slab at each cycle in seven different sections, each delineated by control joints. Concrete for the walls was placed in 10-foot-high lifts, also delineated by control joints. The Bureau required that no concrete be placed in immediate sections of the labyrinth base or wall until the abutting concrete had been in place for at least 7 days. This was done to ensure that the concrete had completed expansion due to the heat of hydration and would be contracted to its final dimensions, providing tight joints and minimizing the possibility of seepage through the structure. This 7-day requirement has complicated placement schedules and forced the contractor to work on several cycles at a time. Yet, even with these scheduling complications and other construction problems, completion is expected in January 1984, before the contract completion date in May 1984.

Some of the major quantities of materials required for the construction of the labyrinth spillway at Ute Dam are:

Excavation - over 5,000 yd^3
Concrete in walls - over 13,000 yd^3

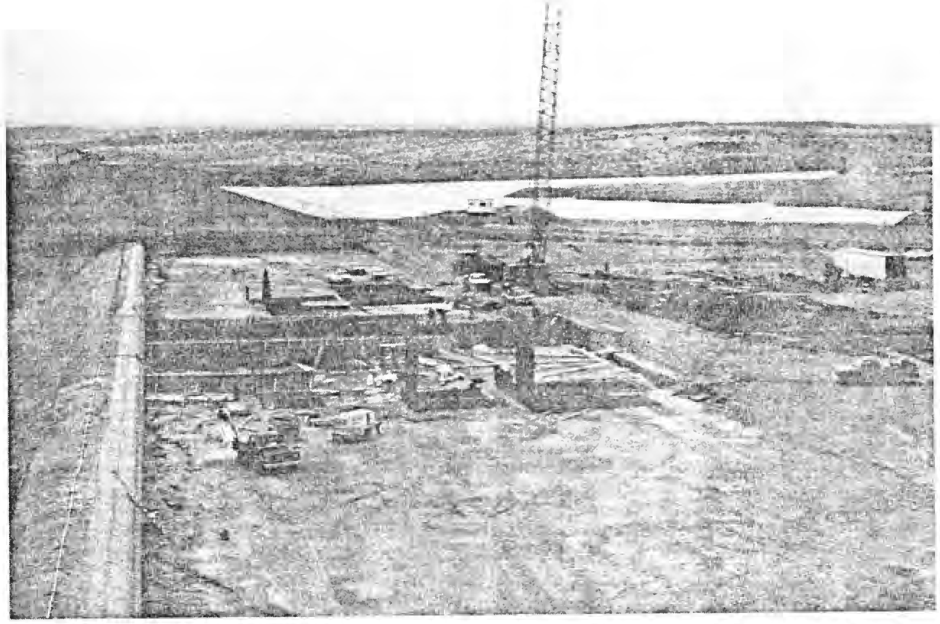


Figure 1-14. - Construction of the cycle of the labyrinth spillway, on March 18, 1983

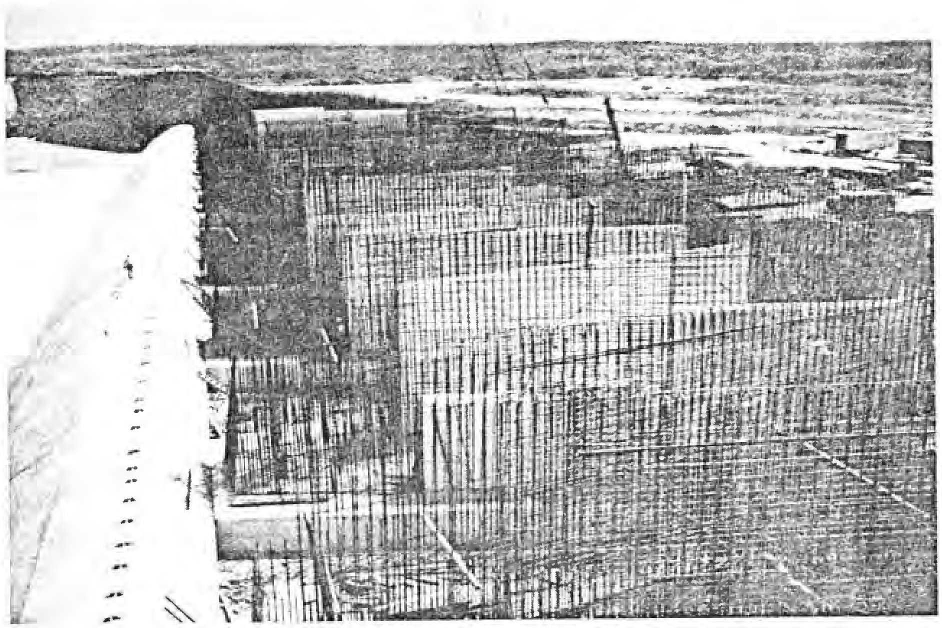


Figure 1-15. - Construction progress of the Ute Dam labyrinth spillway, on August 11, 1983.

Concrete in base slab - over 13,000 yd^3
Cementitious materials - over 7,500 tons
Reinforcing bars - over 7,000,000 lb
PVC waterstops - over 6,000 lin ft
4-inch split drain pipe - nearly 7,000 lin ft

ADDITIONAL MODEL STUDIES AND GENERAL DESIGN GUIDELINES

As a result of the findings associated with the model study of the Ute Dam labyrinth spillway, interest was expressed in better defining the labyrinth parameters. Another site-specific model study was conducted for an auxiliary labyrinth spillway at Hyrum Dam [8]. These studies, combined with some additional testing, produced modified guidelines for labyrinth spillway design. The newly developed design curves will be discussed along with design guidelines and limitations on the structural design.

Hyrum Dam Auxiliary Labyrinth Spillway

The auxiliary labyrinth spillway for Hyrum Dam was designed from the Ute model study data. Hyrum labyrinth was a 12-foot-high, 2-cycle spillway with a design discharge of 9,050 ft^3/s passed with a reservoir head of 5.5 feet (0.5 foot below maximum water surface). The dimensions and parameters of the spillway are:

H_o/P	= 0.5	α	= 8°55'48"
W	= 60 feet	a (U/S)	= 3 feet
w	= 30 feet	a (D/S)	= 1 foot
l/w	= 5	b	= 71 feet
w/P	= 2.5	L	= 300 feet

Principal features investigated during this model study were the spillway approach conditions and the orientation of the spillway [8]. Placing the spillway 19 feet into the reservoir, with curved sidewalls adjacent to the spillway, provided the optimum hydraulic efficiency. Details of the effects of entrance conditions and labyrinth spillway orientation will be discussed in the following sections.

DESIGN CURVES

Hydraulic model results have shown that previously used labyrinth spillway design curves [5] did not provide adequate labyrinth crest length to pass the maximum discharge within the design head value. New sharp-crested labyrinth curves (fig. 1-16) were developed and confirmed by the successful design of both the Ute Dam and Hyrum Dam spillways. However, because these curves were based on sharp-crested weirs, the conversion to the actual prototype crest shape was often tedious and sometimes caused inaccuracies in the design. This led to further model testing and the development of design curves based on a more commonly

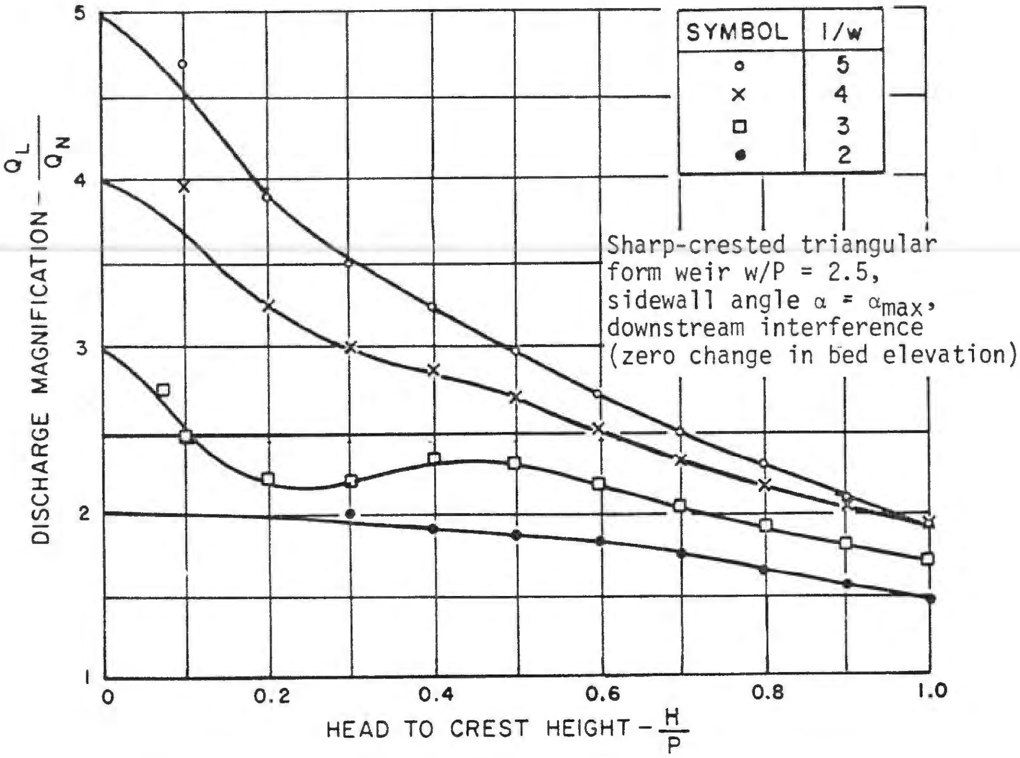


Figure 1-16. - Sharp-crested labyrinth design curves.

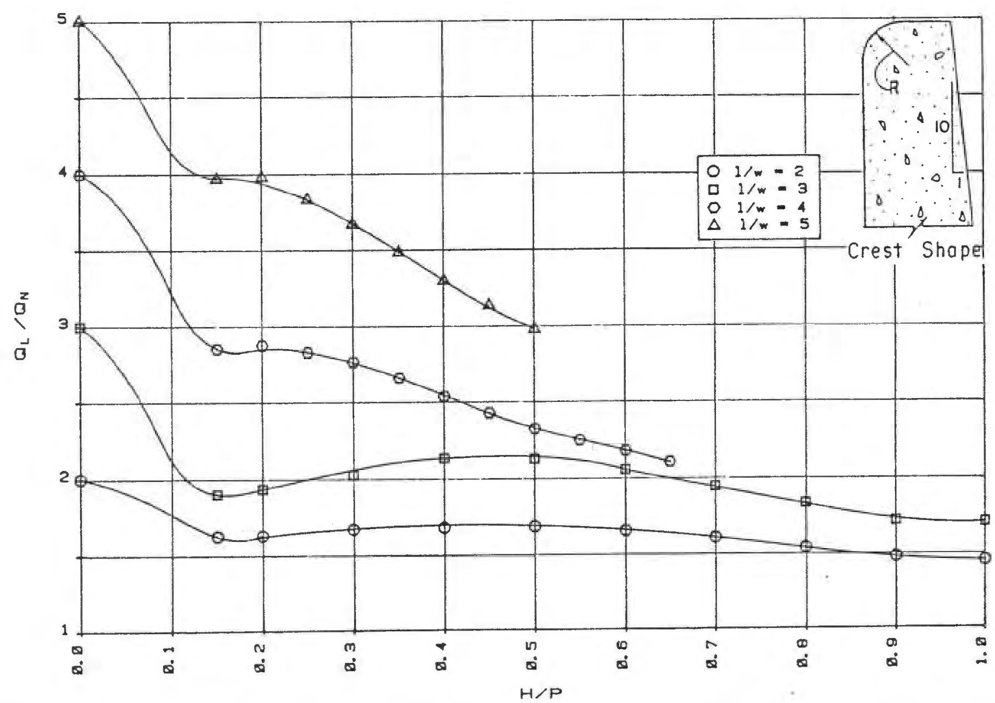


Figure 1-17. - Design curves with quarter-round upstream face, trapezoidal form weir.

shaped crest. Because most previously designed labyrinth spillways have a crest shape with a quarter-round upstream face, which produces a high discharge coefficient, this shape was used in the design curves (fig. 1-17). The design procedure [5] may be simplified by using the design curves based on the quarter-round crest shape, provided the labyrinth spillway under consideration has the same shape.

GENERAL SPILLWAY DESIGN GUIDELINES

The following sections contain general design guidelines for a labyrinth spillway including information on the approach conditions, the spillway placement and orientation, and the performance parameters, w/P, n, and l/w. Also, aeration of the nappe during discharges under low head will be discussed.

Spillway Approach Conditions

The labyrinth geometry makes the spillway sensitive to the reservoir approach flow conditions. The two major factors of the approach condition affecting spillway performance are the direction of the approach flow with respect to the spillway and the shape of the entrance structures immediately upstream of and adjacent to the spillway. Of these, the flow direction is more important because an approach flow parallel to the centerline of the spillway cycles will produce the most uniform flow distribution throughout the spillway and provide a good basis for designing the spillway entrance. The most efficient spillway entrance for most reservoir applications is a curved approach adjacent to each end cycle of the spillway. This will produce uniform approach flow to the end cycles of the spillway. The entrance configuration is very important, particularly when the spillway has only a few cycles, because a significant portion of the total crest length is then affected by the entrance shape.

Spillway Placement and Orientation

The spillway entrance shape should be coordinated with the placement and orientation of the spillway. When installing a labyrinth spillway in a reservoir, the spillway placement is more important than the orientation. Placement should be as far upstream in the reservoir as possible. Such placement will reduce the localized upstream head losses because the area contraction immediately upstream from the spillway is reduced. When the spillway placement has been determined, the orientation or the attachment of the spillway to the abutments or sidewalls should be considered. The importance of spillway orientation is magnified when the reservoir approach conditions are poor or the spillway is placed in a canal. In these cases, with the apexes of the end cycles located upstream, the water surface along the sides is rough, producing a noticeable reduction in head and discharge. The spillway placement, orientation, and entrance are usually determined by the site and availability of a good foundation.

Number of Spillway Cycles and Nappe Interference

The number of spillway cycles should be based on the magnitude of the upstream head, effect of nappe interference, and economics of the design. The number of cycles and spillway height determine the vertical aspect ratio, W/P. In turn, the vertical aspect ratio and the head determine the occurrence of nappe interference. Under high heads the hydraulic efficiency is dependent upon the nappe interference. Nappe interference occurs when the sides of the cycle are close enough that the nappes from the flow over each side intersect or impinge prior to reaching the floor in the downstream channel. This flow condition will reduce the discharge capacity of the spillway. As a general rule, the importance of the vertical aspect ratio and nappe interference increases as the head increases. With normal operating conditions, the vertical aspect ratio should be 2.5 or greater, although this ratio may be lower with low head values because the nappe will be very thin and the spillway will behave almost ideally. An example of the head drop associated with nappe interference is seen on figure 1-18.

Impact Pressures in the Downstream Channels

For the Ute spillway, pressures were measured in the downstream channels parallel to the spillway walls and along the centerline of the spillway cycles. None of the pressures measured were excessive. The pressures were highest parallel to the sidewalls where the jet impinged on the floor after flowing over the crest. However, these pressures and those measured along the cycle centerline decreased as the downstream channel expanded. The pressures will vary according to the tailwater present in the downstream channels, the cycle width, and the geometry of the chute downstream of the spillway.

Labyrinth Spillway Low Flow Conditions

Nappe oscillation and noise will occur when the spillway is operating under low heads. These phenomena are produced by alternating atmospheric and subatmospheric pressures under the nappe. Subatmospheric pressures will increase the flow over the spillway, but should be avoided for structural reasons.

Two methods have been recommended to solve the problem of subatmospheric pressures - placing splitter piers along the spillway side walls and placing crushed stone along the downstream edge of the crest. Splitter piers have been designed for use at Ute and Hyrum Dams. The piers should be located at a distance equal to 8 to 10 percent of the wall length, upstream of the downstream apexes. The height of the piers should vary according to the head range of concern. The piers may be submerged during higher flows. Figure 1-19 shows a spillway cycle passing a low discharge with and without splitter piers. Notice the small splitter piers located on the sides of the left cycle and the break in the nappe in these areas.

Figure 1-18. - Ute Dam labyrinth spillway with Q = 550,000 ft^3/s, H = 19 feet, and a head loss due to nappe interference.

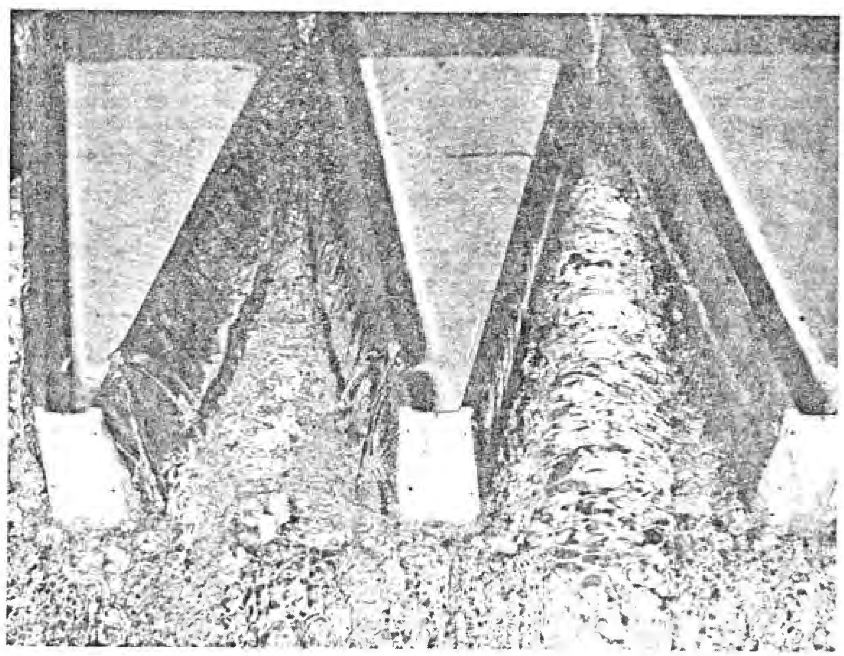


Figure 1-19. - Low flow condition aerated with splitter pier and nonaerated.

Placing crushed stone along the downstream edge of the crest proved successful at Avon Dam [10]. This method, while decreasing the discharge for a given head, successfully provides aeration and is cost effective.

Structural Configuration

Most of the labyrinths built previously are thin, cantilever-type structures because of their ease of construction and hydraulic performance. These labyrinths are relatively short structures with low depths of overtopping. On the other hand, the large labyrinth spillway designed for Ute Dam (H = 19 feet, P = 30 feet) was heavily reinforced to resist the high moments and stresses that could develop under maximum loading conditions. This depth of overtopping and height of wall are near the maximum feasible dimensions because of the difficulty of installing the large amount of reinforcement required. Using a higher labyrinth or a greater depth of overtopping would, most likely, require a gravity section for the walls, reducing the hydraulic efficiency and the economic advantage provided by the labyrinth spillways.

GENERAL APPLICATIONS OF LABYRINTH SPILLWAYS

The labyrinth spillway at Ute Dam was the first labyrinth designed and built by the Bureau of Reclamation, therefore, the spillway required extensive investigation. This included reviewing labyrinths that have been studied and built by other engineering organizations. The location of these spillways and a summary of the major dimensions and discharge characteristics are shown in tables 1-1 and 1-2. Labyrinth spillways have been built with a wide range of sizes and discharge capacities, indicating a variety of potential applications.

The Bureau of Reclamation has considered the use of labyrinths on dams where the discharge capacity of an existing spillway must be increased or where an existing reservoir must be enlarged. Because of their success and the cost savings involved, labyrinth spillways are now being considered for new structures. As the engineering community gains more experience in the design of labyrinths and additional studies are published, the range of applications will increase. Because a labyrinth spillway is suitable almost anywhere an overflow structure is required, labyrinths are an innovative alternative for the design of dams and waterways.

Table 1-1. - Various labyrinth spillways

Name and location	Year built	Total width, ft	Crest length, ft	Design discharge, ft^3/s	Number of cycles
Ute Dam [6], Logan, NM, USBR	1983	840	3,360	550,000	14
Quincy Dam [3], Aurora, CO, CH_2M-Hill	1973	118	348	19,500	4
Mercer Dam [2], Dallas, OR, CH_2M-Hill	1971	18	246	8,000	4
Woronora Dam [4], MWS&DB, Sydney, Australia	1941	484	1,127	36,000	11
Avon Dam [4,10], MWS&DB, Sydney, Australia	1970	448	868	50,000	10
Bartletts Ferry Dam [9] Columbus, GA, Georgia Power Co.	1982	1,230	4,729	240,000	20-1/2
Navet Pumped Storage [11], Trinidad, CO, CH_2M-Hill	1974	180	450	17,000	10
Hyrum Dam [8], Hyrum, UT, USBR	-	60	300	9,050	2
Ohau C. Canal [12], Upper Waitaki Pwr. Dev., Ministry of Works & Dev., New Zealand	-	253	-	19,070	12
Boardman Spillway [1] Boardman Power Project Boardman, OR, Bechtel	-	120	350	13,660	2

Table 1-2. - Cycle data

Project name	Discharge ft	Head ft	Height ft	Width ft	Length ft	a(U/S) ft	a(D/S) ft	b ft	Crest shape
Ute	39,300	19.00	30.00	60.00	241.70	4.31	2.69	114.00	1/4 arc
Quincy	4,875	7.00	13.00	44.50	86.90	2.00	2.00	39.45	1/4 arc
Mercer	2,110	6.00	15.00	18.00	57.90	2.00	1.00	25.94	1/4 arc
Woronora	3,270	4.46	7.25	44.00	102.46	-	-	-	1/4 arc
Avon	5,000	7.10	10.00	44.41	86.80	2.00	2.00	39.40	1/4 arc
Bartletts Ferry	12,000	6.00	11.25	60.00	230.70	1.35	0.19	113.80	1/4 arc
Navet	1,700	5.00	10.00	18.00	45.00	-	-	-	1/2 arc
Hyrum	4,530	5.50	12.00	30.00	150.00	3.00	1.00	71.00	1/4 arc
Ohau C	1,590	3.53	8.20	20.51	123.03	-	-	-	1/4 arc
Boardman	6,830	5.80	9.06	60.00	174.81	0.78	0.38	86.25	1/2 arc

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