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Articulating Concrete Blocks: The Long and Winding Road

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ABSTRACT:

This paper will provide an overview of Articulating Concrete Blocks (ACBs) from three perspectives: 1. the Manufacturer, 2. the Engineer, and 3. the Researcher and will discuss how these independent entities interact with each other and the regulatory community to further the scientific understanding and use of ACB systems. Since their development in the late 1970s, ACBs represent a growing choice of design engineers in economically solving their critical erosion prevention problems as well as in a variety of other non-hydraulic applications. Typical applications of ACBs are found in protecting channels and canals, dam spillways and embankments, bridge piers and abutments, river bank stabilization projects, boat ramps, and wet stream crossings. The ACB manufacturers work closely with both the ACB design engineer, dam safety and environmental regulators, and ACB researchers. Design challenges faced by the engineering and regulatory communities include but are not limited to non-linear flow paths, converging flows, and hydraulic jump. By working with manufacturers, the research community has developed much data and insight into ACB performance and limitations since standardized testing started in the mid-1980s; however, each manufacturer "owns" this information and is reluctant to share with other manufacturers. Recent testing extending the length of the ACB revetment being evaluated has shown the consistent development of aerated flows and potential for stone drainage layer movement, which need to be further researched along with hydraulic jump performance.

Conference Topics: *Spillway Weirs and Flumes, Slope Protection*

Keywords: *Articulating Concrete Blocks (ACB's), Erosion Prevention, Overtopping Protection, Slope Protection, ASTM, FHWA, Factor of Safety Determination*

1. INTRODUCTION

ACBs were developed in the 1970s in an effort to improve the performance and reliability of existing erosion control systems, mainly riprap. In 1987, what is considered the first comprehensive study of ACBs was conducted by the Construction Industry and Research Information Association (CIRIA) in the United Kingdom at Jackhouse Reservoir (Hewlett et al 1987). This study was followed by the Federal Highway Administration's 1988 and 1989 studies on embankment overtopping protection countermeasures at Colorado State University (CSU) in Fort Collins, Colorado. With the FHWA 1988 and 1989 (FHWA 1988, FHWA 1989) testing also came a derived Factor of Safety (FOS) methodology from Paul Clopper (Clopper 1991) and Dr. Amanda Cox (Cox 2010) updated the FOS methodology both of which will be discussed in this paper. The results of the FHWA studies showed ACBs to be a promising technology for erosion prevention of earthen embankments subjected to overtopping flows.

2. ACB MANUFACTURERS, DESIGNERS, REGULATORS, AND RESEARCHERS

Three main groups have played major roles in the development and implementation of ACB Revetment Systems, and these include

1. The Manufacturers of ACB Revetment Systems
2. The Researchers and Research Facilities where ACB Revetment Systems are tested
3. The Design Engineers and Regulators of Erosion Control Projects

2.1. The Manufacturers of ACB Revetment Systems

The Manufacturers of ACBs have been the primary source of information on ACB performance since the CIRIA and FHWA studies in the mid to late 1980s. Due to the competitive nature of the ACB marketplace, much of this information has remained private and not available for inclusion into a large research database. Innovations in ACBs, such as the introduction of tapered ACB revetment systems and a system where the gravel drainage layer under the ACB system is stabilized, have been at the hands of the manufacturers investing in the development and testing of these ideas. Due to the significant investment required to test an ACB system, innovation has been slow in this market. The Manufacturers of ACB revetment systems, to varying degrees, provide technical assistance, design guidance, and serve as a conduit of information for the Engineering and Regulatory communities. The information possessed by the Manufacturers is typically conveyed in person through working on a specific design project or in a seminar or Lunch n’ Learn setting where the Manufacturer is addressing a small focused group of individuals and may include topics delivered by members of the Research community.

2.2. Research Community and Test Facilities

Research facilities focusing on ACB revetment testing and research are a very specialized and small group. Several Universities and associated hydraulic laboratories have run ACB full-scale flume tests over the years; however, at present, the majority of the testing is being conducted at Colorado State University (CSU) on the outdoor steep slope flume. This flume is built on a 2:1 slope, is 3.05 m wide, 30.5 m long, and can be set up to deliver in excess of 1.8 m of overtopping flow, which is approximately 0.345 $m^3/m/s$. It has the ability to expose ACB revetment systems to velocities and shear stresses in excess of 12.2 m/s and 1150 Pa, respectively. Scale model testing of ACB systems has not produced reliable results to date.

The FHWA testing was completed in a horizontal flume where the embankment elevation needed to be built within the flume, and there is typically a height restriction within the limits of the flume that restricts the velocity and shears that can be generated. Typically, a maximum vertical drop of 1.83 m can be attained in a horizontal flume, which would allow for a maximum velocity of approximately 6.7 m/s and a shear stress of 335 Pa at a 4-foot overtopping depth. Generation of the velocities and shear stresses the steep slope flume is capable of producing has proven a difficult challenge for research laboratories with horizontal flumes to remain relevant in the overtopping flow test arena for tapered ACB systems in which the focus is on generating high water velocities.

2.3. Design Engineers and Regulators

Design engineers and regulators have embraced ACB revetment systems with varying degrees of openness and acceptance. The first dams saw ACB revetments in the early 1990s, and now it is estimated that several hundred dams (Nadeau 2015) in the United States have had ACB revetment systems installed to armour the auxiliary spillways or to protect the embankment from an overtopping event. Acceptance of the performance of ACB revetment systems among the design engineers and regulators has grown over the past 30 years, as has the understanding of ACB performance limitations and failure modes. Any new technology has a group of “early adopters” who clearly see the benefits the new technology offers in terms of economics and performance, and there is also a group known as the “late adopters” who prefer to wait and let the technology become proven. Acceptance of the ACB revetment technology, especially when used in potential high-risk scenarios like dam overtopping and spillways applications, were sometimes slow to evolve over the first 15 or so years of product introduction, but they have gained significant momentum in the last 10 years. The Manufacturers, working with the early adopters of the design and regulatory community, have helped widen ACB acceptance in high-risk applications by sharing the latest test results, product innovations, and documented case studies from the field where actual real life performance data has been collected. A growing number of design engineers and regulators are compiling field experiences and subsequent analyses of ACB revetment systems that have experienced flow and sharing this information with their peers at local, national, and international conferences on hydraulic structures and revetment technology.

3. A BRIEF HISTORY OF EROSION CONTROL AND HARD ARMOR SOLUTIONS

The control of unwanted erosion has been a challenge for humans for several millennia. For the purpose of this paper, erosion control practices will be limited to a discussion on channelized flows, sheet flows, and high velocity flows and will not address the issues experienced by the agricultural community relating to farmland as a whole. Since antiquity, man has utilized natural vegetation, flow interruption devices, and rocks (riprap) as measures to stop the ravages of unwanted erosion and has learned each has its range of applicability for successful results. Many products have been invented and tested to improve resistance to erosion of soils when compared to natural vegetation or riprap, and ACBs will be discussed below.

3.1. Definition of Failure of an ACB System

The threshold of system performance for any erosion control countermeasure is a critical term for design engineers and regulators to fully understand as they are undertaking erosion control countermeasure projects. The definition of failure for ACB systems is defined as "the hydraulic conditions (velocity and shear stress) at which the onset of erosion occurs" (ASTM D7277 2008). This is considered a very conservative definition of failure, thus making ACBs suitable for a wide variety of applications. When properly designed, ACBs will require little long term maintenance. Other countermeasures may have different definitions of "failure," and it is important to read and understand each different definition when working at evaluating multiple revetment technologies.

3.2. Riprap, Grouted Riprap, and the Development of Articulating Concrete Blocks

Rock riprap has been used for years to control erosion without reliance on vegetation. The size of the rocks employed is directly related to the hydraulic forces that can be withstood. Quarried rocks, in which flat surfaces are present, were the next logical step in the use of riprap. This was followed by grouting these flat topped surfaces together to form a relatively smooth surface for the water to flow over, thus eliminating many of the moment arms created with angular rocks (as shown in Figure 1) and, thereby, increasing performance of these systems. The USACE developed a "cable tied" concrete mat system in the 1970s, consisting of concrete "blocks" approximately 0.61 m by 1.22 m cast on steel cables and rolled up, which were commonly deployed from barges along rivers to slow down erosion from seasonal flooding (shown in Figure 2). This appears to be the first time individual blocks were connected via cables and can be considered the forerunner of the modern ACB revetment systems seen today.

Figure 1. Grouted riprap

Figure 2. USACE Cable Tied Concrete

ACBs present in today's market are typically cabled systems of varying geometric shapes and have varying hydraulic performance thresholds. Typical modern ACB units range in area from 0.093 m^2 to approximately 0.28 m^2, in thickness from 7.62 cm to 22.9 cm, and in unit weights from 98 kg/m^2 to 440 kg/m^2. Modern ACB systems can be manufactured either by the dry cast or wet cast method. ACB revetment systems can have the individual blocks arranged within the mats in a linear or staggered format, can have the individual units interlocked, and may have the cable either cast into the blocks or inserted after the block has been manufactured. ACB revetments can have "dome" tops or flat tops, and its thickness can vary by 12.5 mm along the direction of flow (tapered ACB). Examples of modern ACBs are shown in Figure 3. Every ACB system is unique and needs to have full-scale flume testing results to determine the performance parameters that can be reliably used by the design engineer.

Figure 3. Typical ACB Systems currently available on the open market

3.3. FHWA Testing and Analysis

The test programs funded by the FHWA and run at CSU in 1988 and 1989 are considered by many as the birth of controlled, measurable, and repeatable testing on ACBs and other such revetment systems. The test procedures employed during this testing were exactly that, a procedure to provide consistent testing and results. From the results of these tests, it is empirically known that on a 1.82 m tall embankment with a 2:1 (H:1V) slope, an overtopping event of a specified depth either failed the system or the ACB revetment system resisted the erosive forces of the flowing water. The test data was analysed, and velocity and shear values calculated based on the hydraulic forces for the given system geometry the revetment system was able to resist the erosive forces applied. Specifically, the most important value determined for each revetment system tested was the critical shear value τ_c, which is defined as the maximum shear the revetment was exposed to that did not fail the system, corrected to a flat surface (0 degree slope). These design parameters, determined through the full-scale flume tests, are of little value unless there is a set of equations or a procedure developed to determine the factor of safety. These formulas are mathematical representations of the physical forces acting on the block, which divides the sum of the stabilizing forces by the sum of the destabilizing forces.

3.4. Factor of Safety Equations

The original FOS equations and currently the industry standard FOS methodology can be found in the NCMA publication "Design Manual for Articulating Concrete Block (ACB) Revetment Systems" (NCMA 2010). A proposed set of improved FOS equations is found in the PhD dissertation of Dr. Amanda Cox "Moment Stability Analysis Method For Determining Safety Factors For Articulated Concrete Blocks" (Cox 2010). The reader is encouraged to review these documents for a more thorough understanding of each of these methodologies, including the underlying assumptions made in their respective development.

3.5. Setting the Factor of Safety for a Project

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 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 0.086 m^3/sec m, there would still be a FOS of 1.5 if the actual flow doubled. The Natural Resources Conservation Service (NRCS) will specify in many designs two FOS targets for the 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 that they do not want to have any maintenance issues associated with the highly probable flow event, and in the case that 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 (m^3/s/m)	VELOCITY (m/s)	SHEAR (Pa)	FACTOR OF SAFETY
0.0431	4.84	316	2.96
0.0863	6.40	474	2.12
0.1726	8.44	718	1.47

Note: FOS Values based 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.

4. IMPROVEMENTS IN TESTING, DATA ANALYSIS, INSTALLATION, MANUFACTURING AND FOS DETERMINATION

FHWA test and analysis protocols set in motion the growth of ACB revetment systems being designed and specified by the engineering and regulatory communities. The 25 years since these protocols were introduced have led to significant changes and improvements proposed and adopted by the ACB user community at large, and these changes are outlined below. These updated protocols are important to be aware of so that the current ACB revetment designs are completed with the best information and methodologies available to the designer. We have learned a lot from history and need to ensure we do not repeat past oversights moving forward.

4.1. ASTM

Currently there are 4 ASTM standards that pertain to 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

Use of these standards by designers and regulators has led to improved system reliability for ACB revetments, with ASTM 7276 and 7277 being the basis upon which the biggest impact has been seen. The data analysis methodology employed on the FHWA involved taking the measured test data from the full scale flume test, calculating the energy grade line (EGL), setting a best fit line to the EGL data, and then calculating the threshold velocity and shear stress values for the given dataset. While, technically, this method will ultimately arrive at velocity and shear stress values, it is very dependent upon who is running the analysis. Stated directly, two individuals can run the analysis on the same data set and come up with different values of velocity and shear, yet both could technically defend their analysis. Additionally, this methodology sometimes violated the fundamental laws of thermodynamics where energy appeared to be created. ASTM 7276 was first adopted in 2008, and it allowed the data generated during a full-scale flume test of an ACB system to be more consistently and accurately analysed. Now, there is a methodology where several people can analyse the same data set and obtain results that are reasonably close. This method employs the stepforewater methodology in which the measured water surface profile data is statistically fit to known hydraulic equations. Dr. Cox showed in her dissertation that FHWA shear stress values were overstated by as much as 70% (Cox 2010).

4.2. CSU FOS Methodology

The development of a new set of FOS equations was undertaken because in the original FOS equations, the lift forces were assumed to be equal to the drag forces. In the original NCMA FOS equations, velocity has no impact on the calculated FOS for a tapered ACB system where the projection height (ΔZ) is set to 0. The CSU methodology treats lift and drag forces separately. When analysing a total of 24 data sets generated in full-scale flume tests on ACB blocks, the CSU methodology was able to correctly predict threshold performance in 23 of the 24 data sets, while the existing NCMA (2006) methodology correctly predicted only 11 of the 24 data sets. A comparison of the results presented in Table 1 with the NCMA (2010) methodology to the CSU FOS results is presented in Table 2. Of particular note is that at the highest flow rate presented, the FOS with the CSU methodology falls under the 1.5 typical minimum value, which is due to the inclusion of velocity in the equations. The CSU methodology returns 4 FOS calculations, the lowest of which is set at the FOS for the project.

Table 2. NCMA (2006) and CSU FOS Methodologies FOS Comparison

FLOW (m^3/s/m)	VELOCITY (m/s)	SHEAR (Pa)	FOS NCMA (2006)	SF_O CSU	SF_P CSU	SF_M CSU	SF_{BED} CSU
0.0431	4.84	316	2.96	7.33	2.80	3.85	2.80
0.0863	6.40	474	2.12	4.40	1.92	2.56	1.93
0.1726	8.44	718	1.47	2.60	1.27	1.64	1.27

Note: FOS Values based bed slope of 3:1 (_H:1V) and Side Slope of 20:1. FOS via NCMA (2006) and CSU Methodologies and Shoreblock SD 475 OCT ACB System. Velocity and shear values at normal flow state.

Again, we note in Table 2 that the FOS is not linearly related to the flow. We also note that the CSU methodology, taking into account both velocity and shear in the FOS determination, produces more conservative and presumed accurate values. Dr. Cox, showed in her dissertation that at velocities in excess of 3.05 m/s, the lift forces dominate compared to the drag forces in destabilizing an ACB system (Cox 2010). The effect of velocity on the FOS determined with both the NCMA (2010) and CSU methodologies is presented in Table 3. For this exercise, shear was held constant at 316 Pa.

Table 3. FOS comparison between NCMA (2006) and CSU Methodologies showing effect of velocity

VELOCITY (m/s)	SHEAR (Pa)	FOS NCMA (2006)	SF_O CSU	SF_P CSU	SF_M CSU	SF_{BED} CSU
4.84	316	2.96	7.33	2.80	3.85	2.80
6.40	316	2.96	4.40	2.23	2.85	2.23
8.44	316	2.96	2.60	1.65	1.97	1.65

Note: FOS Values based bed slope of 3:1 (_H:1V) and Side Slope of 20:1. FOS via NCMA (2006) and CSU Methodologies and Shoreblock SD 475 OCT ACB System.

5. HISTORY AS A TEACHER

ACB revetment systems have been utilized for erosion prevention since the late 1970s, thus providing the industry and designer a large database of experiences to draw upon. The philosopher George Santayana stated, “Those who do not learn from history are doomed to repeat it.” Approaching the understanding of ACB performance from past experience has been a recently emerging theme and is one that is gaining momentum. In recent years, Paul Schweiger P.E. and Darin Shaffer have begun the compilation of field performance results of ACB applications specific to dam overtopping and emergency spillway applications and have written papers for national conferences (Schweiger & Shaffer 2013). This theme has been followed at other technical gatherings of Dam Safety engineers with the database and understanding learned growing every year. The study of past performance of ACB systems has led to some of the innovations discussed later in this paper.

5.1. Current State of ACBs in the Market

ACB systems are currently manufactured in both hand placed and cabled mat systems, interlocked and non-interlocked, and wet cast and dry cast offerings. There are several manufacturers actively selling and promoting ACBs to the engineering community, and each brings strengths and weaknesses in terms of technical knowledge, regional manufacturing capabilities, sales and installation support, as well as testing of the ACB systems to current ASTM standards. Design engineers need to obtain, read, and understand the test data and installation details of each ACB manufacturer they choose to work with. The quality of the ACB product in terms of physical properties as well as performance for a given set of project design parameters vary widely, and the designer should insist on adherence to ASTM specifications and work with more than one manufacturer on their design projects. The designers and regulators need to be diligent in reading technical test reports provided they often are not what they appear.

5.2. Innovations in ACB Systems

The process of innovation and modifications to ACB blocks began soon after the initial product development. Each innovation needs to be evaluated for its merits in improving the performance of ACB systems, and it must be noted that not all modifications made to ACB blocks have resulted in positive improvements on performance. The basic shape of the original ACB block was rectangular and arranged in a linear fashion within mats. The following innovations are discussed briefly as to their role in the furthering of ACB revetment performance

5.2.1. Interlocking Blocks

Interlocking and in some cases staggering every other row of ACB blocks within a mat are innovations that have been widely employed and have seen varying degrees of success in improving the performance and reliability of ACB revetment systems and are depicted in Figure 4. Some interlocking systems are positive interlocking, which means they contain projections similar to those seen in jigsaw puzzle pieces. These projections can cause binding or break if the ratio of block thickness to projection length is not adequate. Should a positive interlocking piece break, the ACB unit will no longer have the representative design characteristics determined from the flume test, potentially putting the revetment at risk of failure.

5.2.2. Dome top ACBs

Roughening of the top surface of the blocks led to an observed increase in Manning’s n as determined from water surface profiles measured during full scale flume tests are shown in Figure 5, while Figure 6 shows a flat top ACB. This roughening was accomplished by adding a “dome” to the top of many ACBs. This had the effect of reducing the velocity and increasing the shear during the full scale flume test, and at that time when this innovation was introduced, it was thought that shear really controlled the ACB performance, so seeing the increased shear was very welcomed by the ACB manufacturers. Thanks to both the dome top and the slower velocities seen due to higher Manning’s n, the effect of the projecting block in the FOS equations was reduced.

Figure 5. Interlocking Dome Top ACBs

Figure 6. Interlocking Flat Top ACBs

5.2.3. Tapered ACBs

The introduction of tapered ACBs led to a major improvement in hydraulic performance for revetments utilizing these products. Tapered ACB systems have been tested to 1.52 m of steady state overtopping depth on a 2:1 (H:V) slope and have not reached the onset of erosion, but they have experienced significant movement of the drainage stone required for adequate hydraulic performance. Early testing showed that tapered ACB systems saw dramatic improvement in performance when a 10 cm stone drainage layer of AASHTO #57 stone with a d_{50} of 19 mm was placed beneath the ACBs on top of the geotextile. Tapered ACBs are the predominant ACB system utilized for dam overtopping and emergency spillway applications.

5.2.4. Length of Flume used in Testing

The original FHWA testing and subsequent tests for at least the following 10 years typically ran a flume set up on a 2:1 (H:V) slope with a 1.83 m to 1.98 m tall embankment (~ 4.6 m of slope length). Starting around 2007, the slope lengths tested on a 2:1 (H:V) slope were extended, initially to 12.2 m, then 21.3 m and, finally, in 2013 to 30.5 m for tapered ACB systems. Typically, untapered ACB systems are run on a flume 15.2 m or less in length as, typically, the threshold of performance is reached for these products at lower velocities; thus, the longer flume lengths are not necessary. Tapered ACB systems have not reached the threshold of performance (onset of erosion) in steady state overtopping flows, even with a 30.5 m flume length. What has been observed with the 30.5 m flume length is that the stone drainage layer becomes unstable and moves, causing the ACB revetment surface to deform at overtopping depths of 0.91 m or more. Basically with this observation, designs of tapered ACB systems have become limited to velocities approximately 6.4 – 7.9 m/sec or less on a 2:1 (H:V) slope. This limitation on velocity is to avoid maintenance that would be required of the ACB system should flows of this magnitude be experienced. ACB systems have experienced in excess of 5 cm of vertical movement in flume testing (CSU 2014). Maintenance would be required to level the stone drainage layer, thus removing any projecting ACB blocks due to this stone movement. Table 4 shows the effect of this projection height on the FOS of tapered ACB systems. As can be noted, the FOS decreases very rapidly with increasing projection height.

One manufacturer is developing a system to stabilize the stone drainage layer, and this will be described in the next section. It should be noted that the exact mechanism that causes this stone movement is not completely understood. Testing of tapered ACBs in 21.3 m flume run to 1.22 m of steady state overtopping depth with a 10 cm stone drainage layer showed no stone movement.

Table 4. Effect of Projection Height on Tapered ACB Calculated FOS

PROJECTION HEIGHT (mm)	**VELOCITY (m/s)**	**SHEAR (Pa)**	**NCMA (2006)**	**SF_O CSU**	**SF_P CSU**	**SF_M CSU**	**SF_{BED} CSU**
0	6.40	316	2.96	4.4	2.23	2.85	2.23
6.35	6.40	316	1.27	1.75	1.02	1.25	1.02
12.7	6.40	316	0.81	1.10	0.66	0.80	0.66
25.4	6.40	316	0.47	0.63	0.49	0.47	0.39

Note: FOS values Shoreblock SD 475 OCT on 3:1 slope (_H:1V) with a Side Slope of 20:1 (_H:1V) and a Unit Flow of 0.0863 m3/s/m at normal flow state.

5.2.5. Stabilized Stone Layer

As a result of the discovery of shifting stone drainage layer under higher velocities generated with longer test flume construction, a system has been developed, and is currently being tested, that aims to stabilize the stone and keep the ACB revetment system from deforming. The system involves a cellular confinement system similar to the Presto Geoweb system placed within the stone drainage layer beneath the ACB system.

5.2.6. Elimination of Half Blocks

Since the introduction of staggered ACB block mats, half-blocks have been present to keep the manufactured mats rectangular. Half blocks are not truly tested because 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, 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.

One option for eliminating the use of half blocks has been dubbed the “lacing detail.” This installation technique involves omitting the half blocks during the ACB mat fabrication process, placing the mats adjacently such that a void is created, running an additional cable through the cable duct then backfilling the void with grout. A schematic is shown in Figure 7. In addition to not using half blocks in the revetment, the potential for linear flow paths between adjacent mats has been eliminated, and the entire ACB system is one contiguous revetment.

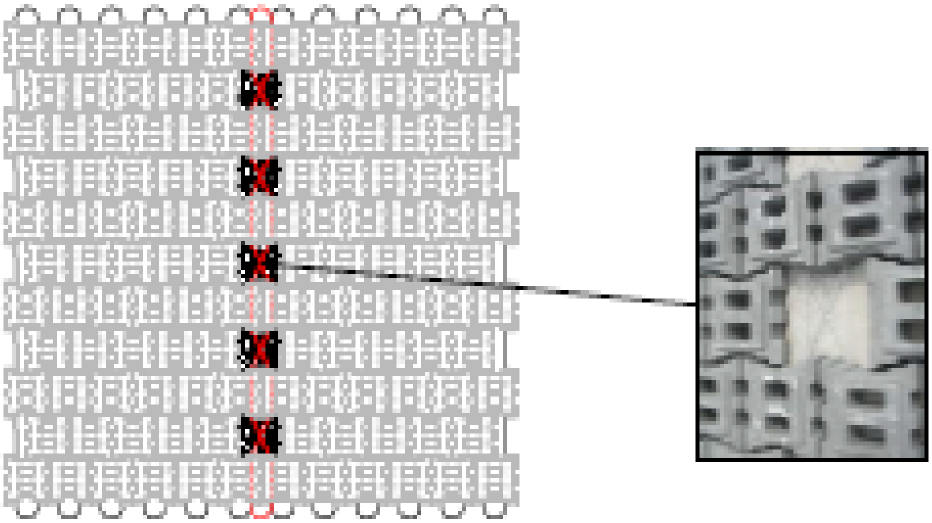

Figure 7. ACB Lacing Detail Schematic

6. AREAS FOR FUTURE RESEARCH AND TESTING

Research, testing, and application of this knowledge gained has led to the continued use of ACB systems for high velocity erosion control applications in risk prone environments. While much has been learned, many topics of future research have been identified through flume testing and in-field performance results. Areas requiring further research include a better understanding of ACB system stability under varying hydraulic jump conditions, rollers caused by converging flow scenarios such as seen in a tapered channel or spillway application, aerated flows and the implications for ACB system performance, and the impact of non-linear flow scenarios on tapered ACB systems.

7. CONCLUSIONS

Since their introduction in the 1970s and with the promising results seen in the early flume testing, ACB revetment systems have proven themselves in terms of hydraulic performance and economics in thousands of field installations. Improvements in flume test protocols, test data analysis, field installation, consistency of manufacturing, and new product offerings will lead to ACBs being used in a wider range of hydraulic applications. The work undertaken in the past 30 years in this field has led to an increased scientific understanding of how and why ACB revetment systems perform and serves as the basis for future research avenues to gain deeper knowledge and confidence in design methodologies employed.

Many manufacturers of ACB systems have entered the market with new ones showing up periodically, which has had both positive and negative impacts on the ACBs systems available. On the positive side for the project owners, ACB prices have been on a downward trend with more product offerings, while on the negative side, more product offerings have led to products not being adequately tested and evaluated in real-time field applications, potentially putting the installed system at risk due to oversights on the part of the manufacturer lacking practical experience and on the part of the specifying engineer in relying on the word of the manufacturer. In an effort to overcome some of the inconsistencies and negatives stated above, ASTM has developed a series of standards and guides that are viewed as the benchmark for the current manufacturers and users of ACB revetment systems. Design guidance for the engineering community is offered in several places including HEC-23, NCMA ACB Design Manual (2006 & 2010) and the CSU FOS methodology of Dr. Amanda Cox. All of these systems have been peer reviewed, and any new system of equations proposed to determine the FOS for an ACB revetment should also undergo this peer review process before being utilized by the designer. Currently, there is a wealth of information, standards and guidance for the engineering community to successfully and economically design an effective ACB revetment system; however, if these standards are not followed, the chances of a successful installation are diminished.

8. REFERENCES

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