EMBANKMENT DAMS
METHODS OF PROTECTION DURING OVERTOPPING

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Embankment Dams: Methods of Protection During Overtopping

Reviewing past and current research can help dam owners choose protection systems that will prevent erosion and eventual failure due to overtopping.

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Editor's Note: In the event of overtopping, thousands of embankment dams across the U.S. could be severely damaged or even fail. Because of this potential hazard, many of these structures are being modified to accommodate the probable maximum flood. One prospective method of modification is to reinforce the slope of the dam with a protection system. Recent and ongoing research indicates this method can, in some cases, provide adequate and economical overtopping protection. Three articles in this issue of Hydro Review *describe results of research on various protection systems and articulate FERC's position on the use of the method.*—M.B.

Overtopping of embankment dams during major flood events can be a viable method for safely conveying large flows. Overtopping essentially means using all or a portion of the dam crest length as an emergency spillway. This technique can be a cost-effective alternative to constructing an auxiliary spillway at dams where increased capacity is needed. However, design engineers and dam safety personnel have had little information to use for predicting the erosive potential of embankment materials or protective systems when subjected to overtopping flow. Today, though, results are available from several recent and ongoing research programs that analyze overtopping flows and embankment protection systems. A review of these results can help dam owners evaluate the capability of either an existing or newly designed embankment dam to withstand overtopping flows. These results can also help owners choose a reliable protection system.

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Based on recent and ongoing overtopping protection research, the Federal Energy Regulatory Commission (FERC) has decided that embankment protection has sufficient merit to allow consideration on a project-specific basis. FERC staff has already approved embankment protection as a solution for inadequate spillway capacity at several hydroelectric projects.

The cost savings at these projects by using embankment dam protection for increasing spillway capacity will amount to several million dollars. For more details, see the article "FERC's Position: Embankment Protection for Increasing Spillway Capacity" on page 52 of this issue.

Evaluating Flow Forces During Embankment Overtopping

Over the years, dam safety inspections have determined that thousands of embankment dams throughout North America have inadequate spillway capacity, and would be overtopped during the Probable Maximum Flood (PMF). Determining whether these embankments can withstand overtopping without failing is complicated. The dam owner must first determine if the compacted embankment material and the dam's contacts with the abutments and foundation will be stable when subjected to the loading associated with the higher reservoir levels. Then, when designing a protection system, the owner must consider both the flow hydraulics and erosion potential of the embankment surface caused by the overtopping flow. The design must take into account the forces imposed on the surface material by flow over the dam crest and brink, down the steeply sloped embankment (an embankment with a slope greater than or equal to 6:1, the ratio of horizontal to vertical slope distance), and if tailwater is present, under the hydraulic jump. (Hydraulic jump is a phenomonen that can occur on the downstream side of the dam when a shallow high velocity flow enters a deep pool of water. This transition zone is quite rough and is characterized, in part, by oscillatory pressure surges.)

Flow Hydraulics Over The Dam Crest

Overtopping flow over an embankment can be viewed as broad-crested weir flow with a sloping approach, where the water is flowing over a wide, flat surface and the upstream face of the dam has a slope. Near parallel flow across the crest occurs when the ratio of reservoir overflow head to crest length in the direction of flow is between 1:3 and 1:12. If the ratio of head to crest length lies within this range, the control point on the

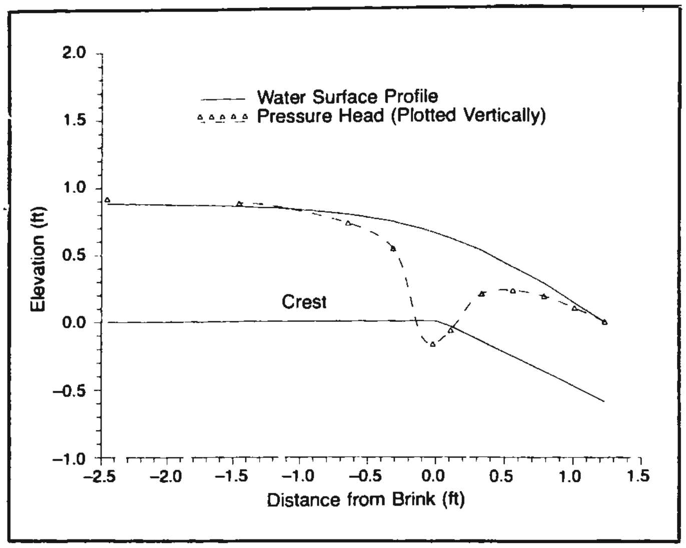


Figure 1: Comparing water surface and pressure head profiles for flow over a 2:1 slope with a unit discharge of 5.6 ft²/s. Pressure measurements by piezometer taps along the crest indicate head decreases gradually from hydrostatic pressure about 1½ feet upstream of the brink, drops rapidly, then returns quickly to the water surface downstream of the brink.

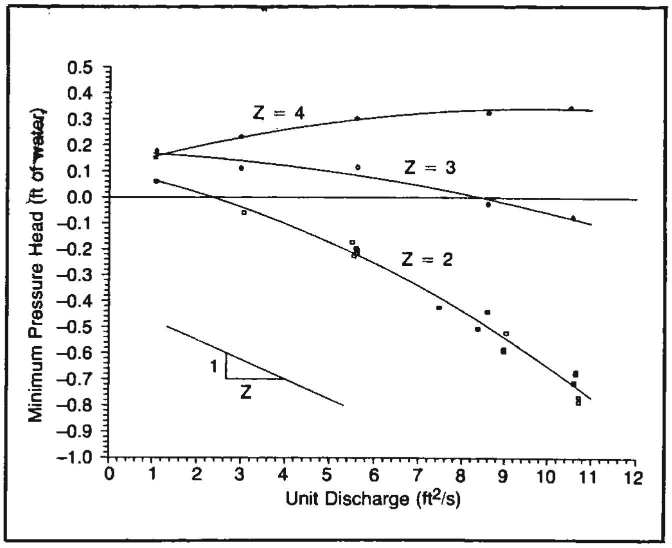


Figure 2: Minimum pressure heads at the crest brink for slopes (Z) of 4:1, 3:1, and 2:1. The minimum pressures for a 4:1 slope are positive and increase with unit discharge. Increasing embankment slope to 3:1 and then 2:1 resulted in marked reductions in brink pressures.

crest, or critical depth, usually occurs in the downstream third or fourth of the crest. Critical depth is the depth that determines the amount of flow that goes over the dam. The location of critical depth varies depending on the roughness of the crest's surface material. From the location of critical depth, the depth and pressure profiles decrease from hydrostatic pressure, and the flow begins curving toward the direction of the slope as it approaches the brink.

Flow Hydraulics Over The Dam Brink

Flow velocities over the crest are relatively low. Therefore, the area just downstream from the brink is often overlooked when determining scour potential. However, investigators have found that erosion often begins just downstream from the brink of the dam.[1,2,3] As a result of this research, the Bureau of Reclamation conducted model studies in 1989 to determine the flow characteristics at the brink of an overtopping dam.

To study brink flow, Reclamation researchers constructed a 3-foot-high, fixed boundary, trapezoidal embankment in a 2-foot-wide rectangular flume. The embankment was built with a 3:1 upstream slope and an 8-foot crest length in the direction of flow. The embankment was tested with three downstream slopes—4:1, 3:1, and 2:1. Unit discharges of up to 11 square feet per second (ft²/s) were passed over the embankment.

The curvilinear flow and the resulting forces were well documented in this study, as shown in Figure 1. These tests have shown that, for the full range of unit discharges and slopes tested, the highest minimum pressures occur within the first ½ foot of the embankment slope.

One way for a dam designer to estimate initial velocities as flow begins down a slope is to identify the ratio of brink depth to critical depth for the slope. (Initial velocities are typically used to compute shear stress. Shear stress is often used to determine the stability of a protection system.) For the slopes being studied by Reclamation, the ratio of brink depth to critical depth for the 4:1, 3:1, and 2:1 slopes averaged 0.729, 0.712, and 0.674, respectively. The decrease in the ratio of brink depth to critical depth as slope increases reflects a rise in the pressure gradient at the brink, as would be expected.[4]

Figure 2 shows the minimum pressures recorded over the full range of unit discharges for each slope.

Even though the extrapolation of these data to higher unit discharges has not been verified, it is apparent that the large pressure gradient at the brink could produce erosion of a compacted embankment or failures of protection schemes. Thus, this area should receive special attention when determining the ability of a dam to withstand overtopping.

Flow Down Embankment Slopes

Flow down embankment slopes has been analytically addressed for many years and by many investigators. The flow characteristics are different depending upon the steepness of the slope. Flow over mild slopes can be described by standard flow equations, given a fairly smooth surface and relatively deep flow. Unfortunately, most embankment dams are not categorized as mild slopes. Therefore, flow characteristics associated with dam overtopping, such as shallow flow over large roughness elements, highly aerated flow, and chute and pool flow, cannot be analyzed using ordinary uniform flow and tractive shear equations.

About eight years ago, the National Park Service discovered that three of its dams, ranging in height from 28 to 40 feet, had to be modified to prevent failure due to overtopping flows. The three unprotected compacted earth embankment dams are located in North Carolina's Blue Ridge Parkway. Under interagency agreement, Reclamation studied how to modify these dams, investigating mechanisms that cause inception of scour, the effect of slope on quantities of scour, and several protection schemes.

In the study, Reclamation tested nine compacted embankments using a 3-foot-wide, 4-foot-high, and 30-foot-long laboratory flume. A linear scale of 1:15 (a scale that reduces all embankment dimensions by 15 and velocities by the square root of 15) was used to

Reclamation's newest laboratory flume facility is being used to develop design criteria for stepped forms of overtopping protection for high embankment dams. The flume is 1.5 feet wide, has Plexiglas walls, and has a variable slope with 15.5 feet of vertical drop. This photograph shows the flume set at a 2:1 slope with a unit discharge of 1.16 ft^2/s and 0.42 feet of overtopping head.

investigate unit discharges of 40 ft^2/s, and 4 feet of overtopping head.[1] Tests of embankment slopes of 6:1 and 4:1 showed a strong effect of slope on embankment scour. The tests indicated five times more embankment volume was eroded from the 4:1 slope than from the 6:1 slope. In both cases, embankment scour started near the top of the embankment just below the crest brink, and progressed down the embankment over time. The study found that if scour did not occur at the brink, it would initiate as soon as there was any change in surface roughness (i.e. downstream of a change in protective materials).

The study also provided an opportunity to physically view the interactions between the flow and erosion mechanisms, and revealed problems inherent to modeling erosion on steep slopes. Reclamation is hoping to develop flow and sediment transport design curves to describe flow down steep rough surfaces. The curves will be based on unit discharge, slope, and aeration effects. To date, the best approach to determine the stability of a steep rough surface is to use design criteria originally developed for sizing riprap. [This approach is described in detail in this article under the section about riprap as a protection system on low head embankment dams.—*Ed.*]

Flow Hydraulics at the Dam Toe

During Reclamation's studies on scour of slopes, a hydraulic jump was not allowed to form on the embankment. Only erosion of the steep compacted embankment was considered. A dam owner's analysis of flow hydraulics must address the impingement of the high velocity jet on the foundation at the toe of the dam if tailwater is not present, and consequently, when a jump will not form on the embankment slope. If tailwater is present on the embankment slope at the toe of the dam, the fluctuating pressures associated with a hydraulic jump must be addressed in the design of the protection system.

If analysis of flow over a compacted embankment indicates the surface is not stable under the PMF, many protection methods may be considered.

Protecting Low Head Embankment Dams

In the last decade, several U.S. government agencies, Great Britain, and the Soviet Union have identified and tested alternatives for overtopping protection of low embankment dams less than 35 feet high. Protection systems tested include: grass linings; riprap; geotextiles and underlying grids; gabions; concrete block revetment systems; and soil cement.

In the various tests, the success and/or failure of these systems were well documented. In many cases, the hydraulic forces imposed on embankment protective materials were not well understood—the embankment protection simply remained stable or failed. In all the studies, failure of the protective systems was similarly defined. Failure occurs for grass-lined channels and geotextiles when the subsoil is exposed and erosion begins. Failure occurs for all the concrete protective systems when there is loss of "intimate contact" between a block, or group of blocks, and the subgrade which they are to protect. This condition results in rapid erosion of the subgrade.

A review of these tests and their results will help embankment dam owners choose the most appropriate systems for overtopping protection. These systems may be applied with considerable confidence up to flow velocities of 25 feet per second, which represents the present limit of testing.

Grass-Lined Channels

The Construction Industry Research and Information Association (CIRIA) in Great Britain and the U.S. Agricultural Research Service in Stillwater, Oklahoma, have both conducted large-scale testing of grass-lined channels. In the mid 1980s, CIRIA contracted with Salford Civil Engineering Laboratory in Salford, Great Britain, to test grass-lined channels. These tests, as well as tests of geotextile systems and concrete block systems with grass cover, were conducted at an old abandoned 35-foot-high embankment dam in Lancashire, known as Jackhouse Dam. This facility consisted of ten trapezoidal channels, each 82 feet long on the upstream face of the dam. Each channel carried unit discharges of up to 10.7 ft^2/s and 2.5 feet of overtopping head, providing measured velocities of up to 26 feet per second.

The results of CIRIA's grass-lined channel testing revealed the grass began showing signs of stress under a discharge of 0.7 ft^2/s after 3 hours, failed under 2.0 ft^2/s after 25 minutes, and failed under 2.5 ft^2/s after 15 minutes.[5] A designer should consider these limitations if investigating grass cover for the downstream face of a dam predicted to overtop.

The U.S. Agricultural Research Service's ongoing study of grass-lined earthen spillway channels uses numerous prototype spillways and three flume facilities for testing. The major flume facility has 12 channels (each 3 feet wide on 20:1 slopes) and has been tested for unit discharges ranging from 7 to 20 ft^2/s for up to 275 hours.

Through its testing, the Agricultural Research Service has developed basic guidelines for predicting the life of grass-lined spillways. Grass root systems should be a minimum of 1 foot deep, and the grass should be dense with minimal irregularities. Irregularities in the grass cover can greatly increase the erosion potential of the surface. The service has developed an allowable tractive shear stress design procedure, and research is continuing with its flume facilities.[6,7]

Riprap

Traditionally, riprap has been placed on the downstream face of a dam simply to protect the structure from erosion during heavy rainstorms. Such riprap protection is normally inadequate to ensure the safety of an embankment dam during overtopping. Reclamation's study of erosion scour on low embankment dams showed that riprap, scaled to represent 6- to 24-inch-diameter rock, was suspended in the flow and washed downstream under the scaled unit discharge of 40 ft^2/s. Extensive analyzes also determined that standard flow equations do not apply to shallow flow over riprap.[1] However, some analytical method is needed to determine if normal riprap protection is adequate. Several investigators have conducted experimental studies to determine riprap stability on steep slopes when subjected to overtopping flow.[8] Although prototype verification in this area is limited, empirically derived design criteria, such as presented by I. Knauss at the International Commission On Large Dams' 13th Congress in 1979, currently offer the best approach.[9]

In his approach, Knauss developed a rock stability function for sizing riprap based on unit discharge, slope, rock packing, and air concentration. The use of unit discharge simplifies the analysis because it eliminates the need to estimate friction factor values. In a more traditional approach, friction factors are generally needed to determine velocity or tractive shear forces on the slope but are hard to estimate. In addition, Knauss determined that aerating the flow increases the critical velocity for which riprap on a steep slope remains stable. Thus, accounting for the effect of air concentration in the flow decreases the rock size required for a slope to remain stable during overtopping flows.

To verify Knauss' design curves, it is still necessary to obtain data from prototype overtopping events that produced both stable and unstable riprap conditions. To help with this verification, Reclamation is currently planning construction of a large research facility with prototype size rock. Testing of this facility should begin this fall, and will allow investigation of riprap stability on a 50-foot-high embankment with 2:1 slope and unit discharges up to approximately 40 ft^2/s. The results from this work will help dam safety inspectors analyze the capability of the many existing dams with downstream riprap protection to withstand overtopping.

Geotextiles and Underlying Grids

Salford Engineering Laboratory, under the direction of CIRIA, tested four geotextiles. The geotextiles were tested at Jackhouse Dam under a good growth of grass that had been maintained for 20 months. All of the geotextiles performed better than the grass-lined channel alone; however, all were eventually tested to failure.[5]

Simons, Li & Associates (SLA), under contract to several U.S. government agencies during the 1980s, conducted testing of various protection systems (including geotextiles and underlying grids) at an outdoor test facility in Fort Collins, Colorado. This facility was a large-scale flume, 90 feet long, 11 feet high, and 4 feet wide. The flume contained a 6-foot-high compacted soil embankment with a crest length of 20 feet (in the direction of flow) and downstream embankment slopes ranging from 2:1 to 4:1. All the systems studied were tested to failure or for four hours at unit discharges up to 25 ft^2/s. The maximum unit discharge produced 4 feet of overtopping head with maximum velocities of 22 feet per second measured at the embankment toe. [For a detailed description of this research, see the article "Protecting Embankment Dams with Concrete Block Systems" by Paul Clopper in this issue.—*Ed.*]

Two of the systems SLA tested were the geotextile Enkamat (both with and without various cover materials) and Geoweb, an underlying grided blanket filled with gravel. Both systems failed either due to poor anchorage or stretching of the underlying material.[2]

Gabions

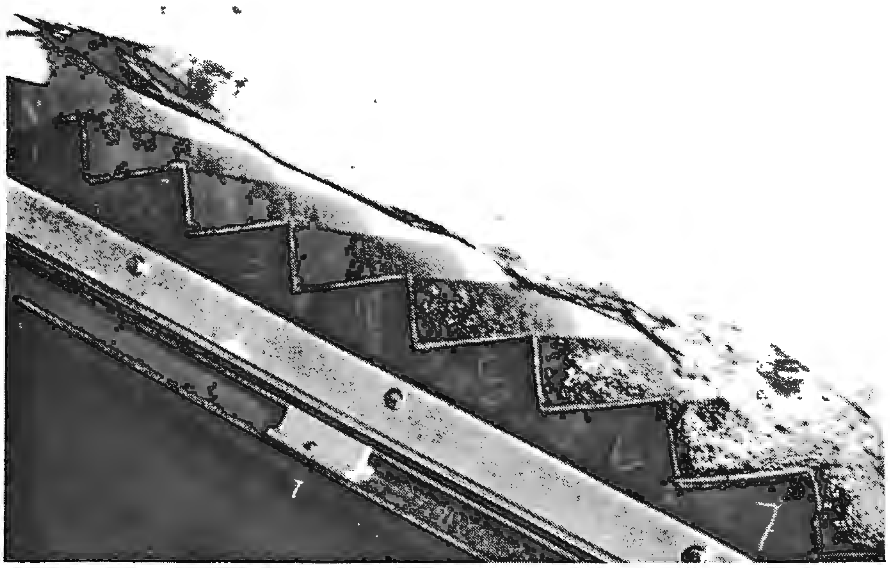
In its small-scale laboratory flume, Reclamation tested thick gabion mattresses filled with 12-inch (geometrically scaled) angular rock over compacted soil embankments. SLA conducted larger scale tests of thinner gabion mattresses with 6-inch angular rock in its outdoor flume. In general, the gabion mattresses performed well. Some deformation occurred as the rock moved toward the downstream end of the thicker mattresses. Migration of rock in the thinner mattresses exposed fabric filter material. The only failures that occurred with the thinner gabion mattresses were due to loss of anchorage on the crest. The tests showed that gabion mattresses need to cover the entire slope to prevent scour of the embankment material due to the change in the surface roughness from the gabion mattress to the downstream embankment material. Gabion mattresses have not been tested at velocities greater than 24 feet per second.[1,2]

Concrete Block Revetment Systems

In its large outdoor flume facility, SLA tested at least five concrete block systems: three cable-tied systems (Armorflex, Petraflex, and Dycel) and two non-cabled systems (concrete construction blocks and wedge-shaped blocks). In the tests, four of the five systems performed adequately at the maximum discharge capacity of the test facility.[3] [For details on the results, see the article beginning on page 54 of this issue.—*Ed.*]

CIRIA funded research on four cable-tied concrete block protection systems (Dycel, Petraflex, Armorflex, and Dymex) at the Salford Civil Engineering Laboratory's Jackhouse Dam facility. Tests of the four block systems showed slightly greater stability of the block systems with a well established grass growth within the block matrices. These block systems were tested with velocities up to 26 feet per second.[5]

The wedge-shaped concrete block was developed in the 1970s by Professor Yuri Pravdivets of the Moscow Institute of Civil Engineering in the Soviet Union. Wedge blocks have been used in the Soviet Union for overtopping protection of cofferdams, and as service or emergency spillways for several embankment dams. The work conducted on the wedge-shaped blocks



In Reclamation's ongoing study of overtopping protection for high head embankment dams, the flow over horizontal steps on a 2:1 slope just below the crest is being analyzed. In the research flume, flow tumbles down the steps just below the crest. When the flow hits the step tread, it either continues downstream or splits off and forms a "roller" above the steps. A recirculating "roller" may be seen in the air bubbles above Step 7.

in the Soviet Union has been accomplished both in small-scale laboratory flumes and on prototype structures. The blocks, up to 2.3 feet thick, have been tested on prototype structures with slopes as steep as 6.5:1 and unit discharges up to 645 ft^2/s with great success.[10]

The most comprehensive study on wedge-shaped blocks being conducted in the West is at Salford Civil Engineering Laboratory. The indoor flume is about 13 feet high on a 2.5:1 slope with unit discharge capability of about 5.4 ft^2/s. By funding this research, CIRIA hopes to develop design guidelines for using wedge-shaped blocks as a protection system for low embankment dams.[10]

SLA's testing of the wedge-shaped blocks with a 6-foot-high embankment has shown agreement with previous findings in the Soviet Union and Great Britain.

Soil Cement

During its years of research, SLA found that the most stable method for dam protection during overtopping was soil cement. It showed no signs of failure up to the maximum unit discharge of 25 ft^2/s and overtopping head of 4 feet. Roller compacted concrete (RCC), a type of concrete similar to but typically stronger than soil cement, would be expected to protect even better than soil cement.

Results from research on various protection systems indicate that low embankment dams can be adequately protected, provided the correct system is chosen. Many systems have been tested, designed, and constructed—with hydraulic performance and cost determining the system of protection chosen. With the success of protection systems for low embankment dams has come the need to further extend this knowledge for application on higher embankments (100 feet high or higher) with velocities that produce greater risks for failure.

Protecting High Head Embankment Dams

Protection schemes for high embankment dams need more detailed analysis than systems for lower structures. Data from low embankment dam studies cannot be extrapolated with confidence to the higher unit discharges or velocities expected with higher dams. Therefore, Reclamation's current research effort, with funding assistance from the Electric Power Research Institute, is focusing on development of design guidelines for overtopping protection of high embankment dams. This effort should lead to standardization of design guidelines, possibly associating success and/or failure with unit discharge capabilities of the systems.

Reclamation has several embankment dams over 150 feet high that are currently under consideration for overtopping at depths of up to 25 feet. One option being studied to protect the embankments is a stepped concrete overlay. Continuously placed concrete overlays with flat step treads are easy to construct and produce excellent energy dissipation.[11,12] Studies of the individual wedge-shaped blocks on low dams have shown that a negative pressure zone develops in a protected area on the tread that allows aspiration of subgrade seepage. Reclamation's goal is to apply the wedge block shape to a continuously placed RCC or reinforced concrete stepped spillway, and thus optimize the step geometry to enhance underdrainage and maximize energy dissipation.

A research facility has been constructed in Reclamation's hydraulic laboratory to develop design criteria for these stepped forms of overtopping protection. The test facility includes a 1.5-foot-wide Plexiglas walled, variable sloping flume with 15.5 feet of vertical drop. The entrance is formed by ellipses on both sides of a broad crest (discharge coefficient equals 3.0). Model overtopping heads up to 2.8 feet can be studied. The flume can be used for unit discharges up to 14 ft^2/s. Tailwater depths of up to 5 feet can be developed at the toe of the flume.

The model scale may be chosen to accommodate any site-specific study. Reclamation is using a linear scale of 1:12 (a scale that reduces all embankment dimensions by 12 and velocities by the square root of 12) for its current study. Data being collected include pressure profiles on the steps, flow depth, location of inception of surface aeration, and velocity profiles measured along the slope for various unit discharges.

Initially, Reclamation is investigating steps with horizontal treads and scaled 2-foot heights on a 2:1 slope (typically the standard geometry for RCC construction techniques). Overtopping flow tumbles over the steps, hitting on the step tread. Then, the flow either continues downstream or splits off and forms a "roller" in the separation zone below the pitch line of the steps. The pitch line is an invisible line that runs parallel to the slope from tip to tip of each step. The separation zone, or offset area, on each step below the pitch line is protected by the next step upstream. With a horizontal step tread, the offset area is one of reduced pressure, although still above atmospheric pressure, because of the presence of a strong upstream component of the impinging jet that forms the "roller."

Reclamation researchers measured pressures on the horizontal steps at three locations down the slope—steps 15 and 16, steps 47 and 48, and steps 79 and 80. They measured mean pressures on both the vertical and horizontal faces of the steps with 22 piezometer taps covering two steps at each location. The resulting pressure profiles clearly indicate the jet impingement on the downstream end of the step tread and the separation zone that forms in the offset area below the pitch line of the steps. Reclamation is using laser equipment to gather velocity data from the crest down the embankment slope. So far, velocities can be measured about 50 steps down the slope. Further down the slope, there is too much reflection from the air bubbles in the flow to use the laser.

Using the pressure and velocity data as a base line for comparison, Reclamation will incorporate the hydraulic characteristics of the wedge block shape to enhance the aspiration of subgrade seepage. By sloping the step tread downward, similar to the wedge block design, the strength of the upstream "roller" jet can be reduced. This action will produce negative levels in the separation zone below the pitch line. This design will produce aspiration of seepage from underneath the protective overlay, and will not allow water to flow into the embankment where concrete cracking is most likely to occur.

Research Leads to Practical Application

As a result of ongoing research, information on the performance of several types of materials to use to protect embankments from erosion due to overtopping floods is available. Dam owners can use this performance data to select a reliable overtopping protection system for their dams. Some block-type revetment systems have proven reliable for protecting low embankments subjected to small overtopping heads, and many embankment dams have been protected with either soil cement or RCC.

FERC recently approved the use of RCC for protection of the embankment dam at Southern California Edison's Bishop Creek #2 hydroelectric plant. As a result of FERC's acceptance of RCC for overtopping protection to add spillway capacity, the utility saved $500,000.

Protective systems for high embankment structures currently favor using RCC or slip-formed stepped or smooth concrete deck overlays. Reclamation's near-prototype research program, continuing for the next four years, will extend the present data base for low embankment dams while providing information on scale effects of aeration and dynamic forces associated with high embankment dam protection schemes. This research should provide the confidence needed to apply overtopping protection to high head embankment dams. Reclamation's first such effort is with the Arthur R. Bowman Dam in central Oregon, 20 miles south of Prineville. The 159-foot-high rockfill structure was built in the 1960s to form the Prineville Reservoir, which is used for water supply, irrigation, and recreation. The dam's uncontrolled ogee crest spillway is only 20 feet wide and can pass a maximum discharge of 11,500 cubic feet per second (ft^3/s). The new PMF estimate of inflow of 268,000 ft^3/s obviously makes the old spillway inadequate. Reclamation is designing a 1-foot-thick, slip-formed smooth concrete deck overtopping protection scheme for the dam. The final design for the deck is due later this year, and the construction contract subsequently will be awarded.

Results of several research programs in the last ten years indicate dam owners can safely protect their embankment structures from overtopping flow with a variety of protection schemes. Overtopping protection is a cost-effective technique for safely conveying large flows over dams, and as more successful applications are made, the method will become more widely accepted. ☐

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