Embankment Overtopping Protection - Concrete Blocks or Riprap

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Abstract

The U.S. Bureau of Reclamation (Reclamation), in conjunction with EPRI (Electric Power Research Institute), and CSU (Colorado State University), has completed a 4-year research study on concrete step overlay protection for embankment dams. The stepped overlay, formed of individual blocks, was successfully tested in a large outdoor facility at CSU in Fort Collins, Colorado. The range of applicability of the block system and design guidelines will be presented for a wide range of dam heights and overtopping flows. Dam overtopping tests in the outdoor facility have been extended to determine stability of large riprap subjected to overtopping flows. Comparisons of initial riprap test results will be made to accepted riprap stability formulae and to the stepped block overlay system.

Introduction

The purpose of conducting large scale tests of overtopping protection methods is to fully verify the performance of stepped overlays and large size riprap and to develop design criteria. Test results from the large-scale facility show that the block system developed from the laboratory data is stable allowing the results to be applied to an actual embankment dam with confidence. Initial testing of large size riprap has been completed in the same facility after maximizing the facility width. Initial riprap results show less stability than predicted with available design criteria. Applicability of the stepped overlay and riprap for embankment dam protection during overtopping will be discussed.

Overtopping Facility and Test Materials

An overtopping facility, sized to be similar in height to a typical embankment dam in need of rehabilitation, was constructed at CSU for testing dam overtopping protection schemes. The concrete flume facility, on a 2:1 (H:V) slope, is 15.2-m-high, with a variable width up to 3.05 m. The facility is capable of passing a total discharge of 4.5 $m^3/s/m$. The overtopping facility has been used for testing overlapping, tapered, concrete blocks and large-size riprap.

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The tapered blocks were 0.375-m-long with a 0.0635-m-high step and a maximum thickness of 0.114 m. Drains, which aspirate water from the underlying filter layer, were formed in the overlapped portion of the block. A combination of 0.61-m-wide and 0.305-m-wide blocks was placed shingle-fashion over 0.152 m of free-draining, angular gravel filter material up from the slope toe. Further description of the blocks and the facility is given in Frizell and Ruff, 1994.

Riprap and bedding were placed in the 3.05-m-wide flume to a total depth of 81 cm, after completion of the block tests. The riprap extended from the crest to about the middle of the flume, a distance of 18 m with a change in elevation of about 9 m. Structural steel angles were bolted to the concrete flume floor to prevent sliding along the slope during placement of the bedding material. The riprap was supported at the end with a flow-through metal and wire frame. The bedding material was a graded gravel material 19 to 76 mm in size with D_{50} = 38 mm and placed to a depth of 20 cm. Graded riprap with stone sizes from 10 to 66 cm with D_{50} = 38 cm was placed over the bedding in a layer 61-cm thick. Riprap gradation was determined by randomly placing a rectangular grid on the pile before placement and on the slope after placement. The three axes of each stone within the grid were measured and an equivalent spherical diameter calculated for each rock.

Tapered Block System Results

The block system remained stable and performance was excellent, with a maximum settlement of 2.54 cm, after two seasons of testing and two winters of freezing conditions. Failure occurred only after a block was artificially pried out of place. Test discharges produced varied flow conditions over the blocks. Very small flows were almost entirely broken up by the block shape producing a tumbling, highly-aerated flow condition. As the discharge increased, skimming flow occurred. Uniform flow was attained for all flow rates tested.

Block design criteria - Model/prototype comparisons, between the laboratory and the outdoor facility, are complete. These results were used to develop general design guidelines that provide the necessary information to design a stepped overlay for embankment dams with downstream slopes of about 2:1 and a 15° block top slope (Frizell, 1994). Briefly, the design guidelines are:

- A discharge coefficient of 1.6 for a typical embankment dam crest should be used for flood routings.

- The block shape is determined by consideration of the stability and energy dissipation requirements for a given dam slope. A block with a 15° top slope is the most stable on a 2:1 slope. The block design is based upon keeping the difference between the block top slope and the embankment slope constant for a given embankment slope. Also, the ratio of the step height to the tread length exposed to the flow should be between four and six. The vertical block face area occupied by the vent port area should be about 2.8 percent (Baker,1991).

- The stability of the block system has been analyzed as a function of the total forces acting on individual blocks down the slope with a net positive force indicating a stable block. The stability of the block system is quantified in figure 1 and includes no block weight or additional stability provided by the block overlap. The submerged block weight of about 5.9 kg has been added to the forces in the curve formed by the dashed line for D_c/H_s = 10.36 to show the additional stability added by a block of minimal, 5-cm thickness. The designer may increase the block weight to provide a stable overlay if excessive seepage is predicted.

• The velocity at the dam toe may be determined for any step height and dam height for use in designing toe protection. Figure 2 allows the designer to vary the step height, for a dam of a given height and known unit discharge, to directly determine the velocity at the toe of the dam as a function of the energy remaining.

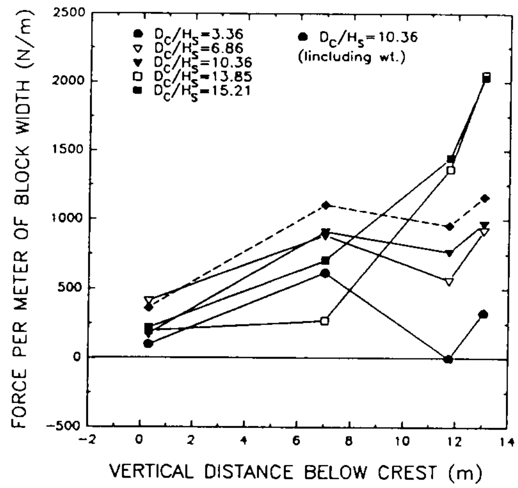

Figure 1. - Block stability diagram. (D_c/H_s=critical depth/step height)

• A Darcy-Weisbach friction factor of 0.11 (Manning's n=0.03) due to step roughness down the slope should be used with the bulked flow depth for designing wall heights. Using this value in a standard step method calculation will determine the nonaerated flow depths down the chute. The wall heights should be raised by 39 percent (average air concentration) above the calculated flow depths for the bulked depth.

• The blocks should be pinned to restrict rotation caused by the dynamic pressure fluctuations of the jump if the tailwater elevation and velocities indicate that a hydraulic jump will occur over the blocks.

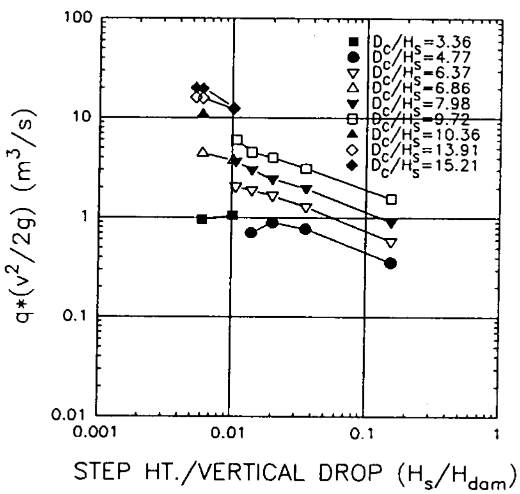

Figure 2. - Flow velocity at the dam toe of a stepped spillway with 15° tapered blocks on a 2:1 slope.

<u>Riprap Test Results</u>

Testing of riprap on steep slopes in the outdoor facility at CSU began in 1994. Flow conditions were observed through side windows and from the surface. Flow through the riprap and bedding contained entrained air, and pockets of trapped air were evident behind many rocks. For flows less than 0.09 $m^3/s/m$, water did not reach the top surface of the riprap layer. For flows up to about 0.15 $m^3/s/m$, water was observed intermittently coming out of the riprap, cascading over a short section of the slope and then disappearing back into the riprap matrix. As the discharge increased to about 0.20 $m^3/s/m$, the entire surface was covered with a highly-aerated, cascading flow. Even though it appeared from visual observations that a considerable amount of water was cascading over the top of the riprap layer, the flow over the surface never completely inundated the riprap matrix and large air voids were observed behind and surrounding the surface rocks.

Instrumentation and measurements - Prior to placement of the bedding and riprap, instrumentation to measure water depth, interstitial flow velocities, and pressure heads within the riprap matrix were installed normal to the slope at three stations, numbered 1-3 down the slope. Conductivity probes were calibrated and used to give a voltage proportional to the depth. Piezometer taps, at five elevations in a tower at each station, were attached to manometer boards and used to measure pressure heads. Interstitial velocities were determined by recording the time of travel of an injected salt tracer between three detector probes located downstream. The first probe was located 0.45 m downstream from the injector, the second 1.37 m, and the third probe 3.20 m downstream. The salt tracer could be injected and subsequently detected at three different levels, 41, 61, and 81 cm perpendicular to the floor of the flume within the riprap matrix, at all three data collection stations.

Tests were conducted for discharges ranging from about 0.05 $m^3/s/m$ to 0.22 $m^3/s/m$. Each increase in discharge was conducted slowly to prevent a surge of water into the riprap before achieving the test discharge. For all tests, the head over the crest, the pressure head readings on the manometers, the flow depths along the slope, and the data for computing interstitial velocities were recorded.

The salt tracer was injected into the flow and the time of travel between downstream probes located in a line parallel to the direction of flow was recorded to determine interstitial velocities. Figure 4 shows the interstitial velocities determined at the three stations based upon data from the detector at the lowest level in the riprap. Interstitial velocities calculated between probes 1 and 3 showed some scatter, but the majority were within a range from about 0.2 to 0.6 m/s and did not show a consistent trend with varying unit discharge.

Pressure readings indicated that the flow depth in the riprap never reached the surface and was about 3 to 7 cm below the top of the riprap even at the highest discharges tested. The piezometer tap located at the surface never indicated a reading, even though highly-aerated flow appeared to be covering the rock surface.

Preliminary air concentration measurements were obtained at a flow rate of 0.14 $m^3/s/m$. Average air concentrations ranged from about 5 to 15 percent in the lower 50 cm of the riprap layer and was a function of trapped air bubbles. Near the flow surface, but below the rock surface, the concentration varied but was usually between 20 to 40 percent.

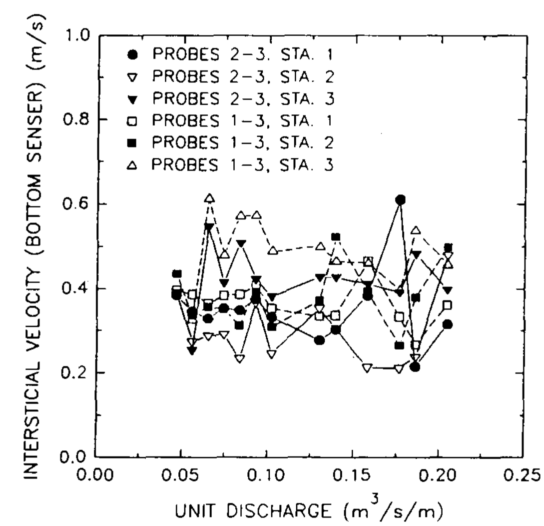

Figure 3. Typical interstitial flow velocities.

Riprap was dislodged from the matrix at a discharge of 0.22 $m^3/s/m$ and two bowl-shaped holes formed about 15.2 m downstream from the crest along the slope exposing the bedding material. This condition was considered to be failure of the riprap.

Summary and Conclusions

The dam overtopping research program and flume facility have provided the opportunity to perform large-scale tests of various embankment dam overtopping protective measures. The block system and large riprap tests have extended the knowledge about these two types of systems.

The block system has been tested well beyond the limits of other concrete revetment systems. The design criteria presented define their application for a wide range of overtopping flows that far exceed the capability of most other revetment systems. Data, for the remaining step shapes (10° and horizontal) on 2:1 and 4:1 embankment slopes tested, are being reanalyzed to include the results from the large-scale facility. These results will allow development of generalized design criteria for embankment slopes from 2:1 to 4:1 and extrapolation up to larger unit discharges.

The initial riprap tests, with D_{50} = 38 cm placed on a 26.6° slope, far exceed available test data used to develop current riprap stability guidelines. Substantial movement of the riprap and failure occurred at a unit discharge of 0.22 $m^3/s/m$. Prior to failure, the flow over the riprap surface was highly aerated and the interstitial flow condition prevailed. Many people have investigated riprap stability with small scale tests and proposed empirical relationships to determine stable rock size for specific sites. Most work has not specifically dealt with flow overtopping riprap on slopes and at unit discharge as great as this study. Stephenson's (1979) and Abt's (1988) equations were both based upon initiation of D_{50} rock movement on steep slopes for a given unit discharge. The point of failure of the tested riprap was compared to these two methods that predict stone sizes and are compared in the following table.

Method	Predicted D_{50} rock size (cm)
Stephenson	61
Present study	38
Abt, Ruff, Wittler	16

Neither equation accurately predicted the test results. This study provides only one measured point for comparison and additional tests are currently underway.

Comparison of tapered blocks to riprap reveals that the block system clearly out performs the placement of riprap on very steep slopes. The block system became more stable with increasing discharge and had to have blocks removed before the system would fail. Before allowing a dam covered with riprap to be overtopped more large-scale testing should be completed; however, the block system has been proven.

References

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