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PROTECTING EMBANKMENT DAMS SUBJECT TO OVERTOPPING DURING MAJOR FLOOD EVENTS

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ABSTRACT

Designers and dam safety personnel have little information available to predict the stability of embankment materials or protective systems when subjected to overtopping flow. Results from past and current Reclamation cooperative overtopping studies are presented. Hydraulics of flow near the crest brink and on steep embankments are discussed. Tests of embankment protection systems are covered for both low and high head structures.

INTRODUCTION

During recent years Reclamation has determined that many existing embankment dams need to be equipped with additional spillway capacity for large flows during rare flood events. A cost-effective alternative to constructing an auxiliary spillway is to use all or a portion of the dam width as an emergency spillway. Reclamation and Electric Power Research Institute (EPRI) are currently co-sponsoring research to develop design guidelines for overtopping protection of embankment dams.

FLOW DOWN STEEP EMBANKMENTS

Designing for flow down embankments must include considerations of both flow hydraulics and erosion of the embankment surface. We must know the forces imposed on the surface material by flow over the crest brink, down the embankment and, if tailwater is present, under a hydraulic jump.

The effects of slope on scour of earth embankments was investigated by Dodge [1988]. Tests of embankment slopes of 6:1 (ratio of horizontal to vertical slope distance) and 4:1 show a strong effect of slope on embankment scour. Of particular interest is the location of the inception of scour. Embankment scour started near the top of the embankment just below the crest brink. Although the scour progressed down the embankment over time, major scour damage occurred on the upper one half of the embankment. This area is often overlooked when determining scour potential as flow velocities are lower than at the embankment toe. It should be

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noted that during these tests a hydraulic jump was not allowed to form on the embankment. To prevent scour from starting, tests of concrete deck and rock gabion inlays at the brink were also conducted. In each case, heavy scour of the embankment material occurred immediately below the protective inlay. These results verified the need to further investigate the hydraulic forces imposed due to curvilinear flow over the crest brink.

Crest and Brink Flow

A 3 ft high fixed boundary trapezoidal embankment was constructed in a 2 ft wide rectangular flume to study brink flow. The embankment was built with a 3:1 upstream slope and a crest length of 8 feet. The embankment was tested with three downstream slopes 4:1, 3:1, and 2:1. Unit discharges up to 11 ft^3/s-ft were passed over the model embankment. Water surface profiles, embankment surface pressures and average velocities were measured.

Overtopping an embankment can be viewed as broad crested weir flow. Flow passes through critical depth on the crest. On a horizontal crest the location of critical depth is a function of boundary roughness. Between the location of critical depth and the brink, the pressure head on the embankment decreases from hydrostatic, changing rapidly just upstream of the brink, figure 1.

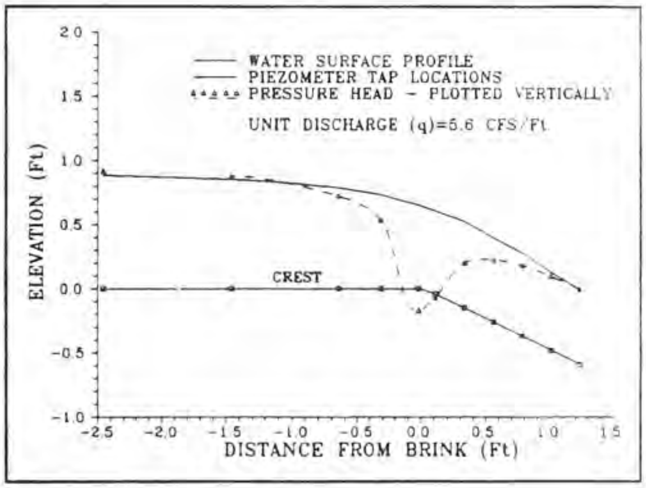

Figure 1. Comparison of Water Surface and Pressure Profiles for a 2:1 Slope.

The ratio of brink depth to critical depth for the slopes 4:1, 3:1, and 2:1 averaged 0.729, 0.712, and 0.674, respectively. The decrease in this ratio with slope reflects an increase in the pressure gradient at the brink. It is interesting that the brink ratio for the 3:1 slope is nearly equal to that of a free vertical drop as given by Rouse [1950].

The minimum pressure head location caused by the brink all occurred within the first 0.50 ft of the embankment slope. Minimum pressure head measurements as a function of unit discharge are given in figure 2. 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 results in marked reductions in brink pressures. For a 2:1 slope the minimum pressure developed drops sharply, becoming negative for unit discharges greater than 2 ft^3/s-ft.

Embankment Flow

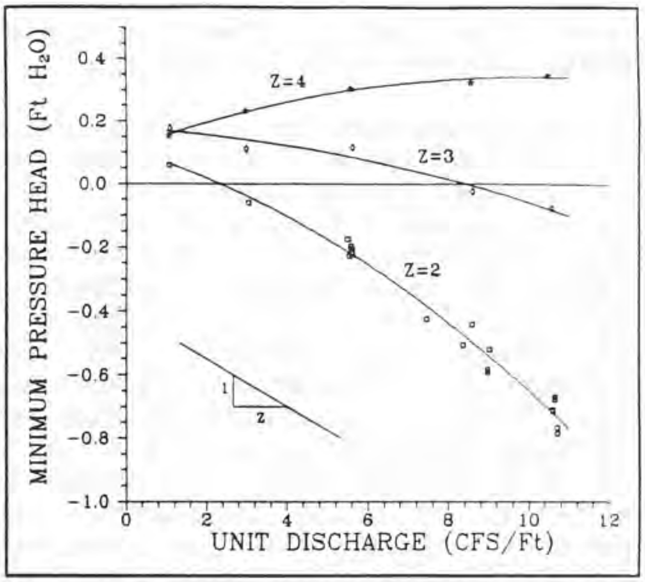

Figure 2. Minimum Pressure Heads Developed at the Crest Brink.

Flow down steep embankments can not be analyzed with standard flow equations. Ordinary uniform flow and tractive shear equations do not apply to shallow flow over large roughness elements, highly aerated flow, nor to chute and pool flow, all of which can occur during overtopping of steep embankments. Several investigators have conducted experimental studies to investigate riprap stability on steep slopes when subjected to flow. Although prototype verification in this area is limited, empirically derived design criteria such as presented by Knauss [1979] currently offers the best approach.

Knauss developed a rock stability function based on unit discharge, slope, rock packing, and air concentration for sizing rock riprap. Using unit discharge eliminates estimating friction factor values needed to determine velocity or tractive shear forces on the slope. Knauss determined that aeration of 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 to remain stable during overtopping flows.

If analysis indicates that embankment riprap is not stable under the design overtopping flow there are many revetment alternatives that can be considered. These are usually divided into those designed for low head and high head structures. Again, in many cases, the hydraulic forces imposed on embankment revetment materials are not well documented.

PROTECTING LOW HEAD EMBANKMENTS

Since 1986 the Bureau of Reclamation has co-sponsored a research program conducted by Simons, Li & Associates Inc. (SLA) at Fort Collins, Colorado. This research resulted in three reports covering embankment erosion, and hydraulic performance of erosion protection systems for steep earthen embankments, Chen [1986], Clopper [1988,1989]. The outdoor test facility included a 90 ft long, 11 ft high, 4 ft wide flume. Water was pumped from a small pond and recirculated via a rock-lined return flow channel. Compacted soil embankments 6 ft high with a crest length of 20 feet were constructed. Test sections had downstream embankment slopes which ranged from 2:1 to 4:1.

Various protection systems were installed along the crest and downstream embankment slope and tested for a range of unit discharges up to 25 ft^3/s-ft. The maximum discharge produced 4 ft of overtopping head with maximum velocities of 22 ft/s measured at the embankment toe. The study included the testing of several types of interlocking concrete block systems. A total of five systems were tested: three cable-tied systems (Armorflex, Petraflex, and Dycel) and two non-cabled systems (concrete construction blocks and wedge shaped blocks). All of these systems were tested to failure or for four hours at the maximum hydraulic loading associated with 4 ft of overtopping head. The definition of failure for these tests was: Loss of "intimate contact" between a block, or group of blocks, and the subgrade which they are to protect. This condition resulted in rapid erosion of the subgrade as the blocks were shifted or washed downstream.

The results of SLA's tests indicated that block system selection and installation are important when protecting embankments from erosion due to small overtopping floods. The study reports contain information concerning detailed system performance, system installation procedures, and design guidelines.

The United Kingdom's Construction Industry Research and Information Association (CIRIA) have also conducted research on various embankment protection systems, Hewlett [1987], including a thorough study on the wedge shaped block, Bramley [1989], figure 3.

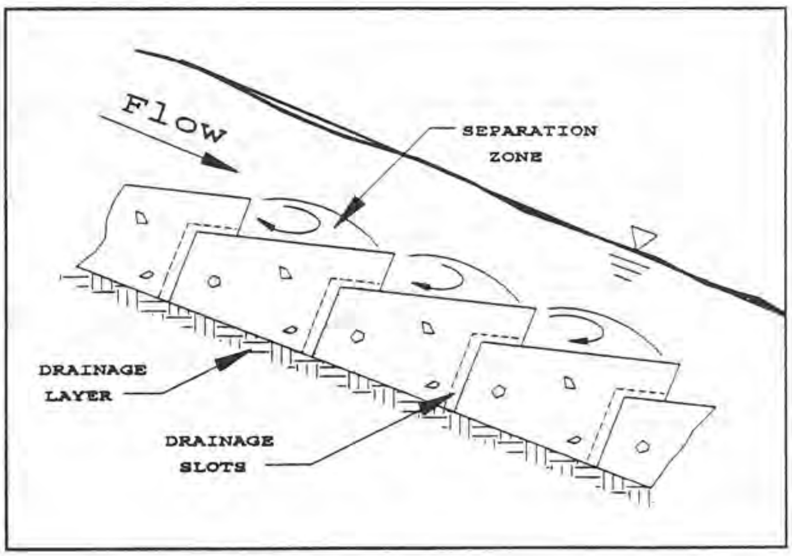

Figure 3. Typical Profile of Wedge Shaped Block System.

Wedge Shaped Blocks

The wedge shaped block was developed in the USSR by Professor Yuri Pravdivets of the Moscow Institute of Civil Engineering. Wedge blocks have been utilized in the USSR for overtopping protection of cofferdams, and as main or emergency spillways for several embankment dams, Pravdivets [1989]. They are designed to take advantage of the flow hydraulics with three key features:

- The upstream face is protected from stagnation pressures which tend to lift or rotate the block. The overlapping design creates a stable protective blanket which is enhanced by hydrodynamic forces.

- Flow over the block's downstream edge causes a low pressure separation region. This region is connected by drainage slots to the base of the block. The pressure differential across the upstream portion of the block thus provides active removal of excess seepage from the underlying drainage layer. This can minimize the erosion and saturation of the embankment material.

- The stepped configuration causes high energy dissipation and a reduced flow velocity, thereby reducing the energy to be dissipated at the toe of the embankment.

PROTECTING HIGH HEAD EMBANKMENTS

Reclamation has several 150+ foot high embankment dams that are currently under consideration for overtopping at depths up to 25 feet. One option being studied to protect the embankments is a stepped concrete overlay. The stepped overtopping protection alternative has many advantages. Wedge block studies have shown aspiration subgrade seepage for low head structures; however, block stability under the action of a hydraulic jump is questionable. Applying the wedge block shape to a continuously placed RCC or reinforced concrete step shows great promise for allowing continuous aspiration of subgrade seepage through the face of the overlay below the pitch line of the step. Concrete cracking is most likely to occur in this offset area below the pitch line. In the presence of a negative pressure zone, cracks will not lead to undesirable seepage through the overlay. The primary purpose of the stepped overlay studies is to optimize the step geometry with two main objectives: enhancing under drainage and maximizing the energy dissipation capability of the step design.

Research on Stepped Concrete Overlays

A research facility has been constructed in Reclamation's hydraulic laboratory to develop design criteria for stepped forms of overtopping protection for high embankment dams, including roller compacted concrete (RCC) and slip-formed concrete. The test facility includes a 1.5 ft wide plexiglas walled variable sloping flume with 15.5 ft of vertical drop. The entrance is formed by ellipses on either side of a broad crest (discharge coefficient = 3.0). Model overtopping heads up to 2.8 ft can be studied. The flume may be used for unit discharges up to 14 ft^3/s-ft. Tailwater depths up to 5 ft can be developed at the toe of the flume. The model scale may be chosen to accommodate any site specific study. A Froude scale of 1:12 is being used as a basis of the research study on high embankment dams. Data collection includes: unit discharge, pressure profiles on the steps, flow depth, location of inception of surface aeration, and velocity profiles measured along the slope.

Initially, steps with horizontal treads on a 2:1 embankment slope are being investigated. At three locations mean pressures are measured on both the vertical and horizontal faces of the steps using 22 piezometer taps covering two steps. As illustrated in figure 4 for the case of 25 ft of overtopping head, the measured pressures indicate the jet impact on the downstream end of the step tread. A separation zone forms in the offset below the pitch line of the steps. This is an area of reduced pressure, although still above atmospheric pressure due to the presence of a strong upstream component of the impacting jet. By sloping the step tread downward, similar to the wedge block design, the strength of the upstream jet component and thus the pressure in the separation zone can be reduced to negative levels.

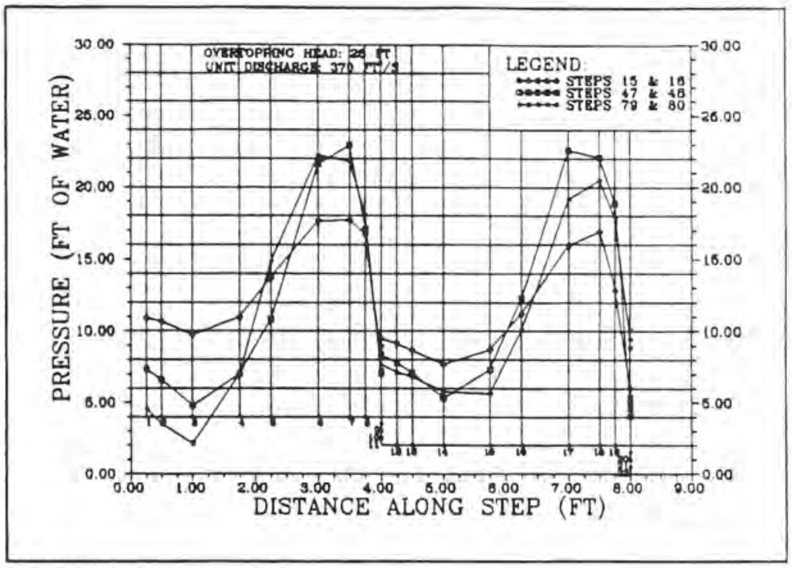

Figure 4. Pressure Head Profiles Plotted Vertically for 2:1 Slope.

To determine how sloping the step tread affects energy dissipation of the flow, velocity profiles normal to the slope are being measured with a laser velocimeter. Velocity profiles are being measured from the crest down the embankment slope until flow aeration prohibits the laser's use. This data will allow for general design guidelines to be developed for both subgrade aspiration and energy dissipation.

SUMMARY

As a result of ongoing research, overtopping of embankment dams during major flood events is becoming a viable alternative for safely conveying large flood flows. Design of overtopping protection must include consideration of crest brink hydraulics, flow down steep slopes, large boundary roughness effects and tailwater conditions. Some block type revetment systems have proven reliable for small overtopping heads on low embankments. But as yet, sufficient prototype scale testing has not occurred to allow this data to be extrapolated to higher unit discharges or velocities with confidence. Protective systems for high head structures currently favor utilizing RCC or slip-formed concrete overlays.

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