# ACCOMMODATING RARE FLOODS OVER EMBANKMENTS AND STEEP REINFORCED CHANNELS - RECENT DEVELOPMENTS

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## SYNOPSIS

Based on research and case history data available from the United States (US) and the United Kingdom (UK) engineers can now feel confident in the design of overflow protection for low embankment dams. The introduction of articulated concrete block revetments, originally designed for coastal protection in wave environments, has produced a viable option for application to steep-slope, high-velocity flow conditions where, if left unprotected, the channel banks and foundation material would be subject to damaging and potentially catastrophic erosion.

## INTRODUCTION

1. With the growing concern about dam safety throughout the world and increasing awareness of the hydrologic inadequacy of many older dams, civil engineers and dam designers are now looking to innovative alternative designs in modifying these dams. The traditional approach for accommodating design flows at embankment dams is to design spillway and outlet structures with sufficient capacity to avoid overtopping of the embankment. Improvements in the collection of historical flood data has resulted in significant increases in the predicted probable maximum flood (PMF). Therefore, many older dams are now considered unsafe due to inadequate spillway capacity. Conventional modifications include increasing the spillway size and/or raising the embankment. However, in many cases, these have shown to be costly or impractical.

2. Since 1983, research in the US and the UK has identified several innovative alternative designs to the more costly conventional modifications. These alternative designs provide methods for protecting the steeply sloped erodible embankment faces to achieve a high discharge capacity by allowing the entire crest, or significant portions thereof, to be overtopped. Traditionally, cast-in-place reinforced concrete would be used to achieve the desired level of performance and stability; however, more recently, roller-compacted concrete (RCC) has been used on several embankment dams in the US at a significant cost savings. Also, the introduction of articulated concrete block revetments, originally designed for coastal protection in wave environments, has produced another viable option for application to steep-slope, high-velocity flow conditions where, if left unprotected, the channel banks and foundation material would be subject to damaging and potentially catastrophic erosion.

3. Earlier performance testing of articulated concrete block systems at Jackhouse Dam in the UK (refs. 1-2) stimulated recent testing to these systems under high-velocity, steep-slope flow conditions (refs. 3-4). The research revealed the characteristics of hydraulic stability and nature and magnitude of destabilizing processes associated with these systems under bare (unvegetated) conditions. Both cabled and non-cabled concrete block systems were tested. Earlier research (1986-1987) of the articulated concrete block systems required installation be in strict compliance with the manufacturers specifications. However, after some failures, modifications to the installation procedures were deemed necessary and tests performed later in 1988 showed improvement. This paper describes the hydraulic testing program, results, and conclusions derived from approximately four and one-half years of study. The paper also briefly discusses current in-house research by the Bureau of Reclamation (USBR) to evaluate the capability of RCC and wedge-shaped blocks to protect the downstream face of an earth and rockfill dam, measuring 48.5 m high, during overtopping flows. Modifications made to other embankment dams to allow overtopping are also discussed.

## TESTING PROGRAM

4. In early 1986, a large-scale flume and recirculating water supply system were constructed by Simons, Li and Associates, Inc. (SLA) to examine the performance of embankment protection systems under steep-slope, high-velocity flows. The flume, was 3.35 m high, 1.2 m wide, and 27.4 m long. An erodible embankment 1.8 m high with a crest surface of 6.1 m and downstream slopes ranging from 2H:1V to 4H:1V was placed on the flume, Fig. 1. Various protection systems were installed on the embankment surface and subjected to overtopping flows of up to 2.8 $m^3/s$. This flow rate yielded 1.2 m of overtopping head, with maximum velocities of approximately 5.2 to 6.7 m/s, depending on system roughness, measured near the downstream toe. This testing program was unique from earlier tests in the US and UK in that the embankment tested was a highly erodible silty sand (SM) which tested the effectiveness of the protection systems rather than the erosion resistance of the embankment soils.

5. Initial performance studies of various protection treatments were sponsored by the U.S. Federal Highway Administration (FHWA) and USBR. In general, the high velocities and large tractive forces developed on the downstream slope of the embankment caused deformation and/or failure of meshes, mats, and wire-enclosed riprap. This type of failure was characteristic of shear-stress dominated deformation at overtopping heads typically in the 0.3 to 0.6 m range, with measured shear stresses ranging from approximately 190 to 720 Pa. Treatments which successfully resisted the hydraulic stresses at full discharge included soil cement, which for purposes of evaluation is considered the same as RCC, placed in 10-cm-thick steps, and several articulated concrete block revetment systems.

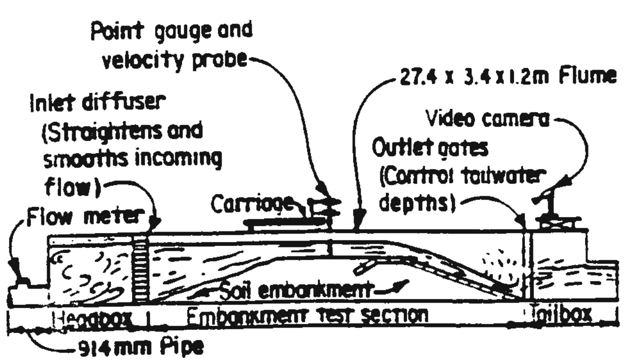


Fig. 1. Profile of testing facility

6. For the final phase of the SLA studies, the FHWA and USBR were joined by the Soil Conservation Service (SCS) and the Tennessee Valley Authority (TVA) to extend the hydraulic testing program to focus directly on the performance of the articulated block systems. Five systems were investigated: three cabled systems (Armorflex, Petraflex, and Dycel) and two noncabled systems [concrete construction blocks and wedge-shaped blocks of Soviet design (ref. 5)]. Fig. 2 provides information relating to the geometric configuration, weight, and dimensions of each of the five systems.

7. The Dycel system, with the largest, area-to-thickness ratio, failed during 0.3-m overtopping head by allowing excessive underflow to accumulate beneath the system. The other four systems performed successfully during overtopping heads as high as 1.2 m.

## HYDRODYNAMIC FORCES AND REVETMENT BLOCK STABILITY

8. Hydraulic Forces - An individual block surrounded by a matrix of identical blocks is subjected to the forces of lift and drag under the action of flowing water. The lift force acts in a direction normal to the plane of the bed, and is typically comprised of the buoyant force

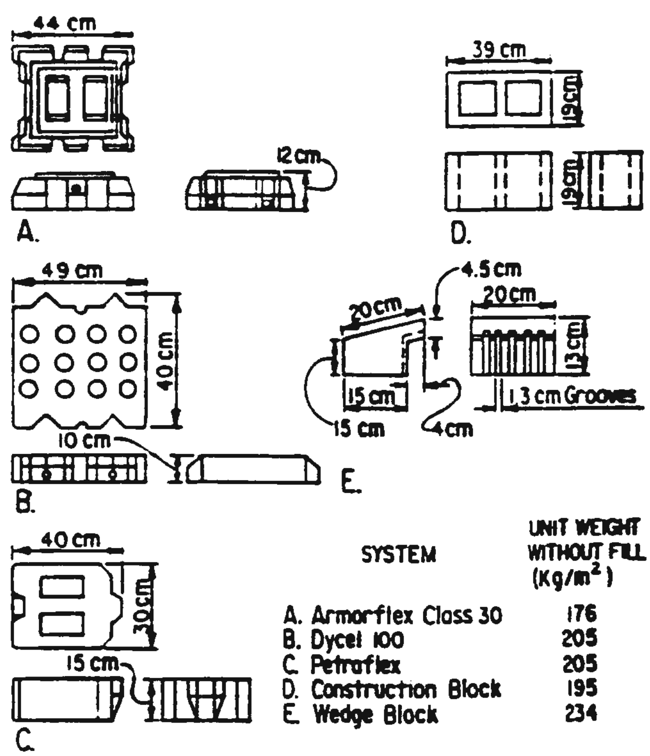


Fig. 2. Sketches of five types of concrete blocks tested.
(NOT TO SCALE)

and differential pressure across the block due to local accelerations. Lift forces can be substantially increased due to excessive seepage pressures beneath the block, and by flow separation which causes a negative pressure to occur on the upper surface of the block. The latter commonly occurs at sharp transitions from a mild bed slope to a steeper one i.e., at the transition point between dam crest and the downstream slope (ref. 6).

9. The USBR recently conducted a study to measure the pressure profile along a horizontal surface and over a sharp transition to a steep slope. This study revealed a large reduction in surface pressure in the vicinity of the change in slope. This pressure change is present over a very short distance in the direction of flow. Apparently the curvilinear flow over the intersection returns to the original flow profile in this short distance. Fig. 3 shows typical piezometric pressure profiles for three different changes in slope at an overtopping head equal to 0.66 m.

Fig. 3

10. The drag force acts in the direction of flow, and is comprised of frictional drag and form drag. Form drag, in particular, can lead to the creation of forces large enough to initiate block movement (rotation) where the block in question presents a frontal profile which is subject to direct impact by the flow (ref. 7). This is possible in instances of irregular subgrade preparation or poor installation where an individual block protrudes vertically above its adjacent neighbors. Cabled block systems have the ability to maintain the amount of projecting frontal area at a practical minimum when cable runs are oriented in the direction of flow, with the maximum height of projection limited to the difference between the diameters of the cable and the cable tunnel (Fig. 4a). Wedge-shaped block systems negate this effect entirely by providing a thin upstream cross section and a thicker downstream one. All upstream edges are therefore effectively "shielded" from direct impact (Fig. 4b). Drainage slots are also provided at the downstream edge, thereby relieving seepage and uplift pressures on the underside of the revetment and enhancing the intimate contact between the blocks and the subgrade (ref. 8).

<u>Definition of Failure</u>

11. Loss of "intimate contact" between a block, or group of blocks, and the subgrade which they are to protect has been identified as the primary indicator of incipient failure (refs. 2-3). Given the nature of revetment mattress installation in typical steep-slope applications, failure due to slipping or sliding of the revetment matrix along the plane of the bed is remote and has never been observed under controlled test conditions. This includes steeply sloped embankments where mechanical or vegetative shear

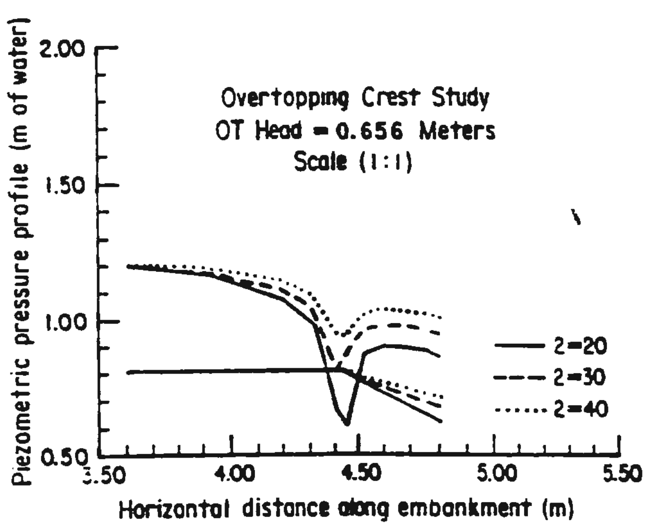

Fig. 3. Pressure profile at a change in slope.

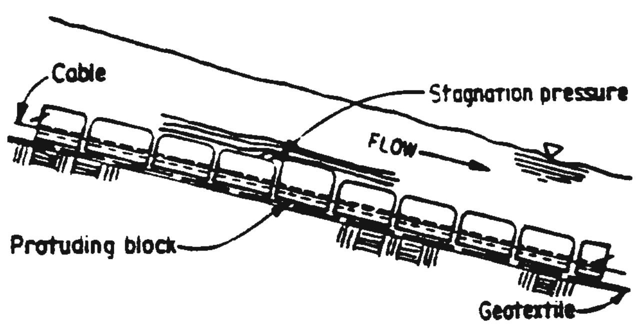

Fig. 4a. Typical profile of cabled revetment system cables in direction of flow.

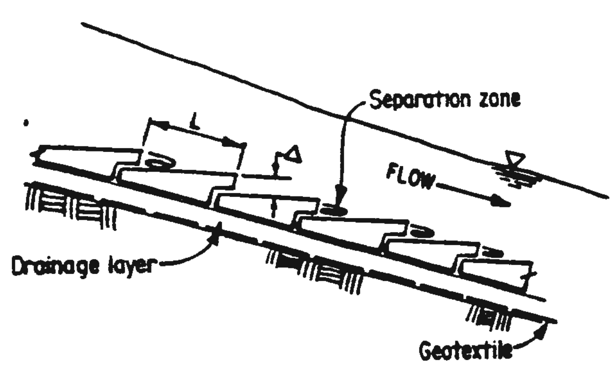

Fig. 4b. Typical profile of wedge block system.

restraint was not provided. Apparently the frictional resistance developed between the blocks, geotextile and/or granular filter, and subgrade soil is usually sufficient to prevent sliding occurrence. The loss of contact, therefore, is the result of overturning forces levered about the downstream edge, or about the downstream corner point when the block is located on the sideslope of an already steeply sloped channel. However, physical dislodgement or even measurable movement does not need to occur in order for the undesirable seepage flow to initiate and progress within the subblock environment, causing erosion of the embankment.

12. Therefore, the definition of "failure" of an articulated block revetment system is when overturning moments are exactly balanced by resisting moments. The dominance of overturning moments denote the condition where the ingress of flow beneath the system is imminent, and loss of contact is initiated. This definition of failure appears reasonably conservative in that the additional shear and uplift restraint provided by vegetative or mechanical anchorage systems is not depended upon by the designer. Likewise, any restraining force which can be attributed to cables should not be considered, because the mobilization of tension forces in cables can only come into play once finite rotation has occurred, by which time the system has already been defined as having "failed."

### Stability Analysis

13. Both lift and drag on a block produce overturning moments proportional to their magnitude and to the length of the moment arms through which they act. The resistance to overturning is provided by the submerged weight of the block acting through the center of gravity and its moment arm. Hydraulic stability is thus dependent on the hydraulic conditions of flow and the size, weight, and geometric characteristics of the block. The analytical method for determining revetment stability by way of the "factor of safety" method was developed originally by Simons and Senturk (ref. 9) in their derivation of a methodology for evaluating the stability of rock riprap in open-channel flow. In their method, the critical shear stress at which particle motion is initiated was determined by the Shields relationship. In the case of articulated block revetment systems, the critical shear stress is determined through controlled hydraulic testing and measurement.

14. The factor-of-safety procedure can be extended to blocks of different dimensions and weights, provided they are geometrically similar to the system for which the critical shear was previously determined through laboratory testing. The blocks must be of the same "family" in terms of method of interlock, profile configuration, and characteristics of boundary roughness and interaction with the flow field. Given this basic similarity, the weight and dimensions of the block in question can be compared with those of a tested block to determine the critical shear stress and a force balance approach.

## MODIFICATIONS TO ALLOW OVERTOPPING AT EXISTING DAM SITES

15. During the 1980s a number of cost-effective modifications have been made to existing embankment dams and grasslined waterways to prevent overflow erosion. Modifications such as the use of gabions, grouted riprap and even well-maintained grass lining have proven to be effective under low overtopping flows (ref. 6). The use of simple concrete construction blocks has shown to be effective in preventing erosion of SCS chute spillways.

16. The use of RCC has been demonstrated to be a cost-effective alternative on several embankment dams in the US by providing erosion protection during overtopping heads in excess of 0.6 m deep. Spring Creek Dam, located in Colorado, has a 15.2-m-high embankment and was modified in 1986 to allow overtopping by the stairstep placement of RCC on the downstream face.

17. The use of articulated concrete blocks to prevent overtopping erosion was first used in the UK (ref. 1), and the wedge-shaped blocks were developed and used in the USSR (ref. 5). These applications allowed for the articulated concrete mats to be placed on the downstream face of an embankment or steep waterway. With the use of soil anchors and grass vegetation these applications have been effective in preventing erosion.

18. Articulated concrete block mats are also currently being used to modify three embankment dams in the Blue Ridge Parkway located in the

Eastern United States (ref. 10). These dams range in height from 8.4 to 12.0 m at their maximum section. The modifications are designed to prevent breaching and erosion from overtopping flows 1.2 m deep.

## RECENT DEVELOPMENTS AND FUTURE DIRECTIONS

19. With the sufficient research and case history data currently available engineers can now feel confident in preparing designs for overflow protection for low embankment dams. However, USBR now faces the challenge of protecting much larger dams during overtopping flows. A. R. Bowman Dam is a 48.5-m-high earth and rockfill embankment located in Central Oregon which is projected to be overtopped by flow depths of up to 6.3 m during the PMF event.

20. A research program has been initiated by USBR, and has the following objectives regarding dam overtopping: 1) design criteria utilizing RCC technology for new dams and overlays for rehabilitating existing embankment dams that comply with Safety of Dams criteria, 2) to determine optimal step geometry as a function of hydraulic forces and energy dissipation, 3) to develop step geometry for embankment dams that uses hydraulic forces to enhance subsystem pressure relief during operation (ref. 11).

21. In addition to laboratory studies, field studies will be made to test and compare at near-prototype conditions the performance of RCC, Russian wedge-shaped blocks, and riprap embankment protection systems. These data will evaluate flow aeration, dynamic pressures and embankment drainage as important variables which influence protection method stability under large overtopping flow conditions.

22. Two adjustable slope test facilities have been built to develop step geometry. One is to investigate embankment overlays on slopes of 2:1, 3:1, and 4:1. The other will be used for concrete dam slopes of 0.6:1 and 0.8:1. These flumes are each 0.45 m wide by 0.75 m high and have a vertical fall of about 4.5 m. The maximum unit discharge for each flume is 1.67 $(m^3/s)/m$. The sidewalls of the flumes are formed in clear plastic. A rail mounted instrument cart is provided along each flume for laser velocimetry, air content measurement, other instrumentation, and photography.

23. These indoor facilities will be used to optimize the spillway step geometry for relief of uplift pressures under RCC overlays on embankment dams by venting through the overlay to low pressure zones of the steps and for increasing of energy dissipation to minimize required toe protection. Pressures, velocity profiles, flow depths and hydraulic jump characteristics will be measured.

24. Early results of this research have confirmed a previous hypothesis that the velocity attained along the downstream slope is directly proportional to the depth of overflow across the embankment crest rather than the length of chute or slope. Once uniform flow is reached the velocity remains constant.

25. A new prototype outdoor test facility will utilize a 2:1 slope, have an approximate 15 m vertical drop, be 1.5 m wide by 1.5 m high, and have a unit discharge of 4.65 $(m^3/s)/m$. An existing prototype chute or a university test facility will be used for a series of near prototype tests to evaluate the effects of aeration, dynamic pressures, embankment drainage, and natural freeze-thaw phenomena on protective system stability.

## SUMMARY AND CONCLUSIONS

26. Based on prototype experience and/or large-scale testing of many erosion-protection systems, those showing sufficient stability to perform reliably under steeply sloped high-velocity flow conditions appear to be limited to (1) traditional cast-in-place reinforced concrete, (2) roller-compacted concrete (or its lower-strength alternative, soil cement), and (3) selected articulated concrete block revetment systems.

27. The articulated concrete block systems may be the most cost effective alternative in many typical low head project settings, subject to availability and proximity of materials and equipment.

28. The proper selection of block type, weight, and dimensions are critical to design performance. These dimensions can be determined by a factor-of-safety method of analysis, provided that initial determinations of critical shear stress are performed under controlled conditions as described in this paper. Also installation procedures should conform to site specific conditions. The block manufacturers' specifications have not always been appropriate.