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The role of hydraulic modeling in development of innovative spillway concepts

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ABSTRACT: The use of hydraulic models to develop and verify the intricate design of waterways to pass flood flows has been closely associated with the development of hydraulic structures over the past 50 years. Since the mid-30's, the Bureau of Reclamation has used laboratory models to develop spillways for large dams such as Hoover, Grand Coulee, Glen Canyon, Yellowtail, and Morrow Point Dams. Documented reports and generalized design criteria have been developed to summarize the results of these investigations. In recent years, Reclamation has developed various innovative spillway concepts which have resulted in cost effective designs for hydraulic structures. This paper will summarize recent laboratory investigations for labyrinth, stepped, and fuse plug spillway concepts as well as retrofit concepts using aerators on spillways and downstream slope protection systems for overtopping low-head embankments.

I. INTRODUCTION

Physical model studies are used to investigate the anticipated performance of hydraulic structures. The model is usually a reduced size representation of the proposed hydraulic structure and is designed to investigate specific areas of concern related to the hydrodynamic performance of the waterways. Modeling laws based on theoretical analysis and laboratory experience have been developed which permit correct simulation of the particular hydrodynamic phenomena under investigation. Once the model laws are understood and proper consideration is given to their limiting range of application, successful laboratory investigations can be completed which will in fact simulate the performance of the full scale structure

In the early 1940's a question was asked of hydraulic researchers "Does the prototype act as the model predicted?" In 1944, the ASCE transactions (ASCE 1944) published case studies of model-prototype correlation. The papers resulted from a symposium held to assemble the results of a wide variety of studies in which actual comparisons had been made so that the engineer could judge the adequacy of hydraulic modeling as a design tool. Since the 1940's, there have been many model-prototype correlations to further assure the adequacy of physical laboratory models (Peterka 1954) and (Burgi 1988).

The hydraulic model plays a key role in the development of final design concepts for hydraulic structures. Although its most important role is to verify the adequacy of the design concept, it is also used to "fine tune" details such as pier shape, height of training walls, etc., which normally produce construction cost savings that more than offset the cost of the hydraulic model investigation. The cost of most model investigations can be equated to placing 100 - 300 m^3 of concrete on the actual structure.

II. Rehabilitation and Modification to Correct Inadequate Spillway Capacity

With recent increases in the probable maximum flood (PMF), it has become imperative for the design engineer to provide more flood storage and/or larger capacity spillways to adequately pass the PMF. Innovative new design alternatives are under consideration to provide larger storage capacity and more cost effective spillway alternatives. In some cases, these new design concepts are used on existing structures where additional spillway capacity is needed. In other cases, the design concepts are applied to new hydraulic structures.

1. <u>Labyrinth Spillways</u>. - The labyrinth spillway is particularly well suited for a restricted length of spillway or in the rehabilitation of an existing spillway structure. The concept illustrated in figure 1 consists of repeated triangular or trapezoidal shapes which provide a developed crest length much longer than the spillway chute width. The ratio of the developed crest length for one cycle, l, to the linear length of one labyrinth cycle, w, is defined as the length magnification, l/w. The vertical geometry of the labyrinth is described by the spillway height, P, and the vertical aspect ratio, w/P.

Ideally the discharge ratio of the labyrinth spillway to a linear spillway, the flow magnification (Q_L/Q_N) should be directly related to the length magnification (Hinchliff and Houston, 1984). Therefore, if the developed spillway length for the labyrinth is three times greater than the linear length, the discharge capacity should be three times as great. This ideal condition is only true for low-head to crest-height ratios (H/P).

Figure 2 illustrates the decrease in flow magnification (Q_L/Q_N) with the increase in head to crest height (H/P). The figure illustrates a 33 percent decrease in flow magnification as the upstream head approaches one-half the spillway height, P.

Several design guidelines are given in the paper. In general the importance of the vertical aspect ratio (w/P) and resultant nappe interference from cycles being placed too close together, increases as the head increases. It is generally recommended that the vertical aspect ratio be 2.5 or greater where a significant spillway head is expected.

Ute Dam is a good example of the successful use of a labyrinth spillway. The dam is owned by the New Mexico Interstate Stream Commission (NMISC) and was completed in 1963. It is located on the

Canadian River in central New Mexico. The existing 36.6-m-high embankment dam had a gated outlet works and a 256.0-m-wide free overflow spillway. It was desired to increase the reservoir storage to permit full storage allotment under the Canadian River Compact and to increase the spillway discharge capacity to 16 055 m^3/s. The NMISC asked Reclamation to consider several alternatives to modify the existing Ute Dam. Appraisal designs and estimates for a traditional gated structure showed a minimum field cost of $34 million (1980 unit prices). After considering several alternatives, the most economical design was a labyrinth spillway combined with raising the dam for an estimated field cost of $10 million.

Numerous investigations were conducted in the laboratory to determine optimum ratios for the length magnification and vertical aspect ratio (Houston 1982). Both sectional flume studies and a 1:80 scale model of the full spillway, figure 3, were tested. The final design consisted of a 14-cycle spillway with a length magnification of 4 and a flow magnification of 2.4. The vertical aspect ratio of Ute is very small at 2.0. Figure 4 illustrates the nappe interference and resultant increased head loss for a discharge of 15 575 m^3/s. In May 1987, a discharge of approximately 85 m^3/s overtopped the newly placed spillway. The discharge was quite small and represented less than 1.0 percent of the design discharge.

2. Fuse Plug Spillways. - The fuse plug spillway is another cost-effective alternative to pass flood discharges. It is normally located on an auxiliary spillway where the fuse plug serves the same function as if gates were installed to restrict the spillway operation to floods of infrequent occurrence. "A fuse plug is an embankment designed to wash out in a predictable and controlled manner when the capacity in excess of the normal capacity of the service spillway and outlet works is needed." (Pugh and Gray 1984)

Model embankments 0.15 to 0.38 m high and 2.7 m long at scales of 1:10 and 1:25 were used by Reclamation to develop fuse plug spillway design guidelines (Pugh 1985). Laboratory discharges up to 0.61 m^3/s were used to determine lateral erosion rates, discharge coefficients, and design of embankment materials. Settling velocity adjustments and dimensionless unit sediment discharges were used to adjust the model sand grain size and/or model sediment density. The laboratory fuse plug embankment was designed with material zones similar to those found in most earth or rockfill dams.

A pilot channel (on the order of 1 meter wide) located high on the fuse plug is designed to wash out quickly once the reservoir level reaches the channel invert. An impervious core similar to that shown in figure 5 is designed into the fuse plug embankment. The core will break off in pieces from the weight of the water and embankment material. As the material downstream from the core is washed away, the core is left unsupported and breaks away. This results in a breach of the embankment at the pilot channel, but soon produces a controlled lateral erosion of the complete fuse plug as shown in figure 6.

The results of these laboratory studies are used by Reclamation to design full scale fuse plugs, such as the 9.7-m-high, 1370-m-long Twin

Buttes Dam fuse plug. The approach channel for the Twin Buttes fuse plug is relatively long and shallow and filled with mesquite (Klumpp 1988). The long approach channel and mesquite affect the head loss and resultant discharge capacity of the auxiliary spillway. Figure 7 shows a decrease in the maximum discharge capacity of 4.0 percent caused by the mesquite.

3. Embankment Protection to Permit Overtopping. - The thought of flood flow over an embankment is very frightening to most engineers. However, in recent years there has been increased interest in investigating various protective systems for the downstream slopes of low embankments (under 15 meters) which may be overtopped during extreme flood events. Various modeling techniques have been used from the full scale tests conducted at Jackhouse Dam by the United Kingdom's Construction Industry Research and Information Association (CIRIA) (Hewlett 1987) to the Reclamation laboratory studies (Dodge 1989). More recently, full scale tests using a 1.83-m-high embankment in a 1.22-m-wide and 18.30-m-long test flume were conducted for four government agencies (Federal Highway Administration, Bureau of Reclamation, Soil Conservation Service, and Tennessee Valley Authority) by Simons, Li, and Associates (Clopper and Chen 1988).

A wide variety of protective systems have been investigated. They include various classes of vegetation (grasses), jute, fiberglass, nylon mat, various concrete blocks, concrete blocks with cables, gabions, various geosynthetic materials, and soil cement. The use of roller-compacted concrete (RCC) steps as embankment slope protection has also been tested in the laboratory (Houston 1988) and placed in the field (Moler 1987). Critical velocities and shear stresses are summarized for a number of these systems (Clopper and Chen 1988). One major and obvious conclusion of these investigations is that the protection systems must be in contact with the underlying embankment. Once the bond is broken, the system's ability to protect the embankment is seriously compromised.

These hydraulic investigations have added considerably to our understanding of design and installation considerations for protective systems on embankments. They have provided significant qualitative data to assist in the selection of protective systems for low embankments. The future engineering challenge related to embankment protection deals with the extrapolation of present knowledge to high embankments. As the size of design floods continues to increase, there is increased pressure to consider these protective systems as alternatives to the more costly traditional spillway designs. What will be the role of hydraulic modeling in this new challenge?

4. Spillway Aerators. - Spillway aerators are another innovative design which were developed and verified using hydraulic models. Cavitation damage to spillways occurred as early as 1944, when the newly completed Boulder Dam (now Hoover Dam) tunnel spillways were placed in operation. A 1 to 60 scale model was constructed by the Bureau of Reclamation and a number of devices were studied to introduce air between the high velocity water jet and the concrete tunnel liner (Bradley 1945). The studies were eventually discontinued when no successful method to introduce air was found.

After the 1967 damage in the Yellowtail Dam tunnel spillway in Montana, a model study was used to develop a conical nozzle (ramp) and aerator slot to introduce air just upstream of the vertical bend (Colgate 1971). This design was installed in the prototype tunnel and verified with field tests conducted in June 1969.

The serious damage to the two Glen Canyon Dam tunnel spillways in 1983, figure 8, resulted in additional model investigations to further improve the aerator design proposed at Glen Canyon Dam (Pugh 1984). Design methods were also developed to identify when spillway aerators are needed on high-head dams. This analysis resulted in the installation of aerators on Reclamation's five highest tunnel spillways - Hoover, Glen Canyon, Yellowtail, Flaming Gorge, and Blue Mesa Dams, and permitted a rational method to determine which of Reclamation's 20 tunnel spillways required aerators.

The repair criteria for damaged concrete surfaces downstream from the aerator at Glen Canyon, Hoover, and Flaming Gorge Dam spillway tunnels were relaxed. Savings of several million dollars were realized by this relaxed surface tolerance criteria (Burgi and Eckley 1987).

III. Stepped Spillways Associated with Roller-Compacted Concrete Dam Construction

The concept of the stepped spillway is not new, but has gained renewed interest in recent years with the use of RCC technology in dam construction. The economical use of RCC depends on the uninterrupted placement of concrete and the compatible design of spillways, outlet works, and other dam appurtenance.

In recent years, there have been a number of RCC dams constructed but very few have used the stepped spillway concept. Galesville Dam has a free overflow spillway section of smooth enriched RCC. Elk Creek Dam has a gated overflow spillway with conventional smooth concrete section.

The stepped spillway concept takes advantage of the normal RCC placement depths of 0.6 to 1.0 meter. The step dimensions are related to the slope of the downstream face of the dam. For low head dams or low unit discharges, the downstream natural face of the RCC may be sufficient. The Kirville Dam in Texas, figure 9, is an example of a low head dam which in 1985 underwent a 4.3-meter depth of overtopping (Smith 1986). For high head dams or high unit discharges facing elements of conventional concrete may be required. Reclamation's Upper Stillwater Dam is an example of a high head dam with conventional concrete facing elements.

Upper Stillwater Dam. - Upper Stillwater Dam is located at the 2440 meter elevation in the Uinta Mountains in the state of Utah. The 88-meter-high gravity dam was completed in 1987 and includes 1.15 million m^3 of RCC and 70 000 m^3 of slip formed facing concrete.

A short construction period due to the low air temperatures during most of the year required dam construction methods which emphasized concrete placement speed. Horizontal slip formed facings were used to place conventional concrete on the vertical upstream face and the sloped downstream face. Each facing element is 0.9-meter high and the lower one-third of the element overlaps the previously placed element. this results in 0.6-meter-high steps on the downstream face of the dam, figure 10.

The major benefit of the stepped spillway is the resulting energy dissipation from flow tumbling down the spillway face. A high percentage of the energy is dissipated before reaching the stilling basin, thus significantly reducing the basin length. Three laboratory models (1:5, 1:10, and 1:15) were used to determine the crest design of the 60-meter-high and 183-meter-wide stepped spillway. The models were also used to study details of the entrance conditions, height of training walls, pressure on the steps, and adequacy of energy dissipation to design the stilling basin. Model scales were chosen based on detail needed for the crest design (1:15 and 1:10) and the need for a full height sectional model (1:15). The availability of existing flumes and pump capacity were also determining factors. These model scales were highly desirable and permitted very accurate predictions of prototype performance.

For the design discharge of 425 m^3/s (2.32 $m^3/s/m$) and $H = 1.07$ meters, the aerated turbulent flow tumbled uniformly down the stepped face with 75 percent reduction in energy. During the course of the study the design unit discharge was increased from 2.32 to 11.6 $m^3/s/m$. This larger design discharge required a head of 3.0 meters. With only minor modifications to the crest end piers, the addition of two steps on the crest, and reinforcement of the RCC end sill in the stilling basin, the design was determined to be adequate for the increased total discharge of 2095 m^3/s. Figure 11 illustrates the 11.6 $m^3/s/m$ unit discharge in the 1:15 scale model.

Figure 12 illustrates the final design of the spillway face. The required stilling basin length for the stepped spillway was 9.14 meters, a reduction of 85 percent over that computed for a traditional hydraulic jump basin.

SUMMARY

Hydraulic modeling has played a significant and essential role in the development of hydraulic structures around the world. Mankind's confidence to build water resources projects such as Hoover, Grand Coulee, Itapu, Tarbella, Kariba, and many other large hydraulic structures has been supported by the verification tests performed in hydraulic laboratories all around the world. In recent years, Reclamation has continued to rely on hydraulic models to develop and verify innovative spillway concepts for hydraulic structures.

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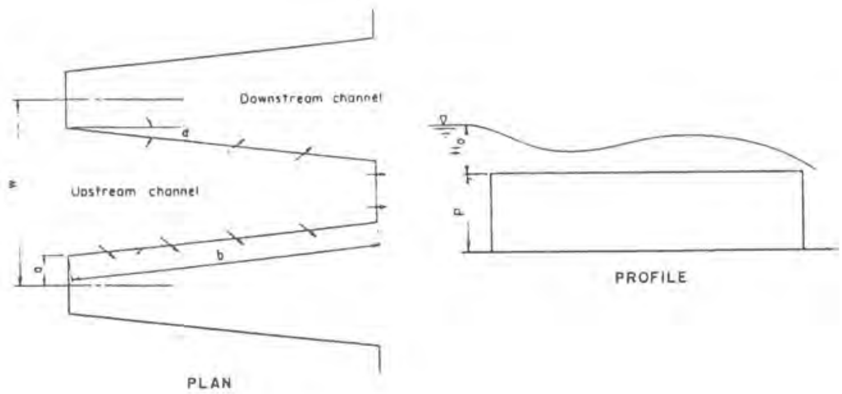

LEGEND

a	= Half length of labyrinth apex
b	= Length of labyrinth wall
H	= Total upstream head over crest (less than H_O)
H_O	= 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. - General plan and section of labyrinth spillway (Hinchliff and Houston 1984)

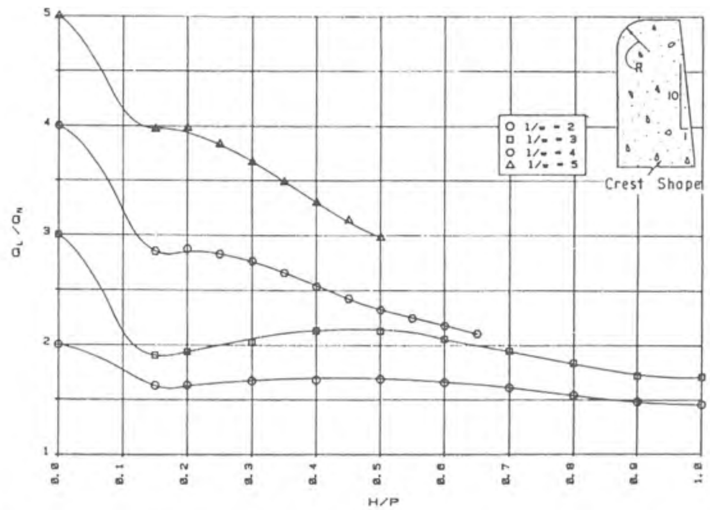

Figure 2. - Design curves with quarter-round upstream face, trapezoidal form weir (Hinchliff and Houston 1984),

Figure 3. - 1:80 scale model of Ute Dam labyrinth spillway (Houston 1982).

Figure 4. - Ute Dam labyrinth spillway with 15 575 m^3/s (Houston 1982)

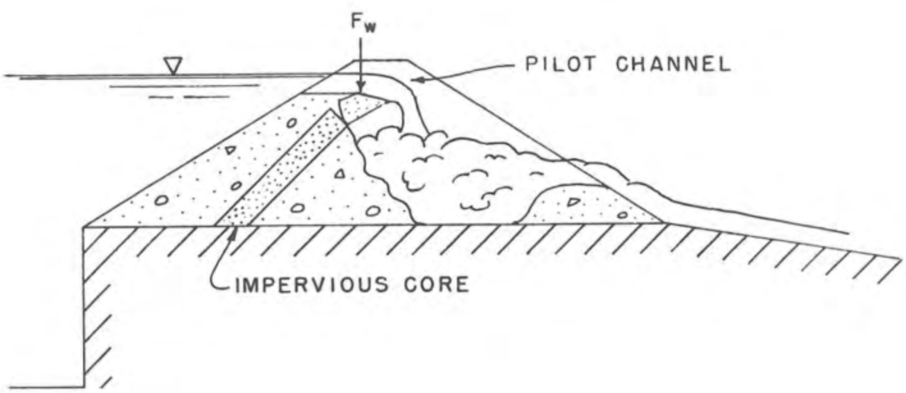

Figure 5. - Flow through the pilot channel showing the mode of failure of the impervious core (Pugh and Gray 1984)

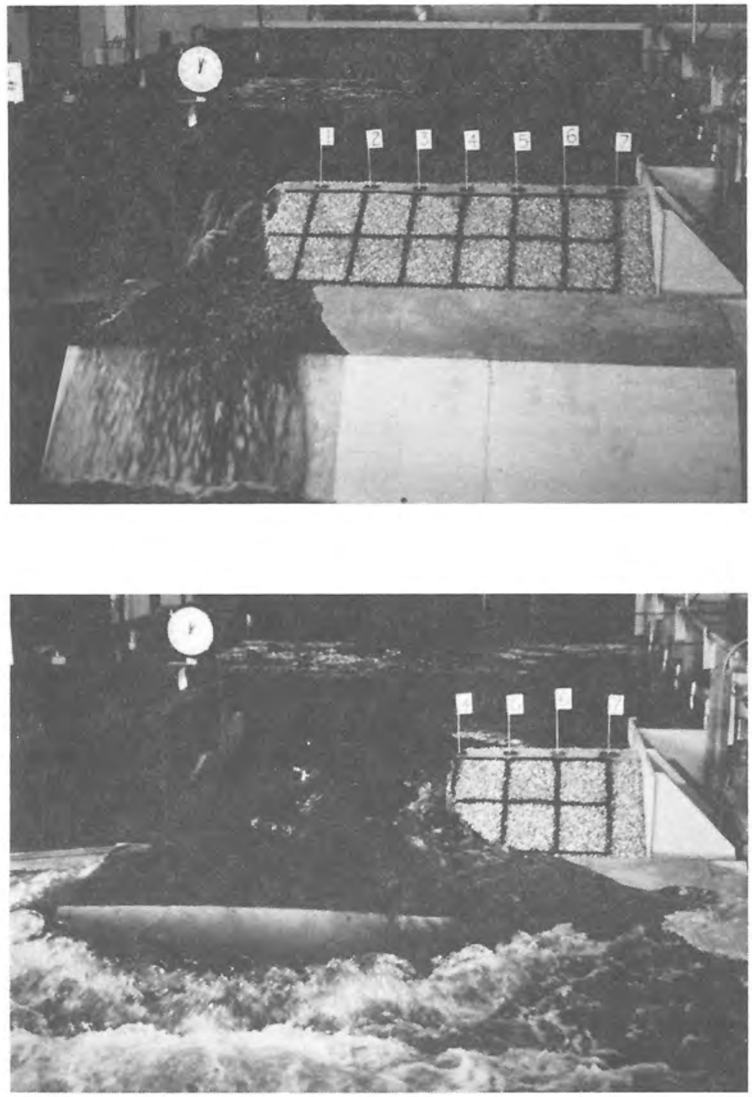

Figure 6. Photographs showing washout process (Pugh and Gray 1984).

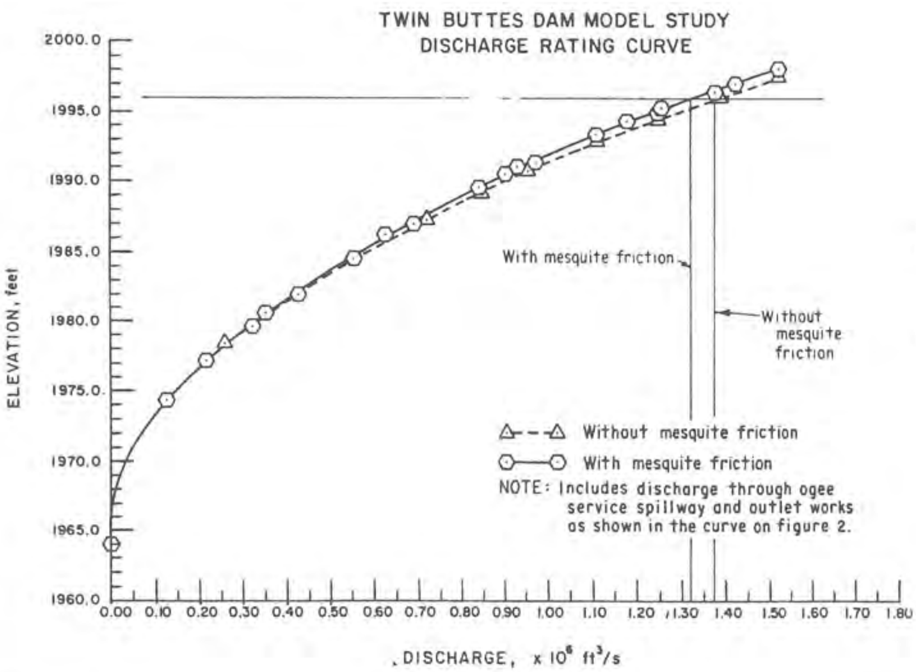

Figure 7. - Fuse plug spillway rating curves with and without mesquite friction (Klumpp 1988). 1 ft = 0.305 m, 1 ft^3/s = 0.028 m^3/s.

Figure 8. - View looking downstream across the 10.7-m-deep hole in the invert liner of the left tunnel spillway at Glen Canyon Dam (Burgi and Eckley 1987).

Figure 9a. - Kirville Dam - 4.3-m overtopping.

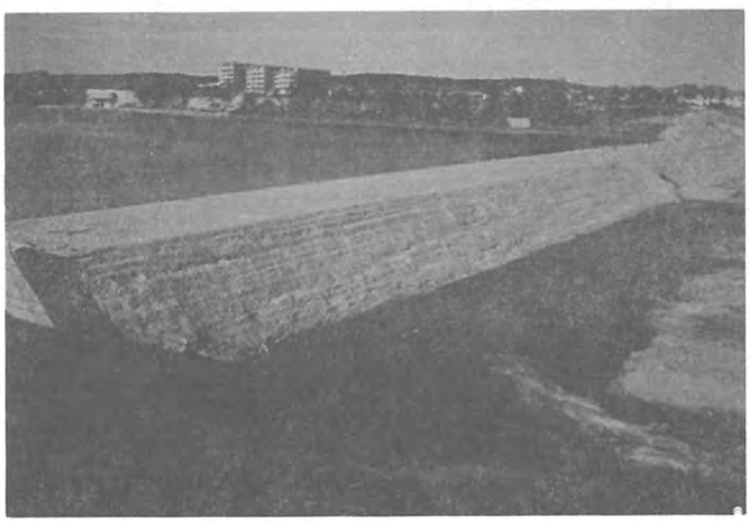

Figure 9b. - Kirville Dam after overtopping event.

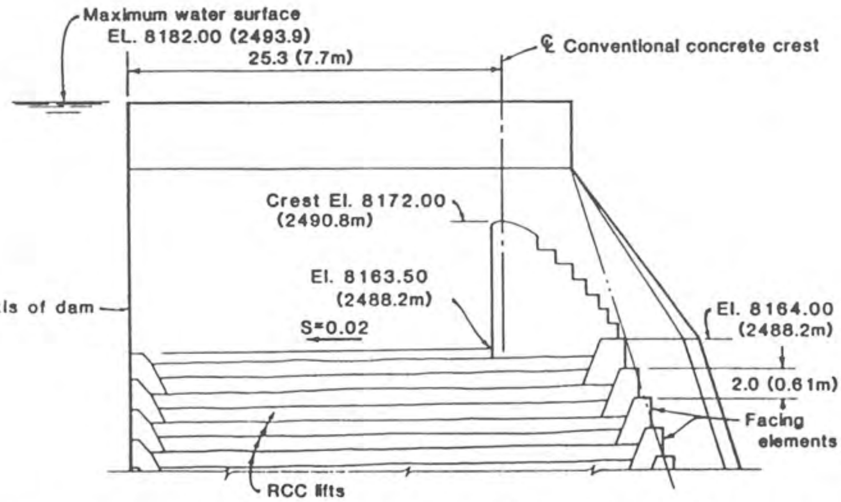

Figure 10. - Upper Stilllwater Dam spillway crest (Houston and Richardson 1988).

Figure 11. - 11.6 $m^3/s/m$ unit discharge on the 1:15 scale model of Upper Stillwater spillway (Houston 1987). 1 $m^3/s/m$ = 10.8 $ft^3/s/ft$.

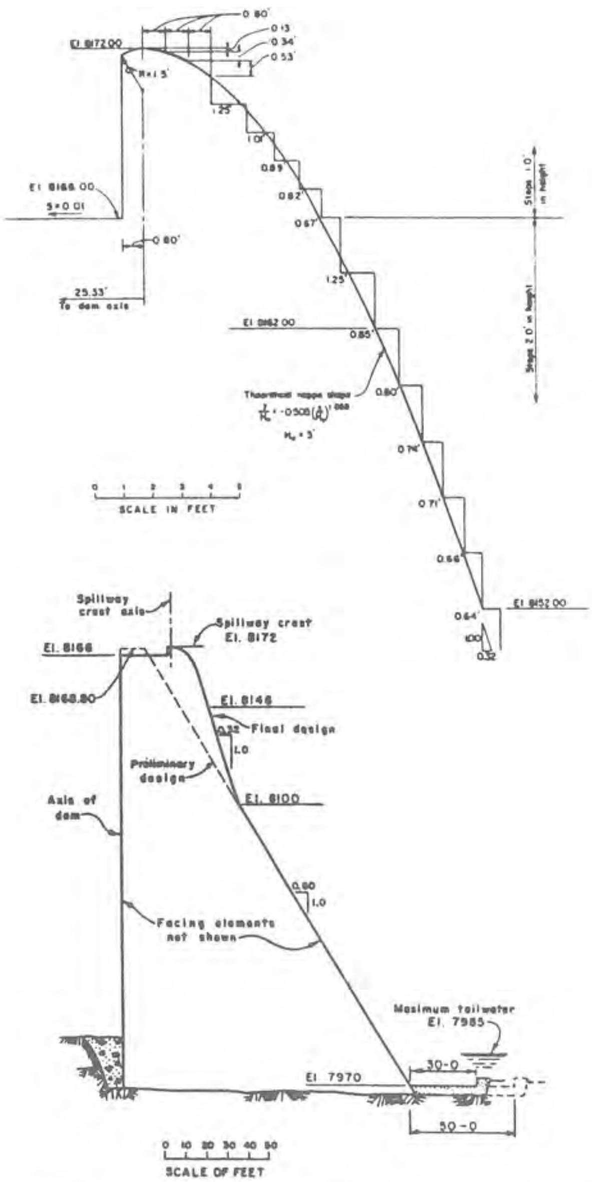

Figure 12. - Section of preliminary and final spillway designs (Houston 1987). 1 ft = 0.305 m.