PAP-524

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by

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1988

PAP file

BEIJING 1988

THE INTERNATIONAL SYMPOSIUM
ON HYDRAULICS FOR HIGH DAMS

Energy Dissipation Characteristics of a Stepped Spillway for an RCC Dam

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SUMMARY: Energy dissipating stepped spillways may be constructed as an integral part of an RCC (roller compacted concrete) dam. For Upper Stillwater Dam, unique solutions were determined for construction of an RCC dam and the hydraulic design of a stepped spillway.

Introduction

Upper Stillwater Dam, located at the 8000-ft (2438-m) elevation in the Uinta Mountains in the state of Utah, is the world's largest dam constructed with RCC (fig. 1). Completed in August 1987, the 290-ft (88-m) high straight gravity dam contains 1.6 million yd^3 (1.22 million m^3) of concrete including 1.47 million yd^3 (1.12 million m^3) of RCC and 90,000 yd^3 (69,000 m^3) of slipformed facing concrete. Water impounded by the dam will be released into the Stillwater tunnel and conveyed to populated areas for municipal, industrial, and agricultural uses as part of the Central Utah Project.

The damsite's high elevation and geographical location result in a very cold site for concrete construction. With an annual mean ambient air temperature of 36 °F (2.2 °C) concrete placements must be made between mid-May through mid-September.

Because of the short construction period, the method of dam construction emphasized concrete placement speed. Horizontal slipformed facings were used for both the vertical upstream face and the sloped downstream faces. Facings were placed by a slipforming machine, traveling from one abutment to the other, consolidating and forming air-entrained, low-slump concrete into a 3-ft- (0.9-m-) high wall or facing element. The lower one-third of the facing element overlapped the previous facing element so each pass of the slipformer raised the dam face 2 feet (0.61 m) as shown on figure 2.

RCC was compacted against the inside faces of the facing elements in two 1-ft (0.3-m) thick layers. In this way, the dam was constructed horizontally in continuous layers from one abutment to the other. Conveyor systems and 35-ton (31.7-t) trucks hauled and placed the RCC. After spreading, the RCC material was compacted by six to eight passes of a vibratory roller. Use of the large construction equipment allowed a peak placing rate of 10,000 yd^3

($7500\ m^3$) per day and all RCC was placed in the dam in a total of 10 months.

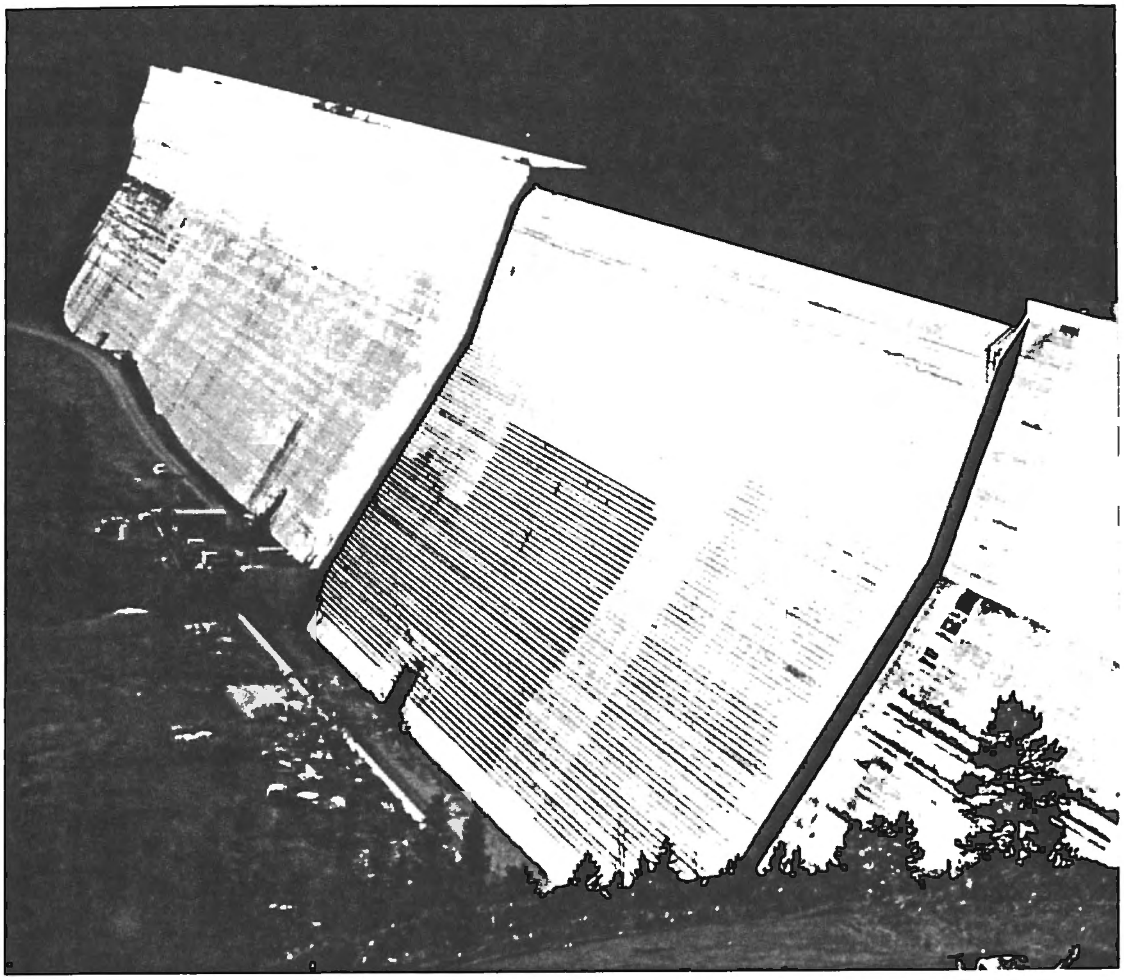


Figure 1. - Upper Stillwater Dam.

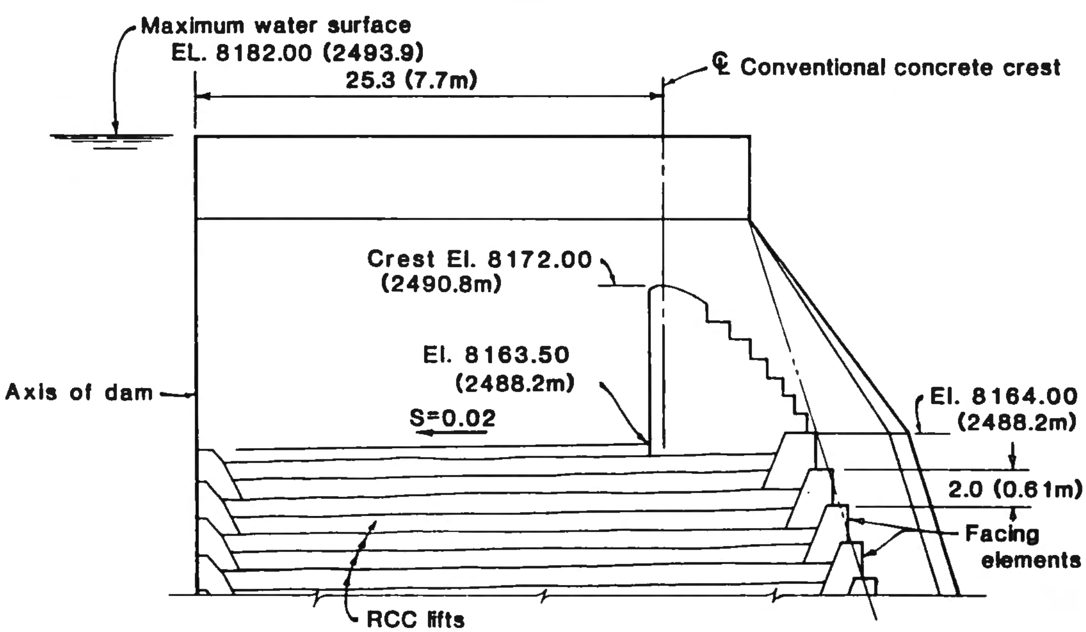


Figure 2. - Upper Stillwater Dam spillway crest.

Spillway Design Considerations

The 200-ft- (61-m-) high spillway was designed for a maximum discharge of 15,000 ft^3/s (425 m^3/s). During construction, the maximum required discharge was raised to 75,000 ft^3/s (2124 m^3/s). Figure 1 shows the completed spillway chute from the crest to the stilling basin. The dark area on the lower right side of the spillway is caused by steps which have not been cleaned after construction. A cross section of the spillway is shown on figure 3.

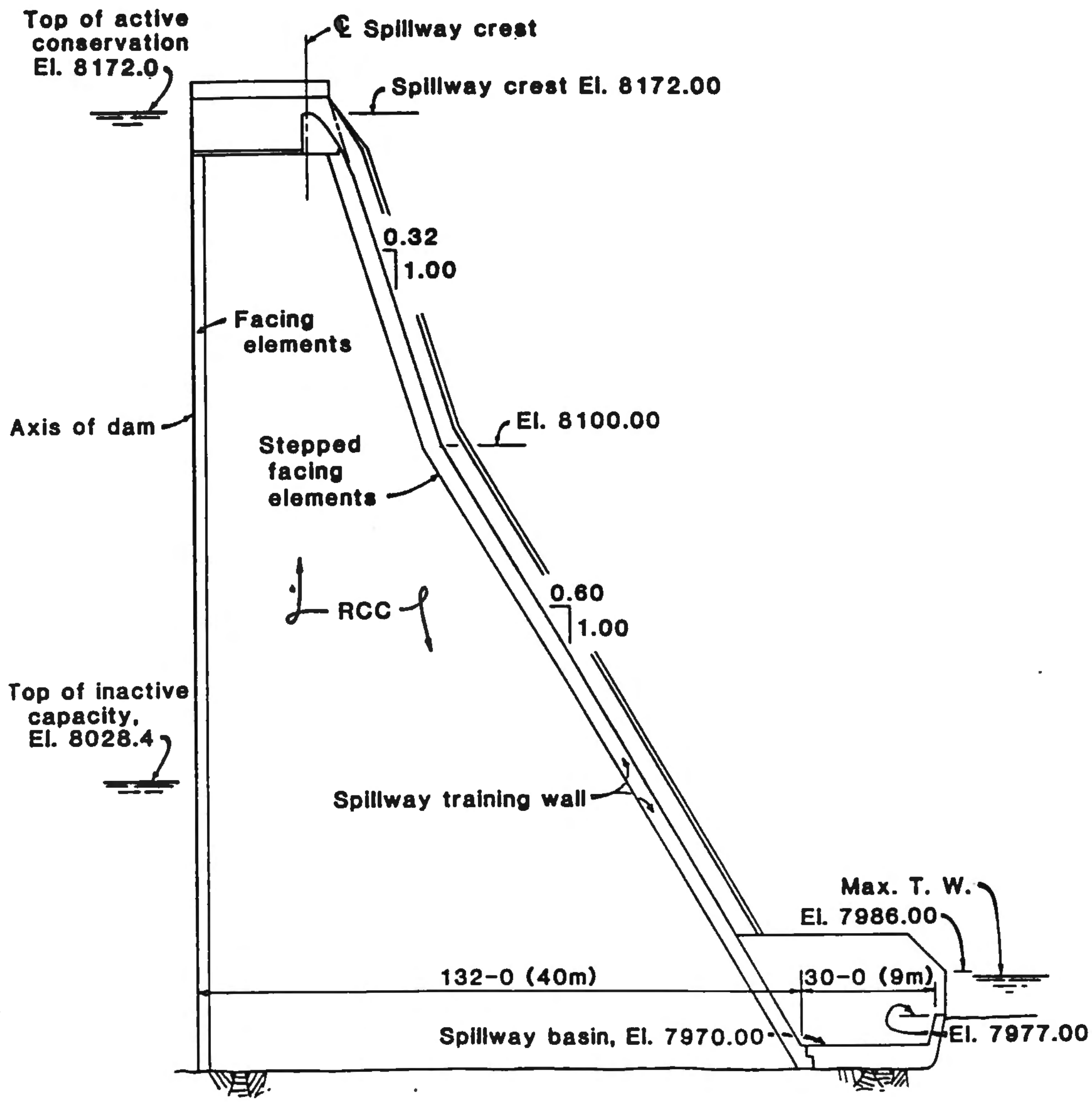


Figure 3. - Upper Stillwater Dam spillway.
1 ft = 0.3048 m.

The primary considerations for the spillway design were that the spillway must not interfere with placement of RCC in the dam and that the hydraulic operation of the spillway would be reliable, since it is expected to operate for a considerable period each year.

Three spillway types were considered: an over-the-dam flip into a basin at the dam toe; an over-the-dam smooth chute spillway; and an over-the-dam stepped spillway.

A 600-ft- (183-m-) wide stepped chute spillway was selected for the following reasons:

1. Spillway construction was compatible with the slipforming and RCC placing methods. Facing elements were extended from the non-overflow portion of the dam through the spillway without changing alignment or interrupting either the slipforming or the RCC placing operations. Steps were constructed by removing a block in the slipformer's mold so the slipformer could change the shape of the downstream element from the non-overflow element to the spillway step element without stopping. The spillway crest construction was simplified by stopping the RCC lift at elevation 8163.0 (2488 m) and placing a reinforced concrete crest aligned with the downstream chute, see figure 2.

2. Steps eliminated the concern about cavitation being initiated at the horizontal joints which would be formed every 2 ft (0.61 m) between each of the facing elements for a smooth spillway. High velocity flow crossing each joint was held away from the joint by the step creating a zone of turbulent, highly aerated water between the concrete surface and the main flow.

3. Placing the spillway on the dam allowed use of a 600-ft- (183-m-) long crest. This reduced the maximum head on the spillway crest to 3.5 ft (1.1 m) in the original design. During construction the design flood was revised creating a maximum head on the spillway crest of 10 ft (3.0 m). Heads within this range were compatible with the stepped spillway.

4. Energy dissipation produced by the steps allowed the stilling basin length to be 30 ft (9.1 m) long, or 50 percent shorter than for the smooth chute type spillway. The cost savings of the smaller stilling basin more than offset the additional cost of the steps.

Hydraulic Model Studies

Hydraulic model studies were performed to optimize the crest geometry and determine the stilling basin length. The hydraulics of the stepped spillway design were investigated with sectional models of 1:5, 1:10, and 1:15 scale in permanent laboratory flume facilities. Initial studies revealed the importance of designing a proper crest section to keep the jet in contact with the downstream slope and produce tumbling flow down the steps. Therefore, extensive tests were performed to finalize the crest shape and alignment of the upper steps before the sectional model of the full spillway height was studied to determine the stilling basin size. During the model tests the slope of the downstream spillway face and the dam width were changed so crest shapes were developed for both geometries. After dam construction had begun, modifications were made to pass the increased design flood. Details of the many hydraulic model tests are published in REC-ERC-87-6 [1].

Final design. - The final design of the spillway is shown on figures 2 and 3. An approach channel was provided upstream of the crest to decrease the approach velocity. The stepped face of the crest was designed to match the underside of the theoretical nappe shape until the point of tangency with the 0.32:1 downstream slope. This required small, 1.0-ft- (0.30-m-) high steps, near the top of the crest to produce the required shape while preventing the jet from impinging upon a step and springing free from the slope (fig. 2). The spillway entrance corners were elliptically shaped to reduce flow separation and aeration of the underside of the nappe which caused the jet to spring free of the downstream face.

The final crest shape produced well developed tumbling flow down the stepped face and was installed in the 1:15 scale model of the full spillway height to determine the stilling basin length. The stilling basin size was determined by observing formation of the hydraulic jump with tailwater only and with various stilling basin end sill locations. The basin length of 30 ft (9.1 m) was determined for a total discharge of 15,000 ft^3/s (425 m^3/s). This provided excellent energy dissipation with calm flow in the river channel downstream. This basin design acted like a submerged solid bucket energy dissipator with a turbulent boil on the surface and a ground roller downstream when the total discharge was increased to 75,000 ft^3/s (2124 m^3/s). This was determined adequate due to the infrequency of the flood event and the condition of the river channel downstream.

Stepped Spillway Flow Conditions

The final results of flow down the stepped face are increased energy dissipation and elimination of cavitation potential. These overall benefits may be explained by discussing the complex flow phenomenon induced by the steps as the jet travels down the stepped spillway face (fig. 4).

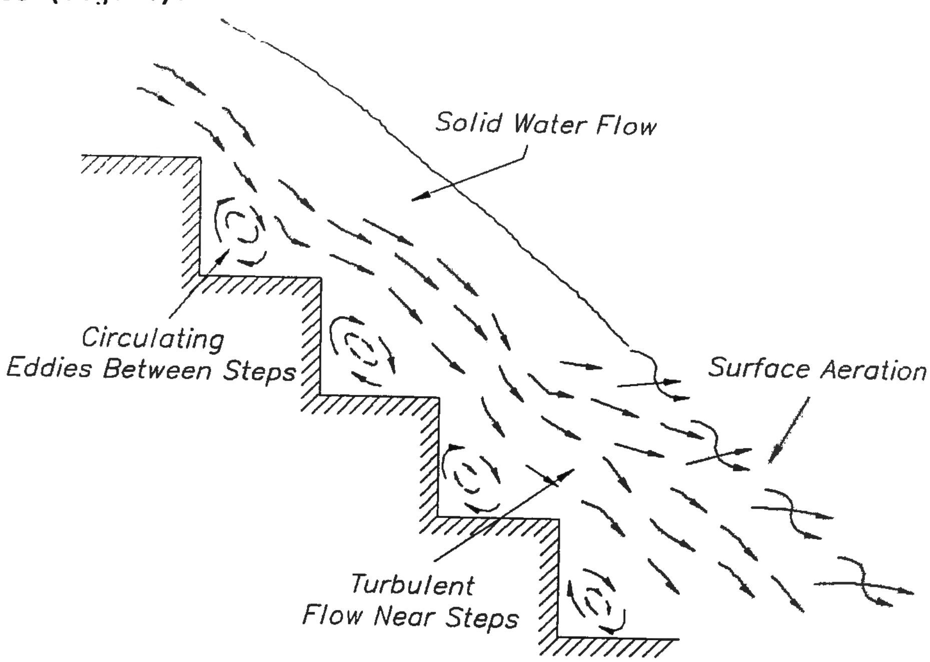


Figure 4. - Stepped spillway flow conditions.

Ideally, the spillway should be designed to operate under low head or small unit discharge to allow the entire thickness of the jet to be influenced by the step roughness. The steps should be viewed as providing a uniform roughness over which the flow travels not as a series of individual roughness elements. Only for very small flow depths does the jet impinge on each step and cascade uniformly from step to step as a series of falls. For all other flow depths, the jet breaks up as it impinges on the steps, creating a small roller or eddy downstream of each step and a turbulent water surface above the steps. The eddy intermittently dissipates and then reforms.

The ideal flow condition is present when the proper flow depth to step height ratio creates turbulence as the jet impinges on the steps to reduce the velocity and provide aeration throughout the flow depth. The evidence of "white water" indicates that the jet is being broken up by the steps. As the flow depth increases the effectiveness of the step roughness is reduced. Flow near the steps is turbulent; however, a zone of solid water is present before the boundary layer reaches the surface to allow surface aeration. In this case, the jet velocity is less reduced resulting in less energy dissipation. Therefore, it is apparent that the flow depth to step height ratio should be optimized to gain the maximum benefit from the stepped surface of the spillway.

Quantifying Energy Dissipation

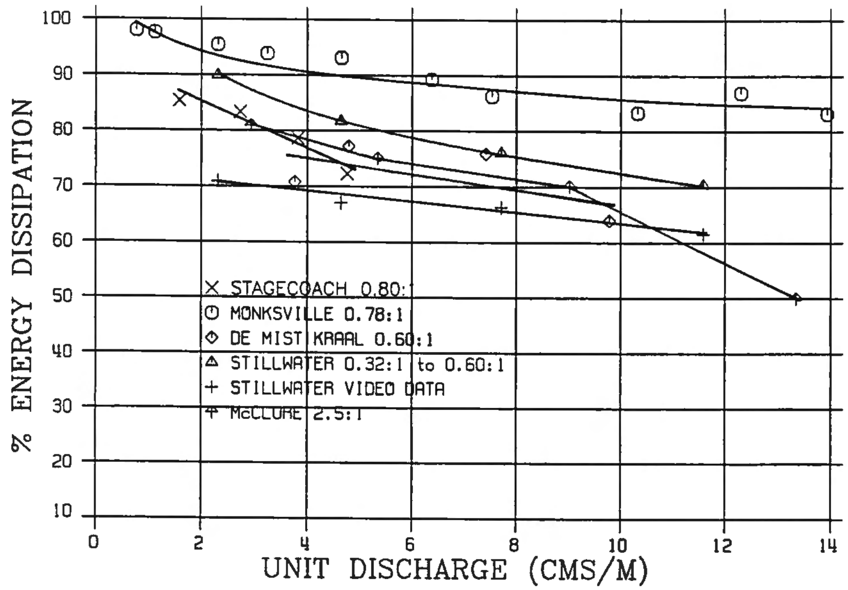
Physical model studies determined the stilling basin size required below a stepped spillway based on observations of the hydraulic jump. During these studies, attempts have been made to quantify the energy dissipated as the flow travels down the steps so that each stepped spillway application would not have to be model tested. Energy dissipation is a function of the velocity present at the toe of the spillway. Several measurement techniques have been used to determine the flow velocity, V_s, remaining near the toe of a stepped spillway. The velocity was measured with a pitot tube or propeller meter or by tracing targets with a video or high speed movie camera. Flow depths were measured with a probability probe or staff gauge and the continuity equation was used to compute the velocity.

The energy dissipation produced by flow over a stepped spillway is determined by comparing the theoretical velocity, V_t, of a smooth spillway, assuming total head, to the measured flow velocity, V_s, over a stepped spillway of the same height. The performance of a stepped spillway is then determined by computing the percentage of kinetic energy lost for a stepped versus a smooth spillway. The percent of energy dissipated is computed from:

$$E = [(V_t^2 - V_s^2)/V_t^2] * 100 \qquad (1)$$

The flow velocity measured during hydraulic model studies of site specific stepped spillways has been reported by several investigators [2, 3, 4, 5]. These data have been analyzed and are presented on figure 5 showing percent energy dissipation versus unit discharge. This figure was developed primarily for steep spillways of varying height and slope with a constant 2-ft (0.61-m) step height. Energy dissipation for small unit discharges, or small flow depths, is very good, varying from 70 to 97 percent but decreases to between

60 to 85 percent as the flow depth or unit discharge increases. Model test results for McClure Dam, a 140-ft (42.7-m) high embankment dam with a 2.5:1 downstream slope were based on 1-ft (0.3-m) step heights. The energy dissipation characteristics were similar but showed a large decrease in performance with unit discharges above 100 ft^2/s (9.3 m^2/s).



1 cms/m = 10.76 $ft^3/s/ft$

Figure 5. - Energy dissipation characteristics of stepped spillways.

This graph was compiled as an attempt to generalize design data for stepped spillways. However, due to the complex nature of the flow conditions, the accuracy of the velocity measurements for stepped spillways is debatable. This may be seen by comparing the two curves for Stillwater, noticing that the data taken with a video camera produce much lower values for energy dissipation. Figure 5 may be used as a general guideline for design but a model study is still recommended.

Conclusions

Stepped spillways are very compatible with RCC construction techniques and are economical to construct as an integral part of the dam. Hydraulically, the potential for cavitation damage on the spillway face is eliminated and the energy dissipated by flow down the steps allows construction of a much shorter stilling basin. The exact amount of energy that will be dissipated by a stepped spillway may not yet be determined without a model study. However, the graph presented may provide general guidelines for a feasibility design. The specific relationship between step height, flow depth or unit discharge, and slope has yet to be determined. To accomplish this, generalized research must be performed with more refinement of present velocity measurement techniques or employing new methods to better quantify the amount of energy dissipation.

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