DEVELOPMENT OF HYDRAULIC STRUCTURES

by

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ABSTRACT: The Bureau of Reclamation was established in 1902. Since that time, Reclamation has constructed more than 220 dams. Each dam, depending on its function, has two or more principal hydraulic structures. The main hydraulic structures are the spillway and the outlet works. The change in concept of these structures and their energy dissipators as developed by Reclamation from 1902 to the present (1988) is described. Included are stepped spillways, labyrinth spillways, traditional chute and tunnel spillways, and many types of energy dissipators. The emphasis during this period has been to establish standards for many hydraulic structures, to develop new concepts, and to provide unique designs when the occasion demands.

The monuments to the success of this endeavor include T. Roosevelt Dam in Arizona, Hoover Dam in Nevada, Grand Coulee Dam in Washington, Hungry Horse Dam and Yellowtail Dam in Montana, to mention a few, and hundreds of irrigation projects throughout the 17 Western States that are the original Bureau of Reclamation domain. International acceptance of these standards is also well documented.

April 19, 1938 - the birth date of the Hydraulics Division and the focus of the 50th Anniversary sessions of this conference. The Hydraulic Laboratory of the Bureau of Reclamation is only a few years older than the Hydraulics Division, so it seems appropriate to discuss the development of hydraulic structures by Reclamation during this period. Actually, Reclamation had been in the "hydraulic structures" business for 35 years by that time, and Reclamation's Hydraulic Laboratory was about 8 years old and had become a very important part of the Reclamation program.

A low-key review of the status of Reclamation's hydraulic structures in 1938 seems appropriate to establish a baseline. Just how big was the Reclamation program?

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Consider these statistics: in its first 10 years, Reclamation built 18 dams, including some biggies such as Theodore Roosevelt (fig.1), Buffalo Bill, and Pathfinder. By the time the Hydraulics Division was formed, the number had grown to 64; and now, 1988, there are more than 220 dams. Each dam has a minimum of two hydraulic structures: a spillway and an outlet works; a powerplant will add to this number, and an irrigation or M&I (municipal and industrial) conveyance system will add many more. Spillways, outlet works, and energy dissipators are probably the structures that are of most general interest.

Figure 1. - T. R. Roosevelt Dam, Arizona

Figure 2, an interesting histogram, shows the number of dams built in each of the seventeen 5-year intervals between 1902 and 1988. It highlights some interesting facts such as the highly productive quarter-century from 1948 to 1972, the post World War II boom, during which 128 dams were completed - over half of the total inventory. Also shown are the low-productivity periods related to the initial startup, 1902 to 1907; the depression years, 1927 to 1932, World War II, 1942 to 1947; and the redirection of Reclamation's mission of the past few years.

In the middle of the second low-productivity period, the Reclamation Hydraulic Laboratory was formed. This does not mean that hydraulic investigations were not performed prior to 1930; actually, some of the design units made studies of control valves and some hydraulic structures on a one-time-only basis using very basic facilities.

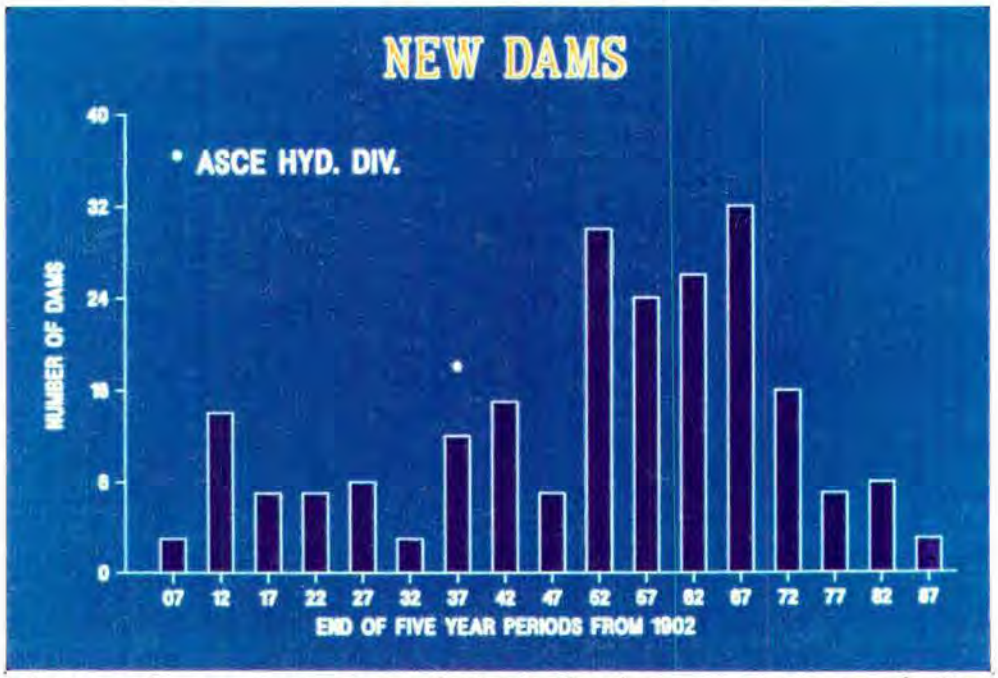

Figure 2. - Dams completed during 5-year periods from 1902-1987.

The Hydraulic Laboratory was formed expressly to fill a need during the design of Boulder Canyon (Hoover) Dam, on the Arizona-Nevada border. This was to be the highest dam in the world, and new technology had to be developed for the structural, mechanical, and hydraulic designs.

Reclamation's first hydraulic laboratory was at Colorado A&M College (now Colorado State University) at Fort Collins. As the workload grew, Reclamation expanded this facility, added a small annex in the basement of the Old Customs House in Denver, and built a huge outdoor laboratory near Montrose, Colorado. Eventually, these facilities were consolidated in the New Customs House in Denver and in 1945 moved to the present location at the Denver Federal Center. The design units were similarly scattered before being consolidated at the Federal Center.

This brings up the question of what governed the design procedures that Reclamation used for the 39 dams and ancillary hydraulic structures built between 1902 and 1930. Historically, their staff was recruited from the parent agency, the United States Geological Survey, a very knowledgeable engineering organization. Other sources were other Government agencies, construction engineers, private practice engineers, and graduates from highly qualified universities. The supervisory staff has always maintained extremely high engineering standards for their personnel.

Apparently, each design leader assembled a design manual based on his/her training and experience; these were passed on to subordinates who, in turn, added to the standards and eventually became even better qualified designers. In early documentation concerned with hydraulic structures, the names Horace W. King, William P. Creager, Julian Hinds, Theodore Rehbock, and many other renowned hydraulicians appeared.

A typical page from a 1933 "design manual" is entitled "Types of Scour Protection Below Dams" (fig. 3).

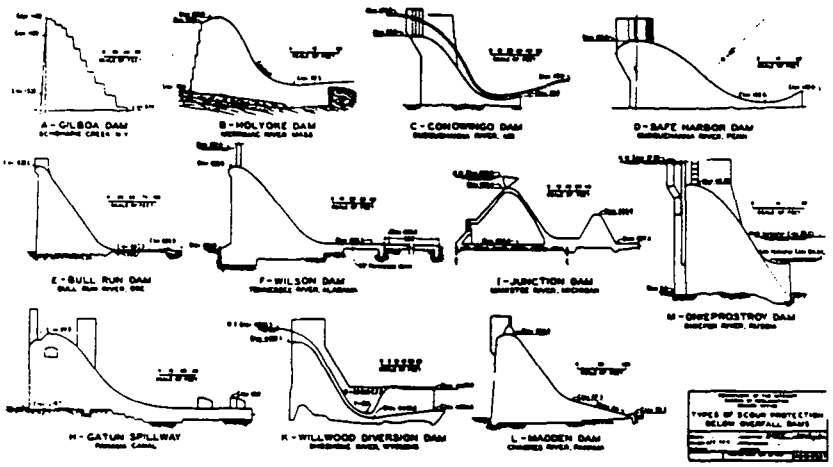

Figure 3. - Typical page from a design handbook - 1933.

This chart was developed by E. W. Lane and W. F. Bingham, research engineers in the Hydraulic Laboratory, and submitted to the Chief Designing Engineer as Technical Memorandum No. 323 (Lane, 1933). Actually, it is a good overview of various types of spillway structures built throughout the world and in use at that time. Eleven structures are shown, including a stepped spillway, several ski jump spillways, a couple with forced hydraulic jump energy dissipators, and some with very long paved aprons, presumably for a natural hydraulic jump.

A review of the early Reclamation dams shows a majority with no energy dissipators. Most of them had controlled or uncontrolled spillways, outlet works, or diversion structures, but energy dissipators were unique. The principle was to control the flow for storage and future use. Control systems were present; radial gates, drum gates, slide gates, cylinder gates, ensign valves, and needle valves were there. But if more water was coming

in than could be stored, it was turned loose and the problem transferred downstream. You can imagine the disasters that could result!

Before the in-house development of Reclamation energy dissipators is discussed, some then-versus-now hydraulic structure concepts are compared. A stepped spillway that was built in New York State in 1926 (Gaussmann, 1923) is shown on figure 3. This spillway had some features that were unknowingly reinvented for the Upper Stillwater Dam spillway (Utah), such as varying the height and width of the steps near the crest (Houston, 1987). Another early version of a stepped spillway was at Lahontan Dam in Nevada, built in 1915 (fig. 4). This is a beautiful structure, and has operated many times. The 1987 version of a stepped spillway is at Upper Stillwater Dam (fig. 5), another imposing structure which, built with modern technology, is much higher and handles a larger discharge than either Gilboa or Lahontan.

Figure 4. - Stepped spillway at Lahontan Dam, Nevada.

Another comparison is a 1910 version of a labyrinth spillway at East Park Dam in northern California (fig. 6). The spillway is a separate structure from the dam. The crest of the spillway is 0.15 m lower than the dam crest but 1.07 m below the dam parapet. The dam parapet was slightly overtopped during floods in 1940 and 1958. Both times the spillway discharge was about 255 m^3/s. The 1985 version of a labyrinth spillway is at Ute Dam, New Mexico, designed by Reclamation for the New Mexico Interstate Stream Commission as an inexpensive substitute for a planned, gate-controlled spillway (fig. 7). In 1987 a flood stored over 9 m of water behind this structure, which was overtopped by only a few

centimeters, probably preventing severe downstream flood damage.

Figure 5. - Stepped spillway at Upper Stillwater Dam, Utah.

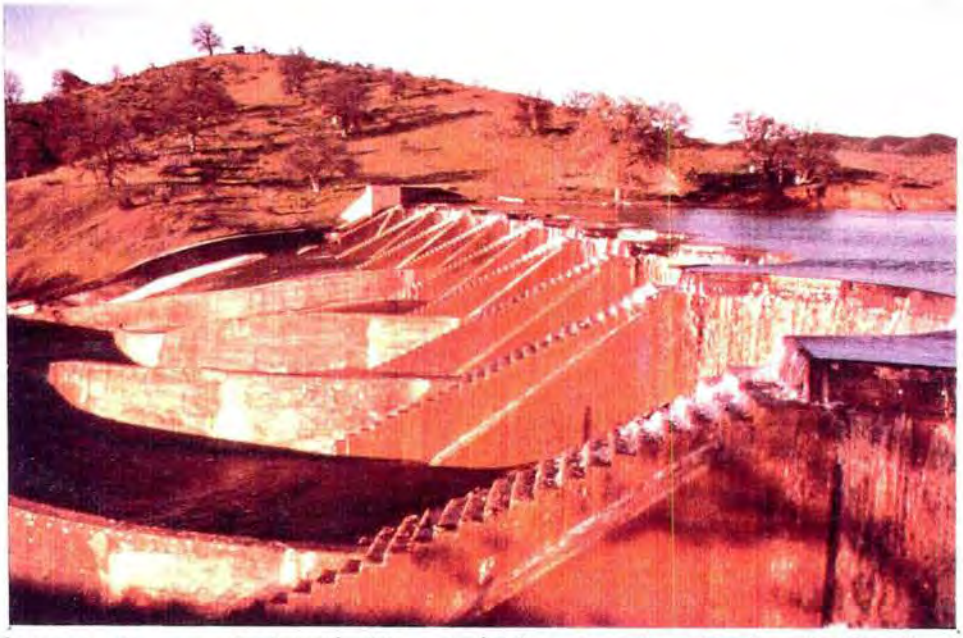

Figure 6. - Labyrinth spillway at East Park Dam, California.

The most prevalent energy dissipator is some form of a stilling basin using the hydraulic jump. The jump has been recognized in one form or another for centuries. Leonardo da Vinci sketched it in one of his notebooks in the 15th century; Venturi wrote about it in the 18th

Figure 7. - Labyrinth spillway at Ute Dam, New Mexico.

century; and Georgio Bidone of the University of Turin (Italy) "discovered" the jump at about the same time. None of them were interested in it as an energy dissipator. Late in the 19th century and early in the 20th century, research studies were made in the United States at Lehigh University, Worcester Polytechnic University, Cornell University, the University of California, and probably many others. Advanced research was also being accomplished at many European universities.

The lack of energy dissipators and the dangers involved were also noted by Reclamation designers. They began to draw on the experience of European designers, the Tennessee Valley Authority, the Panama Canal designers, and many others. The natural evolution was that some of the more exotic structures featured parabolic humps in the floor, gigantic impact blocks, trapezoidal shapes, and practically anything else that would "slow the flow."

These were gradually eliminated in favor of more standardized designs. The Reclamation stilling basin at that time featured a rectangular shape that used as design parameters the inflow-outflow depths derived from the momentum equation; that is, the lengths were a function of the downstream depth and the heights a function of the incoming flow depth. The width and spacing of the appurtenances were left to the discretion of the individual designer, but usually occupied about half of the basin width. The major development in the 1940's to standardize energy dissipators was the work of

Fred Blaisdell and his coworkers at the Saint Anthony Falls (SAF) hydraulic laboratory at the University of Minnesota. SAF was the major hydraulic research station of the Soil Conservation Service. The SAF stilling basin (fig. 8) is extensively used throughout the world and is featured on one side of the ASCE Hydraulic Structures Medal (Bradley, 1961).

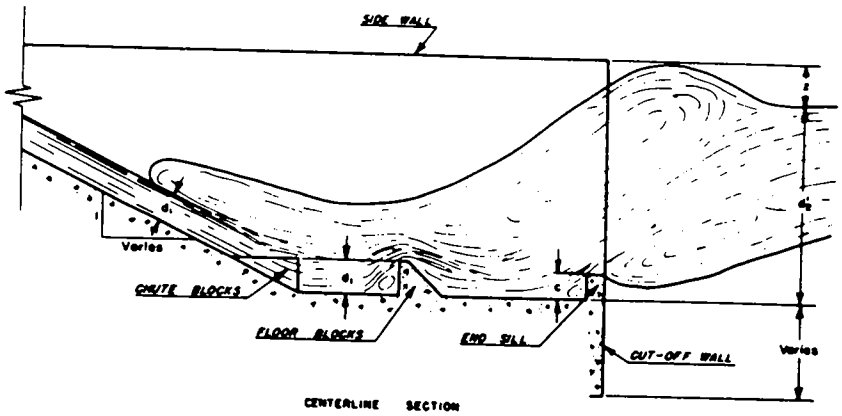

Figure 8. - SAF stilling basin

From 1950 to 1960, Reclamation initiated an extensive research program with the objective of developing standard designs for energy dissipators. The product of this program was Engineering Monograph No. 25, "Hydraulic Design of Stilling Basins and Energy Dissipators" (Peterka, 1964).

The first modified hydraulic jump stilling basin in the monograph is referred to as Basin II (fig. 9). The basin contains chute blocks at the upstream end and a dentated end sill, but no intermediate or floor blocks. The end sill seems to have been patterned after the Rehbock sill, an appurtenance that was developed by Theodore Rehbock many years earlier.

The next most popular basin is Basin III (fig. 10). Basically, it is the same as Basin II except for a solid triangular end sill and a set of floor blocks placed at about the one-third point of the basin. Note the similarity between this basin and the SAF basin.

Basin IV (fig. 11) was developed for low Froude number inflow, principally for small canal structures. Usually, a hydraulic jump in this range is not fully developed, is very unstable, and is accompanied by many surface waves. This basin has been revised and appears in the new edition of Design of Small Dams.

Basin V (fig. 12), the so-called sloping apron basin, has been extensively used in the past but seems to have

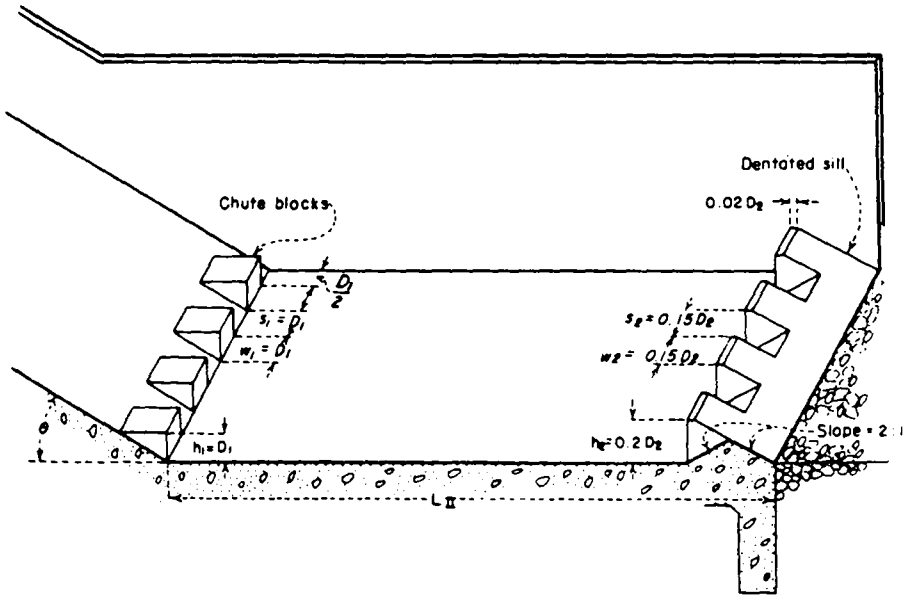

Figure 9. - USBR Type II stilling basin.

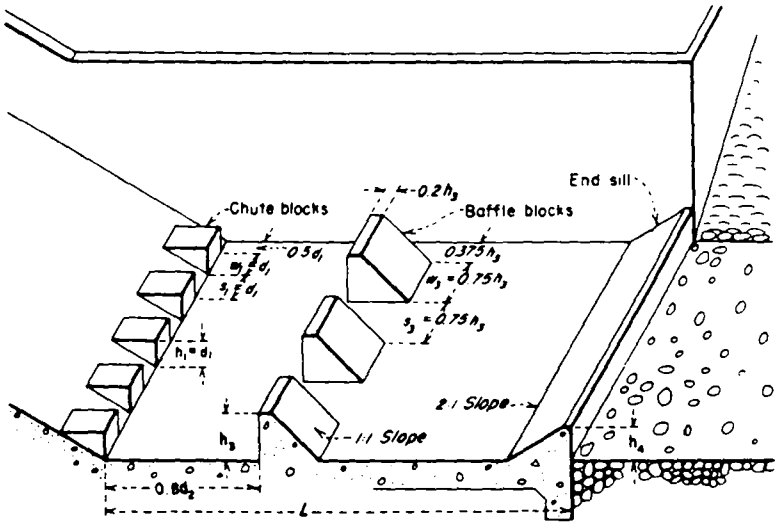

Figure 10. - USBR Type III stilling basin.

fallen into disfavor with contemporary designers. This basin was developed for Madden Dam in the Panama Canal Zone and is also used at Canyon Ferry Dam, Montana, and Folsom Dam, California, among others.

Basin VII, the solid bucket, was developed for Grand Coulee Dam, Washington, in 1933, and a modified version known as the slotted bucket was developed for Angostura Dam, South Dakota, in 1945 (fig. 13). The slotted bucket is also used for Brantley Dam in New Mexico, the newest Reclamation dam.

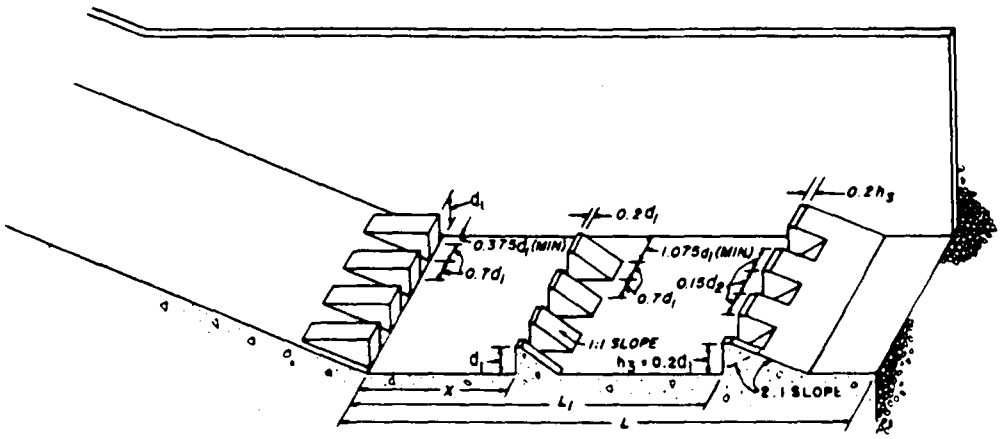

Figure 11. - USBR Type IV stilling basin.

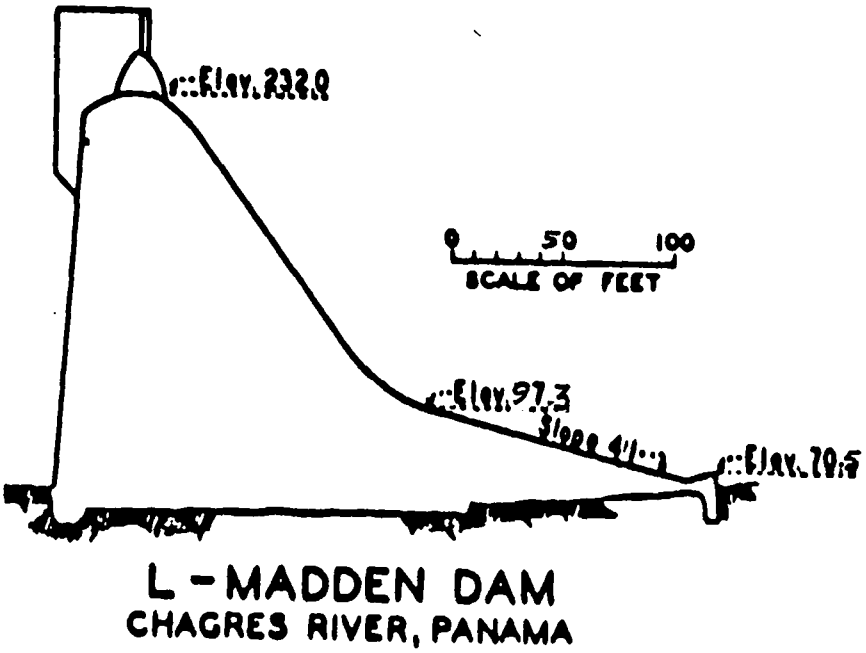

Figure 12. - USBR Type V, sloping apron stilling basin.

The foregoing has been a summary of energy dissipators that feature the hydraulic jump, but there are many effective special-purpose energy dissipators. A widely used energy dissipator in this group is Basin VI, the

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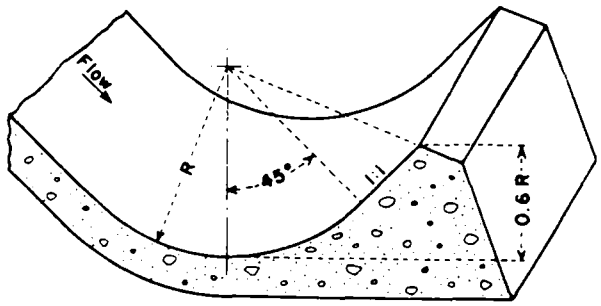
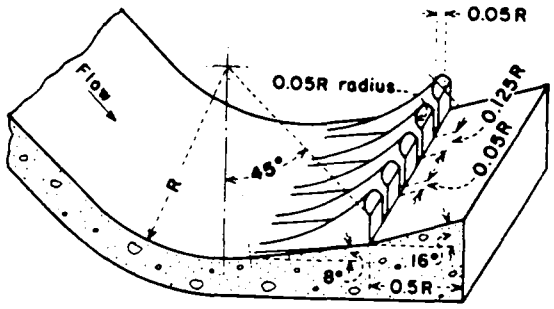
impact basin (fig. 14). This structure is used mostly at canal turnouts, at wasteways, or at the end of pipelines. It is a very effective energy dissipator.



A—*Grand Coulee type solid bucket*



B—*Angostura type slotted bucket*

Figure 13. - USBR Type VII, bucket stilling basin.

Another special-purpose basin is the hollow-jet valve basin (fig. 15). Outlet works controlled by slide gates can use Basin II, Basin III, or a plunge pool; but due to its unusual jet shape, this valve seemed to require a unique basin. Unfortunately, this basin has proven to have some severe erosion problems under certain operating conditions. It has worked exceptionally well at Boysen Dam in Wyoming, Falcon Dam in Texas, and Yellowtail Dam in Montana, but was far from satisfactory at Trinity Dam in California and Navajo Dam in New Mexico. It should be noted that the Trinity and Navajo structures operate at heads several times greater than those at Boysen and Falcon; and although Yellowtail is a high-head facility, the outlet works stilling basin is covered, a feature that apparently helped overcome some of the troubles found at Navajo and Trinity.

The baffled apron is a structure that was developed for use on canals as a drop or wasteway (fig. 16). The hydraulic design is related to the unit discharge (discharge per unit width). The objective of the structure is to dissipate the kinetic energy as the flow

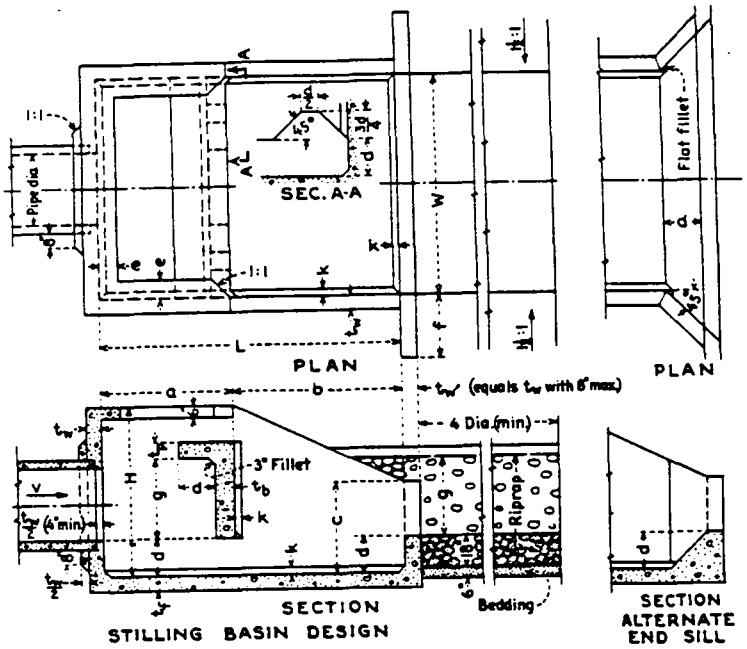


Figure 14. - USBR Type VI energy dissipator.

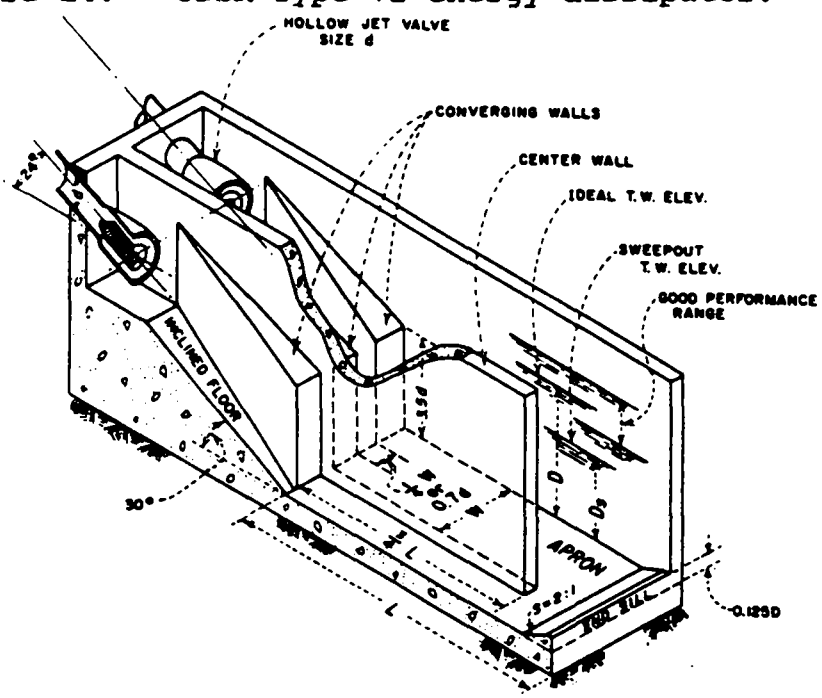


Figure 15. - USBR hollow-jet valve energy dissipator.

passes down the chute so that the residual kinetic energy at the bottom of the chute is equal to or less than the kinetic energy at the top of the chute. This proved to be such an effective canal structure that one of the Reclamation design engineers suggested that laboratory studies be made to develop a structure that could be used for larger spillway-type flows. The studies showed that the unit discharge, originally limited to 5.5 $m^3/s/m$

could be increased to any quantity if it is practical to build the structure needed to contain the flow. In the past 10 years many structures have been built that exceed the original unit discharge limit. These include Conconully Dam (Washington) spillway at 7.3 $m^3/s/m$, Marble Bluff Dam (Nevada) spillway at 10.5 $m^3/s/m$, Soil Conservation Service Dam T or C (New Mexico) at 11.2 $m^3/s/m$, and Utah Department of Water Resources Dam DMAD at 9.3 $m^3/s/m$.

Figure 16. - Baffled apron drop spillway.

The trend for terminal structures has returned to the flip bucket, the principle being to direct the flow away from the structure and downstream a sufficient distance where the water can erode its own plunge pool or flow into a pre-excavated plunge pool. Yellowtail Dam, Montana, has a combined hydraulic jump/flip bucket; that is, it acts as a hydraulic jump energy dissipator up to a predetermined discharge where the jump flips out and the structure acts as a flip bucket for higher discharges. Glen Canyon Dam, Arizona, has tunnel spillways through both abutments of the dam, both terminating in a flip bucket (fig 17). Crystal Dam, Colorado, has an uncontrolled spillway near the top of the dam. A flip bucket directs the jet away from the dam where it impinges nearly vertically into a pre-excavated pool. Flaming Gorge Dam in Utah has a low-angle flip from a tunnel spillway in the left abutment. Trinity Dam, California, tunnel spillway terminates in a flip bucket specifically shaped to disperse the jet and direct it to the right. An example of a pre-excavated lined plunge pool is at Morrow Point Dam, Colorado.

Figure 17. - Flip bucket at Glen Canyon Dam, Arizona.

As previously mentioned, hydraulic jump basins and plunge pools have some inherent problems. These can include abrasion damage due to circulating debris in the basin, cavitation damage to the appurtenances due to high-velocity flow, or damage to the walls due to vibration. Generally, but not always, these factors can be predicted and corrected by model studies.

High velocity flow in chutes and spillways can cause severe cavitation induced erosion to the flow surfaces. The cavitation is usually caused by misalignment at construction joints, offsets into the flow caused by calcium deposits, and offsets away from the flow resulting from popouts. Another major contributor is improperly designed flow surfaces.

Severe damage has occurred in tunnel spillways at three Reclamation projects: Yellowtail Dam (Borden, 1967), Hoover Dam (1942 and 1983) (Houston, 1985), and Glen Canyon Dam (1983) (Falvey, 1990). Extensive research has shown that air admitted into the flow can mitigate potential cavitation damage. Site specific studies made for the above tunnel spillways indicated the optimum method for admitting was by air slots on the periphery of the tunnel. Design criteria were developed for locating and sizing the slots (Falvey 1990). Air slots have been added to all major Reclamation tunnel spillways and to the McPhee Dam chute spillway (Pugh, 1988). Field tests at Yellowtail, Glen Canyon, and McPhee Dams have proved the effectiveness of this method for protecting the flow surfaces.

If you follow the trend in this discussion, you might detect a general theme: Don't be opposed to trying new design concepts. They can be successful and will often lead to more efficient and economical structures.

ACKNOWLEDGMENTS

The material for this paper represents fragments of information I have retained from reading many Bureau of Reclamation Hydraulic Laboratory reports during my 40-plus years of tenure.

Most of the general historical information came from the fine report of the ASCE Hydraulic Division Task Force on Energy Dissipators for Spillways and Outlet Works (Task Force, 1964). The Reclamation historical facts came from the aforementioned laboratory reports supplemented by articles in other Reclamation publications (Loveless, 1977).

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