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Lessons Learned from Articulating Concrete Block (ACB) Field Installations

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ABSTRACT

Articulating Concrete Blocks (ACBs) have been a popular choice for high performance erosion control applications and shoreline revetments for well over 35 years and continue to grow in popularity. Estimates point to over 200 dam embankments and emergency spillways having been armored with ACBs in the past 30 years. As a result of these applications, as well as the thousands of other projects not specific to dams, much has been learned from a theoretical as well as practical application standpoint of properly utilizing ACBs in the field. This presentation will provide information concerning ACB Factor of Safety (FOS) determination, briefly review the ACB testing protocols and data analysis, and discuss the practical uses and limitations of ACB applications. New installation techniques that show promise for improving ACB performance will be discussed. ACBs are a proven cost effective erosion countermeasure, however experience and attention to detail during the design and installation of systems is of paramount importance for expected performance.

Keywords: ACB, erosion control applications, embankment, emergency spillways, cost effective

1. INTRODUCTION

A practical start to this paper will be to address at a high level the ACB testing and design process, highlighting important standards and methodologies that should be employed. The purpose of this approach is to provide a little background to the reader before reaching sections where specific ACB issues are discussed, potential solutions suggested, and advice offered to avoid these situations in the future through a comprehensive ACB project specification.

The first consideration in using an ACB revetment system is to examine the slope upon which it will be placed. The slope must be stable under both dry and saturated conditions. The second consideration is determining the hydraulic conditions to which the revetment will be exposed along with the slopes of the area of ACB coverage for the project. The designer will then need to determine if this is an open channel flow scenario, a wave attack scenario or both. This step will guide the designer to the appropriate design methodology for ACB revetments which should be employed. The remaining considerations in designing an ACB system are generally related to project specific installation details, project specific site conditions, determining the appropriate FOS target with an accepted methodology and following guidance offered in the four ASTM ACB standards.

2. ASTM STANDARDS

The American Society for Testing and Materials (ASTM) is an international standards organization that develops and publishes voluntary consensus technical standards for materials, services, products and systems. Over 12,000 standards are in use worldwide. The ACB standards are part of the D18 Soil and Rock main committee and fall under the D18.25.04 sub-committee.

Currently there are four ASTM standards that pertain to ACB systems and an understanding of them is strongly recommended for design engineers and regulators working with ACB systems.

1. ASTM D6684 – Standard Specification for Materials and Manufacture of Articulating Concrete Block (ACB) Revetment Systems
2. ASTM D6884 – Standard Practice for Installation of Articulating Concrete Block (ACB) Revetment Systems
3. ASTM D7276 – Standard Guide for Analysis and Interpretation of Test Data for Articulating Concrete Block (ACB) Revetment Systems in Open Channel Flow
4. ASTM D7277 – Standard Test Method for Articulating Concrete Block (ACB) Revetment Systems for Hydraulic Stability in Open Channel Flow

3. ACB TESTING AND DATA ANALYSIS

Testing of ACB systems under controlled and reproducible conditions serves, as the basis for developing the design parameters required in the FOS equations. Testing is conducted in a flume where the critical variables (subgrade type and compaction, geotextile installation, slope, and flow) are carefully controlled, measured and documented. These test flumes can be either horizontal, fixed slope or variable slope and can set up a slope length of between 10 feet and 100 feet. ASTM D7277 has set a minimum flume length of approximately 15 feet to ensure enough varied water surface measurements are taken during the data collection to produce meaningful analysis results. The longer the slope length of the flume, the greater the velocity and shear stresses generated, thus pushing the ACB systems being tested towards their threshold of performance limits. A photo of a fixed bed test flume is shown in Figure 1.

Figure 1. Fixed Slope Test Flume at Colorado State University

ASTM D7276 and ASTM D7277 are important to ensure the test protocol and data analysis utilized in the full scale flume testing are correct thus resulting in accurate design parameters being developed and utilized in the FOS determination. Errors of 70% or more have been found in flume test data not being analyzed per ASTM 7276 (Cox 2010).

4. SETTING THE TARGET FOS

The methodologies developed to determine the FOS of an ACB revetment system for a given project allow the designer to place a cushion of performance for the system in the given design. The result of these FOS equations is a mathematical interpretation of this cushion. The target FOS for each project needs to be set and typically this is done by the design engineer and or regulatory community. A typical industry "default" FOS for ACB applications with well-defined hydraulic conditions is 1.5, however other levels can be set for any given design. When setting the FOS for a project, engineering judgement is exercised to set an acceptable minimum FOS based on risks associated with failure of the ACB revetment system, uncertainty in the hydraulic model employed to determine the flows and overall project costs. There are no widely accepted methodologies to set the minimum FOS for a project, however a guide is presented in HEC-23 (FHWA 2009). A practical approach to setting the FOS is to look at a range of flow conditions as illustrated in Table 1. In examining the FOS presented in this example, one can readily see that the relationship between flow and FOS is not linear. If the FOS for this sample project had been set at 2.0 for a design flow of 5 CFS/ft, there would still be a FOS of 1.5 if the actual flow doubled. The Natural Resources Conservation Service (NRCS) in many designs will specify two FOS targets for design, one typically set at 2.0 for a highly probable flow event (stability hydrograph) and another (typically 1.0) for an extreme flow event (freeboard hydrograph). The rationale behind this approach is they do not want to have any maintenance issues associated with the highly probable flow event and in the case the extreme flow event is realized they want to ensure the dam is not breached.

Table 1. Factor of Safety Comparison at Various Flow Rates, NCMA (2006)

FLOW (CFS/ft)	VELOCITY (ft/s)	SHEAR (lb/ft^2)	FACTOR OF SAFETY
5	15.9	6.6	2.96
10	21.0	9.9	2.12
20	27.7	15.0	1.47

Note: FOS Values based on bed slope of 3:1 (_H:1V) and Side Slope of 20:1. FOS via NCMA Methodology and Shoreblock SD 475 OCT ACB System. Velocity and shear values at uniform flow state.

5. CALCULATING THE FACTOR OF SAFETY

Once the project design conditions have been determined, the sizing of the ACB system blocks needs to be undertaken. There are separate design methodologies employed for open channel flow and wave attack applications which are briefly described below.

5.1. Open Channel Flow

Upon completion and analysis of the FHWA testing, a reliable and fundamentally sound methodology to determine the FOS of ACB revetment systems needed to be developed. The reader is encouraged to study the literature review and history of the ACB equations found in the doctoral dissertation of Dr. Amanda Cox (Cox 2010) for a more complete explanation on this topic. Stated simply, the FOS calculation result for an ACB revetment system is the ratio of the sum of the stabilizing forces divided by the sum of the destabilizing forces which act upon the ACB revetment.

The current “industry standard” method for determining the FOS of an ACB is referred to as the NCMA methodology, the details of which can be found in “Design Manual for Articulating Concrete Block (ACB) Revetment Systems” (NCMA 2010). A second methodology developed by Dr. Amanda Cox (Cox 2010) and colloquially referred to as the “CSU Methodology” is gaining in acceptance. When designing with tapered ACB systems, the project design velocity has no impact on the calculated FOS with the NCMA methodology due to the fact that the lift and drag forces in the equations are assumed to be equal. This limitation was corrected in the CSU methodology and lift and drag forces are independently analysed.

5.2. Wave Attack Design

ACB revetments that will be exposed to wave action require a different design methodology than described above. The accepted methodology is often referred to as Pilarcyzk’s Method, the details of which can be found in “Geosynthetics and Geosystems in Hydraulic and Coastal Engineering” (Pilarczyk 2000). This method returns a block thickness rather than a FOS. The FOS was included in the parameters found in the equations and set at 1.3.

6. LESSONS LEARNED FROM ACB FIELD INSTALLATIONS

We now will examine several performance issues noted in the field and briefly discuss each. While ACBs are a durable and proven effective erosion control countermeasure, other factors need to be considered and ensured during the design and installation of the revetment to guarantee proper long term performance. Several specific items are discussed below which need to be addressed during the design, specification and installation phases of a project.

6.1. Installation Errors

Installation of ACB systems, per the established guidelines developed by the engineering community and manufacturers, is of paramount importance to the successful performance of these revetments. The issues presented here underscore the need for proper language in the specification calling out the specific installation details, the need for a pre-construction meeting prior to laying of the revetment and the proper on-site construction inspection protocols. The left hand photos in Figure 2 show a case where the plans called out that the toe-in trench be filled with non-erodible material. It was determined by the contractor that sand was non-erodible and that is what was placed in the trenches. The embankment experienced an overtopping flow of approximately 6 inches which washed out the sand backfill and caused deformation under the mats resulting in the subsequent removal of the mats, and required repairing of the subgrade and relaying of the mats. Part of the repair consisted of backfilling the trench with concrete, which is considered non-erodible. Subsequent flow events have occurred without incident.

Figure 2. Examples of Installation Errors of ACB systems

The photo to the far right in Figure 2 shows a potential problem with rilled subgrade. The ACB mats cannot be placed on the subgrade in this condition as the rills will only worsen beneath the ACB revetment as each subsequent flow event occurs, thus placing the system at grave risk of failure. This type of scenario occurs when the contractor gets too far ahead on the final grading and a flow event occurs before the slope can be protected. The designer is encouraged to consult ASTM D6684 and the various ACB manufacturers for specific installation details for each unique revetment project.

6.2. Geotextile Issues

The geotextile is a critical component of any ACB system for proper functioning and long term performance. The geotextile needs to be properly "sized" for the specific subgrade with HEC-23 Design Guide 16 (FHWA 2009) providing an accepted methodology in terms of strength recommendations and aperture sizing. The geotextile also needs to be properly installed with no tears or rips, proper overlapping of the seams both lateral and in the direction of flow and wrinkles removed such that the fabric is in intimate contact with the subgrade. Cases have been seen where a very small flow event has failed an ACB system where the geotextile was overlapped into the direction of flow, allowing for water to get under the fabric and start the erosion process. If one looks closely at the left hand photo in Figure 1, it can be seen where the geotextile is protruding between two mats. It was discovered that the fabric was "butted" and not overlapped the prescribed 2 feet during the installation. This caused problems along with those previously discussed and the repair was made during the reconstruction. A second issue with the geotextile is shown in Figure 3. In this case the wind was gusty during the installation of the ACB system so in order to hold the fabric in place, grade stakes were driven through the geotextile to secure it until the stone drainage layer was placed. No effort was made to repair the holes in the geotextile fabric and as a result localized erosion was noted around the majority of the locations where the fabric's integrity was compromised.

Figure 3. Geotextile Installation Issues

6.3. Subgrade Issues

The subgrade conditions at installation and over time are critical for ACB performance. The subgrade should be relatively free draining, adequately compacted and free of organic materials such as stumps and roots. The goal of these specifications of the subgrade is to avoid differential settlement over time. Eliminating pockets of organics and woody materials from the subgrade is an important step towards minimizing differential settlement as is avoiding installing ACB revetments during winter periods where the ground in frozen. Frozen soil is very difficult if not impossible to adequately and uniformly compact and the results typically show up as differential settlement the following spring or summer. The effects of differential settlement of the subgrade is shown in Figure 4. The cause was pockets of peat in the subgrade as well as a generally poor draining material. The remedy was to remove the ACBs, excavate the poor subgrade and replace with adequate borrow material that was free draining, free of organics and compacted adequately to avoid long term differential settlement. Once these fixes were completed, this system has been performing adequately for several years.

Figure 4. Subgrade Differential Settlement

6.4. Exceeding Design Considerations

ACB revetment systems, whether utilized in open channel flow or wave attack slope protection are subject to limitations of performance based upon design conditions. Should the actual field conditions experienced by the installed revetment exceed the design conditions used to size the ACB blocks and the FOS cushion, failure of the system is a predictable result. Figure 5 shows two such examples. The left hand photo in Figure 5 shows a revetment system which was subject to wave attack. The owner of this project designed the system himself and specified 4.75 inch thick ACBs. Hurricane Jeanne hit the area around this project and generated waves that exceeded the capabilities of the revetment system installed resulting in damage. The failure mechanism was a combination of mats “rolling” because they were not tied together in a contiguous revetment as well as subgrade loss due to the ACB blocks being lifted from the soil surface due to being undersized. A comprehensive engineering analysis for the revetment system using Pilarcyzk’s Method returned a result that an 8 inch thick ACB was the proper design for this project. The photograph on the right in Figure 5 shows an ACB system at a pipe outfall in a highly developed flashy urban watershed. The ACB’s were designed based on a HEC-RAS model run by the design engineer which provided the velocity and shear stress design values needed to size the ACB system. Upon further investigation of this failure, it was determined that the HEC-RAS model upon which the design was based was a “Steady State” model which included several feet of tail water. This system failed because the 8 foot diameter outfall pipe was flowing full before steady state tail water conditions had developed resulting in velocities that exceeded the limits of the ACBs installed. The failure mechanism was most likely due to velocity of the flowing water exceeding the limits of the ACB system either due to the lift generated on the ACBs, which was not accounted for in the NCMA FOS methodology utilized on this project, or the effect of a projecting ACB block or perhaps both of these.

Figure 5. Exceeding Design Conditions

6.5. Inherent Design Conservatism

There are several inherent conservative assumptions made in the realm of ACB flume test data analysis and design FOS methodologies. A partial itemized listing with a brief description appears below. These represent the largest conservative assumptions made in ACB technology. It is important to understand these built in “conservatisms” as they quietly add to the calculated value of FOS and reliability of the ACB revetment system. Stated directly, in a case where the actual hydraulic conditions were to be such that a less than 1.0 FOS resulted, this may not necessarily lead to a catastrophic system failure.

6.5.1. Definition of Failure of an ACB System

The definition of “failure” of an ACB system is the starting point to the understanding of the conservative assumptions built into the FOS design methodologies. Failure of an ACB system is defined as the hydraulic conditions experienced by the ACBs that generate the onset of erosion. This is further defined in ASTM 7277 and 7276. If during a full-scale flume test, the onset of erosion is not reached, the most extreme hydraulic conditions experienced by the ACBs are assumed to be the threshold of performance. In practice, erosion can start on a field installed ACB system and "damage" occur without ending in catastrophic failure, such as a dam breach, as has documented in several cases (Schweiger et al 2016).

6.5.2. Extrapolation Methodology

In most cases, when an ACB system is tested, only one thickness or weight of block is evaluated. The design parameters, namely critical shear (τ_c) are extrapolated to blocks of differing thickness utilizing the similitude equation appearing below. In this equation the subscript U refers to the untested ACB and T refers to the tested ACB. Unpublished test data has been analyzed and it can be estimated that when extrapolating the critical shear value from thinner to thicker blocks, the result shows that the extrapolated value is indeed less than if the actual thicker block had been tested. The reason for this result it is hypothesized is due to inter-block friction, which is not accounted for in this calculation.

$$\tau_{CU} = \tau_{CT}\left(\frac{W_{SU} l_{2U}}{W_{ST} l_{2T}} \cdot \frac{l_{3T} + l_{4T}}{l_{3U} + l_{4U}}\right) \tag{1}$$

6.5.3. Hydraulic and Hydrologic Conservatism

The hydraulic inputs required to determine the FOS of an ACB are design velocity and shear, which are determined from project geometries and total design flow over the revetment. The total design flow is determined from a hydrologic model, which typically has some degree of inherent conservatism built in. The degree of conservatism in the hydrologic model is difficult to estimate but can vary widely depending on the risks associated with the project and the watershed complexity that is being modeled. Once the design flow is set, the velocity and shear can be calculated accurately by using a modeling program such as HEC-RAS or conservatively using Manning's Equation, which returns the velocity and shear at uniform flow conditions, which may or may not be reached. Use of Manning's Equation may add a level of conservatism into the inputs when determining FOS.

6.6. Physical Deterioration and Vandalism

ACB blocks are manufactured to meet or exceed the physical properties listed in the project specification. ASTM D 6684 also provides a good starting point for the required physical properties of an ACB block. The Project FOS is determined based upon specifics of an ACB system which include design data derived from the full scale flume testing and data analysis as well as the physical attributes of the ACB unit having the FOS determined for a specific project. The physical attributes of the ACB unit input into the FOS equations include various moment arms and block dimensions, block weight and block surface area. Details of these physical dimensions can be found in the NCMA FOS Methodology (NCMA 2010) or the CSU FOS Methodology (Cox 2010). These dimensions, weights and areas need to remain constant over time and cannot change due to cracking or disintegration of the ACB units due to freeze thaw cycling or physical damage due to perhaps excessive vehicular traffic. Should this type of deterioration occur, the revetment no longer will have the FOS originally calculated, thus potentially putting the installation at risk of failure should a flow event occur. The ACB specification needs to clearly establish minimum physical properties (including freeze thaw durability if applicable) that must be met in order to ensure the long term integrity of the ACB blocks. Special consideration to unique environmental conditions which could also deteriorate the blocks needs to be undertaken for each design. Of particular note is cases where the concrete blocks may become exposed to moderate to strong acids either naturally or through accidental spills. This case may require special mix designs or alternate materials be used for the revetment.

The effect of vandalism and physical damage on engineered erosion control performance needs to be carefully considered and addressed for each project location. As with deterioration described above, physical damage which can for example be caused by excessive vehicular traffic and loadings or by vandals breaking or removing pieces of an installed revetment will lead to the same issues of impaired performance previously described. This issue should be discussed during the design process and appropriate measures be instituted to minimize or eliminate the detrimental effects vandalism or physical damage may cause.

7. ACB RECENT INNOVATIONS

The understanding and development of the ACB technology is based in an excellent history of successful installations and continued research, but is still ripe for change and innovation. Two recent innovations are discussed below which aim to improve the overall performance and reliability of ACB revetment systems.

7.1. Elimination of Half-Blocks

Since the introduction of staggered ACB block mats, half-blocks have been present to keep the manufactured mats rectangular, aiding in the installation process. Half blocks are not truly tested as when they are used in the flume they are retained by an angle iron bar along the edge, thus the focus of the testing is the free floating full blocks. FOS calculations only use the design parameters developed for full blocks in the flume which are not restrained and there is no accepted extrapolation to estimate the performance of the smaller half blocks utilized in the industry. Additionally, half blocks in most staggered interlocking ACB mat systems are secured with only one cable, thus there is a potential for the half block to roll on this single cable, compromising the revetment system. The lacing detail is an installation procedure that involves leaving the half blocks out of the mats creating a void as shown in Figure 6. The mats are placed side by side leaving a full block space. A cable is laced through the cable ducts of the adjacent mats tying them together. Once the lacing is completed, the open area is filled with concrete or grout.

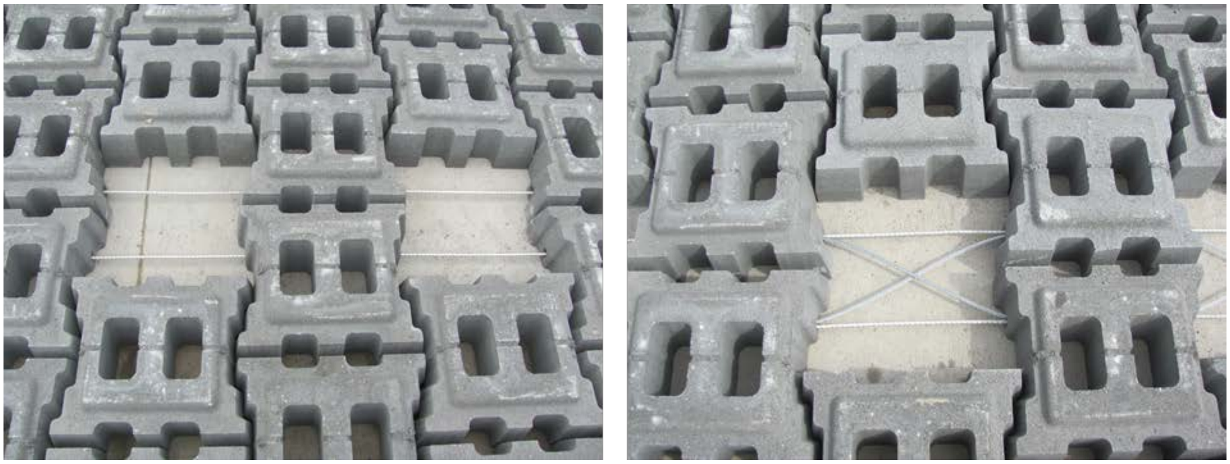

Figure 6. Lacing Detail

7.2. Stabilized Stone Drainage Layers

Recent testing of tapered ACB systems has focused on extending the length of the revetment tested in the flume in efforts to maximize the velocity and shear to which the ACB's are subjected. One such tapered system which was tested on a 100 foot long flume on top of a 6 inch thick layer of AASHTO #57 (d_{50} of 0.75 inches) stone showed ACB movement vertically in excess of 2.5 inches due to shifting of the stone beneath the ACBs (CSU 2015.) While no erosion was noted with the subsequent ACB movement thus not meeting the threshold of performance, the possibility of required maintenance to ensure the deformed revetment remains up to design standards pertaining to projecting blocks exists.

A system has been proposed and is currently being tested at Colorado State University (CSU) where the stone drainage layer is stabilized with the addition of a geoweb, similar to that shown in Figure 7. This system has the potential to increase ACB revetment reliability in terms of long term maintenance requirements after flow events, improve hydraulic jump performance of ACB systems and to help ensure when a 4 inch thick drainage layer is specified a uniform 4 inch thick drainage layer is actually installed in the field. Details of the testing will be published in future papers discussing various topics in ACB technology and application science.

Figure 7. Typical Geoweb System

8. ACB SPECIFICATIONS

Attention to detail when developing the ACB specification to be included in a project is of paramount importance in ensuring that the revetment installed will meet the specific conditions of the project. The language used in the ACB specification is important for a successful project and long term performance of the ACB revetment installed. The following guidance is offered regarding an ACB project Specification

1. Write a performance based specification based on actual design values for the project (slopes, velocity, shear etc.)
2. Call out three different ACB systems you have pre-qualified.
3. Call out the specific FOS target and methodology to be utilized to prove ACB system performance.
4. Call out ASTM specifications, especially ASTM 7276 & 7277 the flume test and data analysis protocols.
5. Be very specific in specifying the geotextile with the index properties. The strongest fabric meeting the hydraulic properties required for the project is typically recommended.
6. Develop the installation details specific to the project with the manufacturer and include in the contract plans for each of the specified ACB systems.
7. Ensure the proper physical properties of the ACB system have been called out. This is vitally important if the revetment may be exposed to harsh environmental chemicals or freeze thaw conditions in both fresh and saline waters.
8. Require alternate materials be submitted and approved 14 days prior to the bid and that the complete submittal package must be PE stamped by a duly licensed engineer in the projects jurisdiction.

9. CONCLUSIONS

ACBs have proven a robust and reliable erosion control countermeasure with a history of performance approaching 35 years, which during that period we have learned how to successfully install these systems in field applications. Equally as important, by studying issues experienced in field installations we have learned what not to do. This knowledge gained, when shared with the designers and regulators leads to more robust revetment systems being deployed, adding to the public safety downstream of the dam. History is a powerful teacher and much can be learned through failure and the desire not to repeat history. The performance of ACBs is sensitive to several factors including installation details, subgrade conditions, geotextile selection and integrity and long term physical integrity. All of these are readily controlled with a little forethought and attention to detail during the design and specification development process of the project.

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