ACB Armoring Potential Failure Modes At
Dam Embankments and Spillways

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ABSTRACT

Over the past 26 years numerous embankment dams and earth-cut spillways in the United States have been armored using Articulating Concrete Blocks (ACBs) to provide erosion protection. Several dams and spillways armored with ACBs have been overtopped and performed satisfactorily with overtopping flow depths and velocities approaching 4 feet and 30 feet per second, respectively. Over the same period, some ACB overtopping applications have failed and others have experienced damage requiring maintenance to make the ACB system functional again. Much has been learned about what works and what does not work. Of the ACB installations that have failed or experienced damage, the underlying issues have been attributed to one of several potential failure modes that may not have been understood or adequately addressed during the design.

The purpose of this paper is to share information on several recent ACB embankment armoring and spillway armoring failures, and to describe the specific failure modes associated with these incidents. Suggestions for incorporating design features to address these potential failure modes are also provided. This information is important for engineers to consider during their designs, and for regulators reviewing ACB armoring designs, so that future failures and unnecessary damage resulting in costly maintenance can be prevented.

Keywords: Potential Failure Modes, ACB, Armoring, Overtopping, Embankments, Spillways

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1.   BRIEF HISTORY OF ACBs

Armoring earth embankments with ACBs has its origins from technologies first developed to armor open channels traversing steep slopes and subject to high velocity flow. Prior to the advent of ACBs, the channel banks of flood control projects subject to erosive flow conditions were armored using thin reinforced concrete slabs or hand-placed riprap. The success of hand-placed riprap is highly dependent on the quality of the workmanship and careful attention to transition and end details. Experience with hand-placed riprap demonstrates the need to rigidly control placement so that stones are tightly knit with no open spaces, and final exposed surfaces are as hydrodynamically smooth as possible. Since hand-placed riprap relies on mutual support of adjacent stones to be stable, the loss of one hand-placed stone can result in failure of the entire armored surface.

Although dumped-riprap requires less labor and is more forgiving if some of the stones are displaced, it is normally considered unstable for high velocity flow   conditions on steep slopes. Long-term satisfactory performance of dumped-riprap placed on steep slopes has not been successfully demonstrated except for low flow depths or very large rock sizes, or both (Powledge, 1989). Small scale overtopping tests by the USBR and case histories demonstrate that riprap can become fluidized and quickly eroded.

Commencing in the early 1980s and continuing to date, several organizations including the Construction Industry Research and Information Association, Lancashire, England (CIRIA), United States Bureau of Reclamation, Denver Colorado (USBR), U.S. Army Corps of Engineers, Vicksburg, Mississippi (USACE), United States Department of Transportation (USDOT), Tennessee Valley Authority (TVA), Colorado State University, Fort Collins Colorado (CSU), and several private vendors of erosion protection systems performed considerable research. This research included small-scale and large-scale flume studies to analyze economical methods of armoring small embankment dams (see Figure 1). Erosion protection systems evaluated include bare soil, vegetation covers, geotextiles, chemical soil stabilizers, gabions, riprap, articulating concrete blocks, and asphalt pavements. Cement treatments such as soil-cement and roller- compacted concrete (RCC) overlays have also been studied.

Of the erosion protection systems evaluated, cable-tied concrete blocks, also referred to as articulating concrete blocks (ACBs), were found to provide the most effective protection against high-velocity induced erosion in full-scale tests conducted in Great Britain and the United States (Powledge et. al., 1989; USDOT, 1989). Analyses demonstrated the stability of ACB armoring systems on embankment slopes as steep as 2H:1V with overtopping depths exceeding 4 feet and terminal flow velocities exceeding 26 feet per second.

Engineered ACB systems continued to be developed and refined to provide more economical and reliable armoring solutions. The term "articulating" implies the ability of individual blocks of the system to conform to three-dimensional changes in grade while remaining interlocked or otherwise laterally restrained by virtue of the block geometry and/or additional system components (Leech, 1999). Here, a distinction needs to be made between cable-tied blocks, interlocking blocks, wedge- shaped blocks, and cast-in-place concrete block systems. The results of studies indicate that the effectiveness of any armoring system depends upon maintaining a composite construction with intimate contact between the component parts. Once intimate contact is compromised, a system's ability to protect against erosion and uplift is significantly diminished (USDOT, 1988).

Figure 1. Full-Scale Laboratory Testing of ACB Systems at Colorado State University (Photos by Armortec)

Because non-cabled block systems are susceptible to progressive block dislodgement that could lead to catastrophic failure, almost all embankment armoring systems used to date in the United States have been cabled

systems. In addition to preventing block dislodgement, other advantages of cabled ACB systems over non-cabled ACB systems include:

    (1) mechanical installation requiring less manual labor,
    (2) minimizing vertical movement between individual blocks,
    (3) increasing restraint using soil anchors at select locations (eg. toe),
    (4) adaptability for use in underwater installation applications; and
    (5) more readily accommodates local repairs, if needed.

Cables for ACB systems can be made of stainless steel, galvanized steel, or polyester. Most cabled ACB systems use polyester rope consisting of a parallel core of filament polyester with a tightly braided polyester cover. Factors that affect durability of the polyester cables include UV exposure, hydrolysis, and chemical degradation.

Prior to 2000, all full-scale testing of ACB systems was performed using overtopping depths of 4 feet or less (unit discharges less than 25 cfs per foot). Some testing facilities had flumes too small to simulate terminal flow conditions for the higher overtopping depths. Prior to 2008, there was no ASTM standard for testing ACB systems. More recently, some testing facilities like the Colorado State University (CSU) Engineering Research Center, under the leadership of Dr. Christopher Thornton, have improved their flumes to be capable of testing revetment systems for up to ~6 feet of overtopping on 2H:1V and flatter slopes with a total height of 50 feet. The CSU facilities are capable of achieving a maximum discharge of 40 cfs per foot and sustaining this discharge for four hours or more with a 4-foot wide flume. A picture of the CSU Flume is shown in Figure 1. Over 65 revetment systems have been tested at the CSU facility. Most of these tests were completed after 2000.

An important unknown about the performance of ACB systems was how they performed under the influence of a hydraulic jump. In March 2006, CSU performed the first hydraulic jump testing of an ACB system for Armortec Erosion Control Solutions, Inc. (AECS), [Thornton et. al., 2007]. Three full-scale tests were conducted in controlled laboratory conditions for the purpose of identifying stability threshold conditions under the influence of a hydraulic jump. The tests were performed in a 4-foot-wide flume on a 65-foot-long slope with a 7.7H:1V (12.6%) grade. A picture showing the hydraulic jump testing is shown in Figure 2. The block system tested was the AECS 50T ACB system which is a tapered open-cell block with a maximum thickness of 6 inches and an average weight of 82 pounds. A 4-inch thick filter layer of gravel was installed directly on the concrete floor of the flume under the blocks with a Filterweave® 500 geotextile placed between the gravel layer and blocks. The open cells were also filled with gravel. The ACB system was tested to see if it could endure 1-hour of overtopping without any visible block lifting. The discharges used to test the ACB system were 21, 90, and 168 cfs. The 168 cfs was the highest flow possible that could be retained within the 6-foot high flume walls and corresponded to an overtopping depth of approximately 5.8 feet. No movement of the revetment system was observed for all conditions tested including for the most severe hydraulic jump that could be contained within the flume.

In February 2011, CSU conducted hydraulic jump tests on the SD-475 OCT ACB system manufactured by Premier Concrete Products, Inc. [Pluemer et. al., 2011]. The SD-475 OCT block system is a tapered open-cell block with a maximum thickness of 4.75 inches and an average weight of 65 pounds. The tests were performed in a 4-foot-wide flume on a 70-foot-long slope with a 2H:1V slope. An 8-inch soil embankment was placed on top of the concrete flume floor. Propex Geotex 1201 non-woven geotextile fabric was placed onto the compacted subgrade embankment over which 4-inches of gravel drainage material was placed and leveled. Fortrac 30G Geogrid was placed onto the gravel drainage material before placing the SD-475 OCT blocks and chinking the open cells with gravel drainage material. The ACB system was tested in 1-foot increments of overtopping for 2-hour durations. The first test with approximately 1-foot of overtopping (15 cfs) was observed to be stable. Test 2 with approximately 2 feet of overtopping (30 cfs) yielded a transition point between stable and unstable conditions, with observed localized block instability but no loss of intimate contact. The performance threshold, as identified as loss of intimate contact with the subgrade, was reached during Test 3 corresponding to approximately 3 feet of overtopping. The aforementioned tests appeared to indicate that on flat slopes, ACBs can be stable when subjected to the influence of a hydraulic jump. As the slope becomes steeper and the unit discharge is increased, ACB systems can become unstable.

Figure 2. Full-Scale Test of Hydraulic Jump on ACBs in CSU Flume (Photo Courtesy of Chris Thornton)

In 2010, Ms. Amanda Cox completed her PhD dissertation on the subject of "Moment Stability Analysis Method for Determining Safety Factors for Articulated Concrete Blocks" [Cox, 2010]. This work was completed at Colorado State University under the direction of Dr. Christopher Thornton. The focus of the research was to evaluate existing ACB design methods with a full-scale database to develop a comprehensive design methodology applicable to channelized and overtopping hydraulic conditions. Through the investigation of assumptions, Ms. Cox identified that the previous assumption used for the high-velocity, steep-slope ACB design examples of equal lift and drag forces was unsuitable for flow velocities greater than approximately 10 fps. A new safety factor design methodology was therefore developed using a moment stability analysis coupled with the computation of hydrodynamic forces using both boundary shear stress and flow velocity. Computation of the lift force for the safety factor method uses the flow velocity with a calibrated lift coefficient.

An explanation of the limitation of the early test results of ACB systems and the significance of some of the assumptions made to extrapolate full-scale testing of ACB systems for use in design is provided in a recent paper by Jim Nadeau [Nadeau, 2011]. The paper provides a comparison of full-scale flume tests of ACB systems before ASTM 7276-08 standards were established and shows that some of the critical shear values used in the factor of safety (FOS) methodologies prior to these ASTM standards should be corrected. Factors contributing to the problem include significant variations in the testing facilities, with the main concerns being the length and height of the flume. Tests performed in smaller flumes cannot reach terminal conditions for higher unit discharges or overtopping depths. Some of the shear values presented by ACB manufacturers based on pre-ASTM 7276-08 testing standards may be overstated and need to be corrected to establish the threshold performance of the system.

For additional developments in the testing and design of ACB systems refer to the Author's prior papers on this topic [Schweiger 2000; Schweiger, et al 2012].

2. BRIEF SUMMARY OF ACB PERFORMANCE

As of 2001, when the author's first paper on this topic was published, there were approximately 25 embankment dams armored with ACBs [Schweiger, 2001]. At that time, none of these projects had experienced overtopping flows. Since that time, many more ACB armoring projects have been constructed, including armoring of spillways and cofferdams. Several dams and spillways armored with ACBs have been overtopped and performed satisfactorily with overtopping flow depths and velocities approaching 4 feet and 30 feet per second, respectively. Over the same period, some ACB overtopping applications have failed and others have experienced damage requiring maintenance to make the ACB system functional again. These case studies provide important information for designers on the performance of ACB systems.

Of the ACB armoring installations that have experienced overtopping flows, none have experienced overtopping flows equal to or approaching their design flows, with the exception of the temporary cofferdam used to construct Portugués Dam. Portugués Dam is a roller-compacted concrete thick arch dam on the Portugués River, three miles northwest of the city Ponce, in Barrio Tibes, Ponce, Puerto Rico. Construction on the dam began in April 2008. The primary purpose of the dam is flood control to provide flood protection for 40,000 people and over 13,000 residential structures. The cost of the dam was approximately $375 million.

Since the project was located in a flashy watershed, the contractor elected to construct an earthen upstream cofferdam armored with ACBs to accommodate overtopping. The cofferdam was constructed with earth fill to a height of approximately 50 feet with a 2H:1V downstream slope. The downstream slope was armored with 46,436 square feet of ARMORTEC 70T open-celled ACB mats having a maximum block thickness of 8.5 inches and an average weight of 120 pounds per block. These are the largest open-celled tapered blocks manufactured by ARMORTEC/CONTECH. The mats were cabled together with polyester rope. The foundation treatment under the ACB system consisted of placing a geotextile (CONTECH C100NW) on the earth embankment followed by 6-inches of gravel, then another layer of geotextile (CONTECH C100NW) with a geogrid (Tensar BX 1300) on top of the geotextile. The reason for placing the second layer of geotextile on top of the gravel drainage material is unknown. The sides of the ACB mats were not connected to each other and no special toe treatment appears to have been specified. A row of concrete jersey barriers lined the roadway on both the upstream and downstream sides of the top of the cofferdam. Construction photos of the cofferdam are shown in Figure 3.

The cofferdam was overtopped several times, with a maximum overtopping depth of approximately four feet. Photos showing the cofferdam during a significant overtopping event are provided in Figure 4. This is the most significant example of an earthen embankment armored with ACBs that was overtopped that the authors are aware of. Although the downstream toe of the ACB armoring was damaged (see Figure 5) during the most severe overtopping event, the cofferdam did not erode, and performed satisfactorily throughout construction of the RCC dam. Some of the damage to the ACBs may have occurred as a result of the concrete jersey barriers and other debris being washed off the crest of the cofferdam and tumbling down the slope.

The Portugués cofferdam demonstrates that ACBs can be effective at providing overtopping protection for significant embankment dams with overtopping depths of 4 feet. Possible modifications to the Portugués ACB armoring design that could have improved its performance and that may have eliminated damage to the system include:

1. Eliminate the geotextile between the gravel drainage layer and the ACBs, but leave the geogrid.
2. Lace the sides of the ACB mats together to provide additional stability and prevent separation of the mats.
3. Flatten the slope of the cofferdam at the toe.
4. Eliminate the concentrated flow conditions at the groins.
5. Eliminate the concrete jersey barriers and concrete paving on the dam crest.
6. Anchor the ACB mats at the toe of the cofferdam using soil anchors.
7. Use stronger cables.
8. Use concrete armor units at the toe of the cofferdam.

These and other modifications or details for ACB armoring systems are discussed in more detail later in this paper in context with potential failure modes observed at this and other ACB installations.

Figure 3.   Photos Showing Installation of ACBs on Portugués Cofferdam, Puerto Rico (Photos Courtesy of Jacksonville District USACE)

Figure 4. Photos Showing Overtopping of Portugués Cofferdam during Significant Overtopping Event (Photos Courtesy of Jacksonville District USACE)

Damaged ACBs removed for repair

Figure 5.   Photos Showing Damage to Bottom of ACB Armoring Following Overtopping of Portugués Cofferdam (Photos Courtesy of USACE)

Of the remaining ACB armoring installations, most have performed well with only cosmetic or superficial damage, and successfully fulfilled the primary purpose of preventing the embankment or spillway from eroding and breaching. Some ACB armoring installations, however, like the ACB overtopping installation at Kingstowne Dam, experienced complete failure and breaching of the dam. Other ACB armoring installations that experienced overtopping flows showed signs of more serious damage, where, had the overtopping flow persisted, would have resulted in certain failure of the dam. It is understanding the potential failure modes of these latter two categories of case studies; (1) complete failure, and (2) near failure, that are the primary subject of this paper.

When discussing potential failure modes, it is understood a potential failure mode (PFM) is a sequence of system responses, triggered by an initiating event that could culminate in an uncontrolled release of stored water. For ACB systems, the initiating event is anytime there is flow over the ACBs. For the PFMs presented in this paper, failure of the ACB system was broadened to consist of any situation that results in unexpected movement or deterioration of the ACBs. An argument can be made that just because the ACBs move or deteriorate, it does not necessarily mean that the dam will fail with an uncontrolled release of stored water. The Portugués Cofferdam is a good example of where the ACB system technically failed but continued to protect the embankment from eroding and did not result in an uncontrolled release of water. On the other hand, had the overtopping event continued indefinitely, it can be postulated that the embankment may have eventually failed as the ACB system continued to move and deteriorate. For the PFMs presented herein, the potential failure mode is presented only up to the point where the ACB system moves or deteriorates.

3. POTENTIAL FAILURE MODES FOR ACB ARMORING OF DAM EMBANKMENTS AND SPILLWAYS

PFM #1 - Uplift of ACB Mats Due to Improper Foundation Under Treatment (Geotextiles Under ACBs). From the beginning of full-scale testing of various ACB systems in the late 1980s it became apparent that the undertreatment of ACB systems was important and a key factor in determining why some ACB systems failed under relatively small overtopping flows while others could not be made to fail under the maximum capacity of the testing flumes [USDOT FHA, ,1989]. Although not clearly understood, systems with an effective drainage medium underneath the blocks appeared to perform better than those without a drainage layer.

For some of the early ACB overtopping designs, engineers elected to deviate from the drainage configurations used in the full-scale ACB testing programs, and incorporated an additional detail or feature that appears to be detrimental to the performance of the system for embankment overtopping applications. The detail consists of including a geotextile between the drainage material (normally a gravel layer) and the ACBs. Although this detail is standard practice for channel erosion protection, it is not recommended for embankment overtopping protection. Based on hydraulic testing, the geotextile between the ACBs and the gravel drainage layer may not be adequately permeable, resulting in excessive uplift forces on the ACBs and destabilization of the blocks (see Figure 6). For this reason, some State Dam Safety agencies, like the New Jersey Department of Environmental Protection, do not allow the use of geotextiles between the ACBs and the gravel layer unless the ACB manufacturer can demonstrate that the use of the geotextile is appropriate [Moyle, 2007]. Use of a geogrid at that location is generally used to prevent the loss of drainage gravel through the block openings.

Figure 6. Photos Showing Example of PFM #1

The potential failure mode associated with placing a geotextile directly beneath the ACB mats consists of seepage flowing vertically downward through the ACB mats and geotextile both on the downstream slope of the embankment and beyond the formation of the hydraulic jump. The seepage then flows into and along the gravel drainage layer and exits upward through the geotextile and the ACB mats just upstream of the hydraulic jump where the tailwater is lowest. If the permeability of the geotextile is inadequate, or if the geotextile clogs, the geotextile will act like a geomembrane and result in uplift under the ACBs. If the uplift force exceeds the combined weight of the water and ACBs above the geotextile, the ACBs will displace upward as shown in Figure 6 and illustrated in Figure 7.
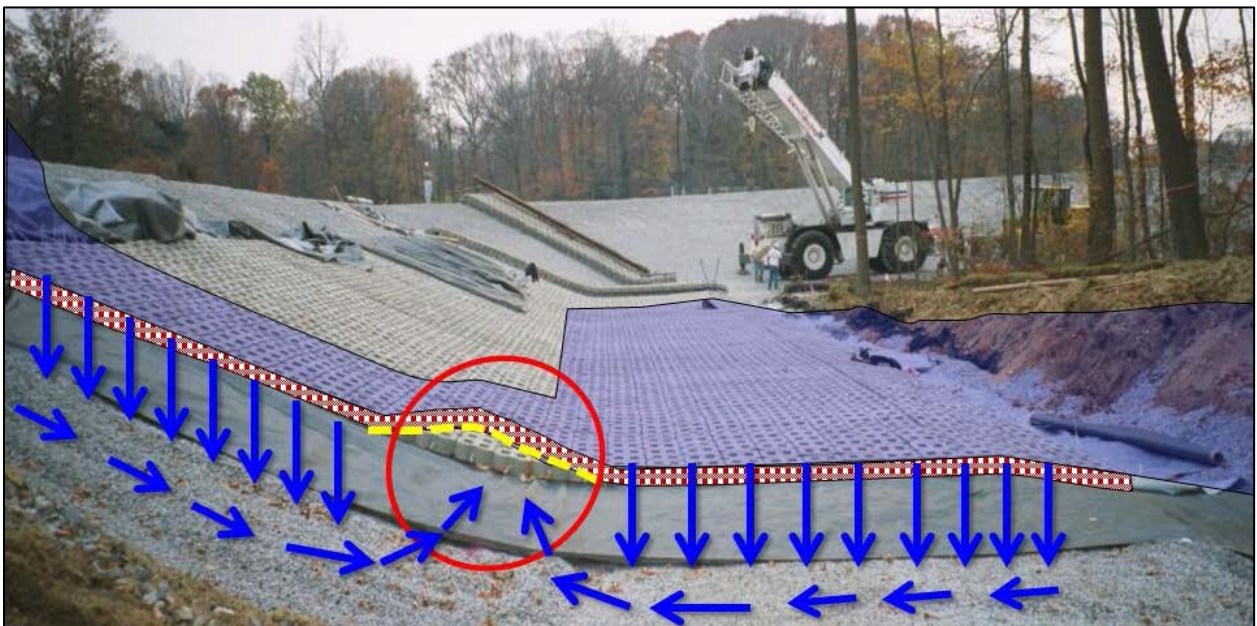

Figure 7.   Schematic Illustrating Concentrated Flow from Under Geotextile to the Lowest Water Level Just Upstream of the Hydraulic Jump (PFM #1)

PFM #2 - Piping Under ACB Mats. Classic "piping" occurs when soil erosion begins at a seepage exit point and erodes backwards, supporting a "pipe" or "roof" along the way. Four conditions are needed for development of piping: (1) a concentrated leak/ source of water (of sufficient quantity and velocity to erode material), (2) an unprotected seepage exit point, (3) erodible material in the flow path, and (4) material capable of supporting a pipe or a roof (Von Thun 1996). In the ACB embankment armoring example shown in Figure 8, the ACB- lined channel on the embankment is perched at the toe of the dam creating a hydraulic gradient from the flow in the spillway chute to a low point beyond the left side of the ACB armored chute. The hydraulic gradient must be sufficient to cause seepage and erosion at the exit point. If the seepage exit is unfiltered, the earth material along the flow path can erode. Erosion or piping is then initiated and can continue from the unfiltered outlet and progress upstream under the ACB armored layer towards the crest of the embankment. In the photo in the top of Figure 8, the piping erosion terminated near the crest of the dam because the flow over the spillway stopped. Had the flow over the ACB armoring persisted, the piping would have progressed through the crest of the dam embankment and ultimately breached the dam.

Figure 8. Photographs Showing Piping Under the ACB Armoring Over an Embankment (Top) and the Piping Outlet (Bottom).

PFM #3 – Installation Errors of ACB Armoring. For steep-sloped, high-velocity applications, the additional destabilizing force associated with form drag, where the frontal profile of the block is subject to direct impact by the flow often controls the selection of the ACB system. A vertical projection of 0.5 inches is often assumed for typical project conditions (Armortec, 2000). The tapered ACB system consists of a downstream thickness of approximately 0.5 inch greater than the upstream. The taper is designed to eliminate/minimize the effects of the vertical projection (see Figure 9).
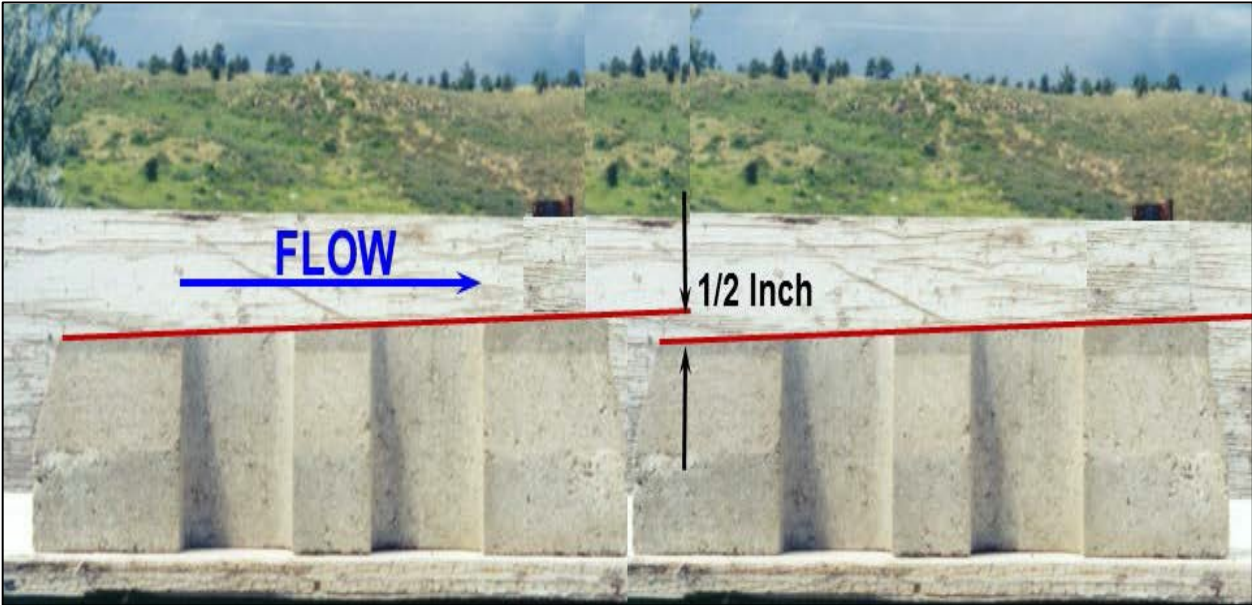

Figure 9. Photograph Illustrating Tapered Block System.

The authors have observed ACB mats being installed backwards with the tapered blocks facing the wrong direction. This mistake can occur if the contractor is not aware that the blocks are tapered, since the taper can be subtle and the ACB mattresses are symmetrical. If the ACB blocks are installed backwards, the blocks will have a protruding upstream face that will result in significantly increased form drag that can destabilize the system.

A recommended requirement is to have the ACB manufacturer's technical representative onsite during installation of the ACB system to ensure that the ACBs are installed correctly. Some ACB systems have arrows stamped onto the blocks, or paint on the downstream edge of the block to help contractors install the ACB mats correctly.

PFM #4 – Damage to ACBs Due to Impact from Debris. Although concrete blocks can be manufactured to be highly erosion resistant and durable, they remain unreinforced and brittle. Under severe impact loads, it is possible for blocks to become damaged. At Shavers Creek Dam, during installation of the ACB system on the downstream slope of the dam, a dump truck traversing on the installed ACB armoring became unstable and flipped over onto its side. Surprisingly, the damage to the ACB system was minimal. At Portugués Cofferdam, however, during one of the more severe overtopping events, when the cofferdam was overtopped by approximately 4 feet, the jersey barriers lining both the upstream and downstream sides of the crest of the cofferdam became unstable and were washed down the ACB armored downstream slope. The 8-inch thick cast-in-place concrete cap on the crest of the cofferdam also became uplifted and dislodged, and also washed down the ACB armored slope. Following the flood event, the ACB system was inspected and some of the blocks were observed to be damaged (see Figures 5 and 10).

Figure 10.   ACB Armoring on Portugués Cofferdam Damaged from Debris Impact (Concrete Jersey Barriers and Concrete Slabs).

Despite the damage to the ACBs, the system remained intact and continued to provide erosion protection. Following the overtopping event that caused damage to the ACB armoring, the contractor repaired the damage and replaced the concrete jersey barriers with plastic jersey barriers (see Figure 11).

Figure 11. Photograph showing plastic jersey barriers used to replace the concrete jersey barriers at Portugués Dam to prevent impact damage to the downstream ACB armoring should the jersey barriers become unstable and wash down the downstream face of the ACB armored cofferdam.

PFM #5 – Disintegration of ACB Blocks Due to Poor Manufacturing Quality Control. ASTM technical committee (ASTM Subcommittee D-18.25 Erosion and Sediment Control Section D-18.25.04), under the jurisdiction of ASTM Committee D-18 on Soil and Rock, was formed with the mandate to develop ASTM Standards for ACB revetment systems. One of the first ASTM standards to be published by this committee was ASTM D 6684-4 (2010), Standard Specification for Materials and Manufacture of Articulating Block (ACB) Revetment Systems. The purpose of this Standard is to provide specifications for articulating concrete block (ACB) revetment system structural components, material composition and physical properties, manufacturing methods and testing requirements. Specifications for ACB systems should reference this ASTM standard and require adherence to its requirements to ensure that the manufactured and installed ACB system will remain resilient throughout its design life.

The authors are aware of one ACB installation at Lake Mokoma Dam in Sullivan County, Pennsylvania where the installed ACB system experienced premature deterioration and disintegration of some of the concrete blocks (see photos in Figure 12). Initially it was believed that the problem was related to insufficient compaction and "popcorning", a phenomenon in the dry cast concrete process that sometimes occurs at the end of a manufacturing cycle/batch with dry cast material. These blocks are normally culled at the point before the concrete blocks are moved onto racks and into the kiln. After curing is the last opportunity to discard the blocks before the blocks are incorporated into mats. Regardless of the exact reason why the blocks were of poor quality, the problem was related to the manufacturing of the blocks and poor quality control at the plant. This appears to have been an isolated incident, however, it reinforces the importance of specifying random testing of the ACB blocks being installed along with other quality control measures.
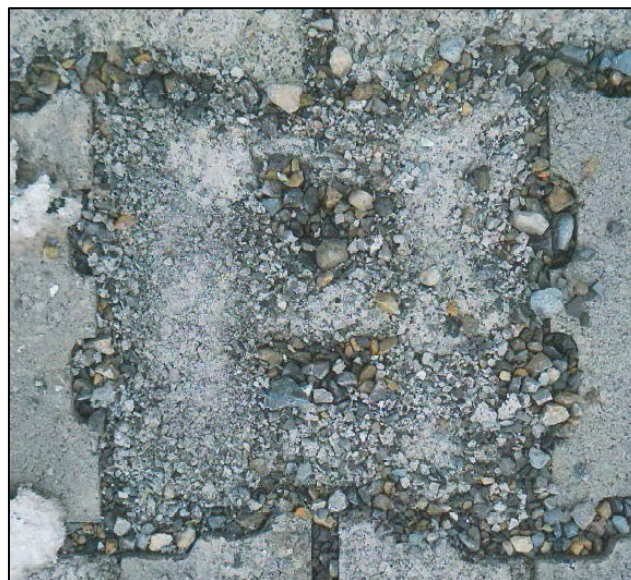

Figure 12. Photographs of Deteriorated ACB Blocks Due to Poor Quality Control during Manufacturing

PFM #6 – Use of Unproven ACB Systems and Installation Details. Full-scale flume tests on a closed-cell ACB system was performed at the CSU testing facility in 2004. It was determined that the revetment system reached performance thresholds after only 8 minutes of overtopping flow (~1-foot of overtopping) due to buckling of the blocks near the toe plate. The testing was stopped upon observing the buckling of the blocks. The highest lift of individual blocks was approximately 0.5 feet at the peak of the deformation (see Figure 13). This full-scale testing demonstrates that there are differences between ACB systems and their under treatment that can make a significant difference in their performance and stability. Therefore it is very important that only ACB systems with satisfactory laboratory or other performance data be used.

Figure 13.   Photograph Showing Laboratory Testing of an ACB System that Failed after 8 Minutes of Testing Under 1-foot of Overtopping (Photo looking upstream).

Similarly, the authors have observed ACB armoring installations where the installed ACBs did not emulate the same ACB system in the laboratory. Differences included the under treatment of the ACB system (see Potential Failure Mode #1) and the configuration of the ACB armoring. To date, the laboratory testing of the ACB systems has not included converging abutments or irregularities in the downstream slope such as berms or obstructions. Designers should be cautious about making deviations from what has been modelled in the laboratory. The authors recommend that ACB designs emulate modelled laboratory modelled conditions or other proven details as much as possible.

PFM #7 – Deterioration from Exposure. If the ACB system is exposed, it may be subject to deterioration from normal weathering and erosion. Forest Lake Dam is an embankment dam in Columbia, South Carolina that was armored with a Fabriform ACB system in the 1980s. The Fabriform Articulated Block revetment system consists of rectangular concrete blocks cast in place within a nylon fabric or quilt, and linked together by reinforcing cables (if required) inserted between the two layers of fabric prior to fine aggregate concrete injection. Forest Lake Dam was overtopped in 2015 and successfully protected the embankment from erosion (see Figure 14). Similar embankment dams located upstream and downstream that were not armored failed or were significantly damaged as a result of overtopping.

Inspection of the Fabriform ACB system at Forest Lake Dam after the 2015 overtopping event showed that the system remained intact. The nylon material that holds the concrete blocks together, however, was showing significant signs of deterioration (see photographs in Figures 14 and 15). The deterioration consists of missing nylon fabric over the tops of many of the concrete blocks. Some of the exposed remaining nylon fabric was weak and easily removed by hand. The nylon fabric that was not exposed (around the edges and underneath the concrete blocks) appeared to remain strong and durable. As the exposed nylon fabric continues to deteriorate, the concrete blocks will eventually lose the benefits of this restraint (unless the system included the optional internal cables) and lose their full capacity to protect the embankment from overtopping flows. At some point, the condition of this ACB system will need to be assessed and potentially reinforced or replaced to continue providing the needed protection for the embankment.

Figure 14. Photograph of Forest Lake Dam Showing Overtopping of Embankment Dam Armored Using Fabriform ACB System during Hurricane Joaquin

Figure 15.   Photographs Taken in 2015 Following a Overtopping of Forest Lake Dam during Hurricane Joaquin Showing Condition of Fabriform ACB System Installed in the 1980s

For most ACB systems, deterioration of the concrete blocks can be addressed by specifying a suitable mix design that is appropriate for the exposure conditions. For example, a mix design with a higher compressive strength may be specified for exposure conditions subject to frequent freeze-thaw cycles or aggressive soil or water conditions such as salt water or acidic soils. Oversized nylon or stainless steel cables can also be specified for greater durability. Completely covering the ACB armoring with topsoil and seeding is another option to protect the ACB system from deterioration due to exposure.

PFM #8 – Vandalism. If the ACB system is exposed, it may be subject to vandalism. Although less susceptible to vandalism than gabions where the wire baskets can be cut or damaged, or riprap, where individual rocks can be rearranged or taken, some features of ACB installations have been prone to vandalism. In particular the end treatment where armoring units (A-Jacks) have been used at the toe of the ACB system to provide energy dissipation (see Figure 16). Figure 17 shows photographs of armoring units that have been damaged by vandalism. It is reported that the damage to the armoring units shown in Figure 17 was the result of kids tossing large rocks against the units. A simple solution to prevent this type of vandalism is to bury the units so that they are not exposed. This may be feasible if the overtopping protection is not frequently activated. If the overtopping protection is frequently activated, covering the armor units with riprap may be sufficient.

Figure 16.   Photograph of ACB System with Armoring Units Installed at the Toe of the System to Provide Energy Dissipation of the Flow

Figure 17. Photographs Showing Armoring Units Damaged from Vandalism

PFM #9 – Poor Transition Details. The upstream and downstream ends as well as the sides, and wherever the ACB system transitions or is connected to another structure, require special attention and details. These transition areas, if not adequately protected can lead to block movement, erosion of the subgrade, and head cutting of the ACB system. Figures 18 and 19 show two examples where problems with the transition details led to movement of the ACB systems, however, there was no uncontrolled release of water.

Figure 18. Photographs of ACB Installation at Grover's Mill Dam Showing Armoring Units Damaged from Inadequate Transition Details at the Top of the Installation
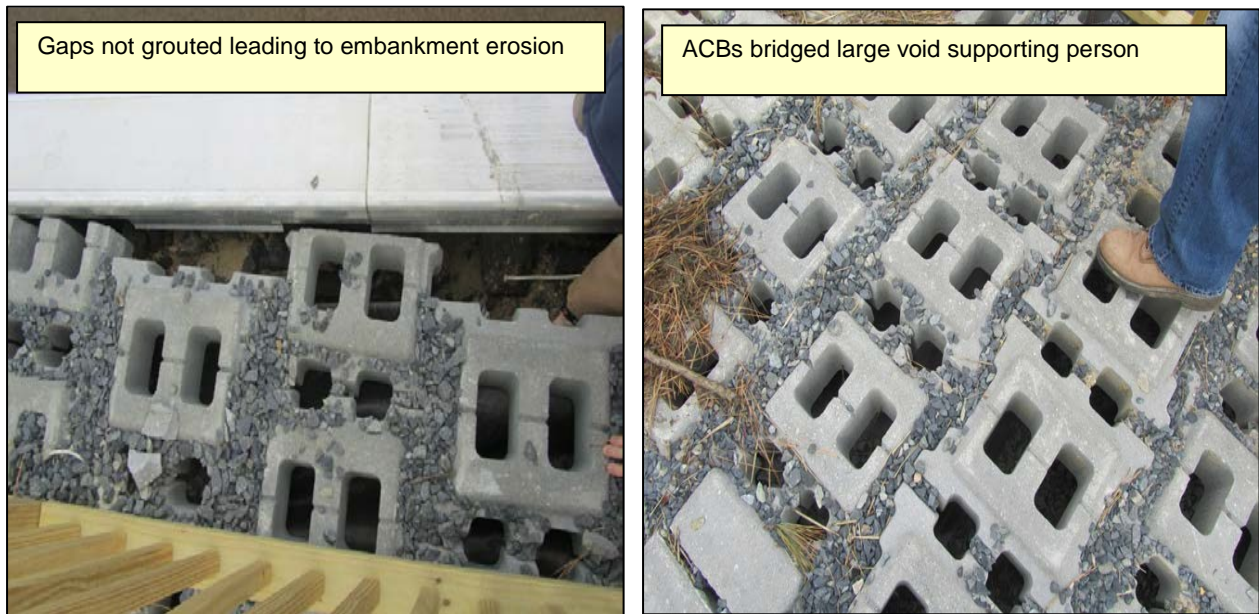

Figure 19. Photographs of ACB Installation at Lake Riviera Dam Showing Inadequate Transition Details along the Right Side of the ACB Installation

4. SUMMARY

In summary, much has been learned over the past 26 years about the performance of ACB revetment systems through full-scale flume testing and actual overtopping events. New ACB installation details and products show promise in improving the performance of ACBs for overtopping protection. Even with these advancements, engineers need to be aware of the potential failure modes associated with ACB armoring designs, and provide measures to eliminate or address these potential failure modes. The collective experience of the authors researching, evaluating, and designing ACB revetment systems for overtopping protection presented herein is intended to help dam owners, regulators and designers make informed decisions and develop successful designs with this evolving technology.

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