The Effect of a Stabilized Stone Drainage Layer on ACB Performance in Open Channel Flow Applications

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Abstract

This paper will document and discuss the results of full scale flume testing of a tapered ACB system utilizing a stabilized stone drainage layer (Shoretec EPEC) under both steady state and hydraulic jump induced flow conditions. Articulated Concrete Block revetment systems have documented performance improvement when a stone drainage layer is included under the blocks, which was initially discovered in the late 1990's and has largely remained an unstudied area of ACB testing for the past 25 years. In 2010 testing of a tapered ACB system was conducted in which the length of the test section was increased from 40 feet to 70 feet with a 4-inch-thick stone drainage layer resulting in no apparent issues with the movement of the drainage layer. In 2013 more flume testing was conducted on a tapered ACB system in which the test section was increased from 70 feet to 100 feet and the stone drainage layer was increased from 4 inches to 6 inches. The results of this test showed significant ACB block movement at the 3,4 and 5.5 ft OT depths, in some instances exceeding 2.5 inches. In 2017 a 90 ft test flume was constructed for a tapered ACB system (Shoretec EPEC) utilizing 6" of stone as a drainage layer with a 3-dimensional load platform added for stone stabilization. The results of this test run show that at 5.5 ft of OT depth ACB block movement was kept to under 0.625 inches in the vertical and hydraulic jump stability was attained up to the maximum discharge flow of 27.5 CFS/ft on a 2:1 slope. Using the new design data, graphs will be presented showing the new range of hydraulic conditions now suitable for ACB tapered revetment systems with a stabilized stone drainage layer. In addition, design criteria necessary for the successful deployment of the 3-dimensional transfer platform system will be presented.

1 Introduction

Movement of ACB blocks tested on stone drainage layers was first documented in 2013 (Thornton et al., 2013). Upon closer examination of this result, impacts on accurately determining the Factor of Safety (FOS) of an ACB revetment were identified, as were necessary changes in the definition of "threshold of performance" found in ASTM 7276 and ASTM 7277. A proposed solution to correct the issue was developed and tested, the results of which will be presented in this paper along with a background discussion underscoring the importance of addressing these identified issues. ACB systems, since their introduction, have always relied on conservativism in their designs. The performance improvements realized with a 3 dimensionally stabilized stone drainage layer maintains this conservative approach while expanding the potential range of ACB revetment applications available in practice.

The confining of the stone drainage layer was accomplished using 3-dimensional transfer platform developed by Shoretec LLC and Presto Geosystems. A cross section of the flume set up is shown in Figure 1. Figure 2 shows a photograph of the EPEC ACB System as it is being installed in the flume in preparation for testing. The 3-dimensional transfer platform includes the geotextile, a 3 dimensional physical confinement system, and geogrid which function as a single entity as outlined in Figure 1.

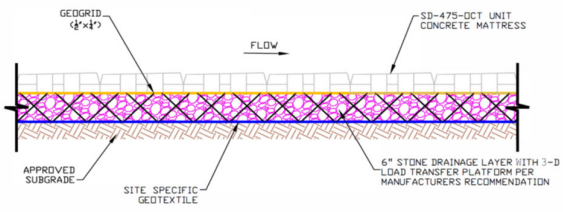

Figure 1 – Flume Cross Section for Shoretec EPEC Testing

Figure 2 – EPEC System During Flume Installation

2 ACBs on Unconfined Drainage Layer

Figure 3 shows the results of ACB testing on a 4 inch thick unconfined stone drainage layer. Changes in the surface elevation of the ACBs occur but at a rate that was not noticed with casual observation upon completion of the testing. In contrast Figure 4 shows the same elevation change of the ACB surface when tested on a 6 inch thick unconfined stone drainage layer and the change in surface elevation is dramatically magnified, thus raising question of how to best account for this movement to have the hydraulic design parameters (threshold velocity and shear values) determined from flume testing remain conservative and produce a reliable FOS calculation that does not violate any of the underlying assumptions made in their respective developments.

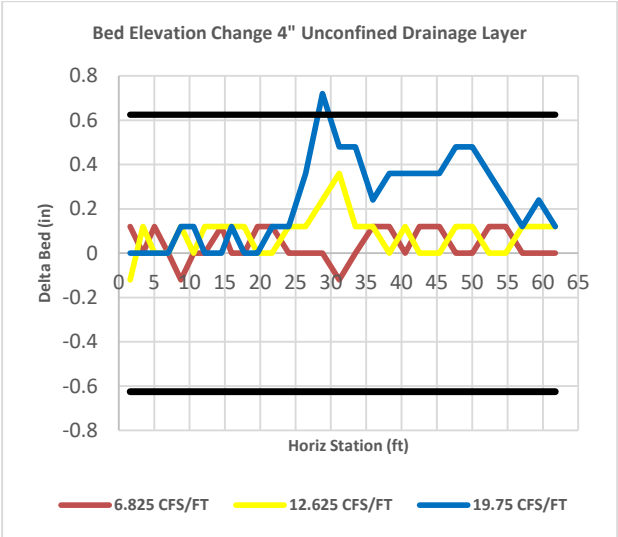

Figure 3 – ACB Bed Elevation Change on a 4 inch Unconfined Stone Drainage Layer

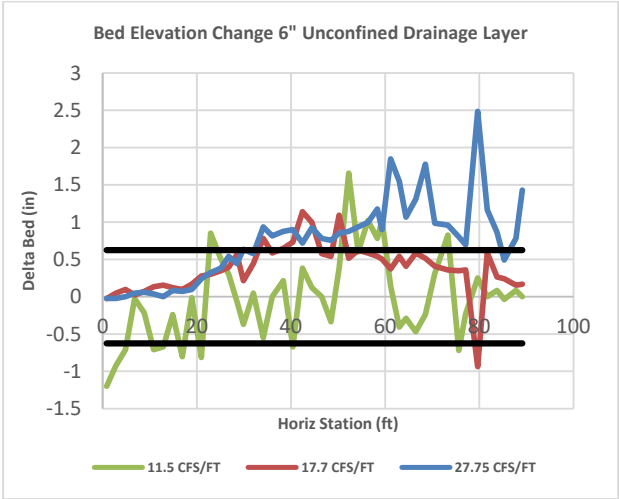

Figure 4 – ACB Bed Elevation Change on a 6 inch Unconfined Stone Drainage Layer

3 ACBs on Stabilized Drainage Layer

The results of stabilizing the 6 inch stone drainage layer are shown in comparison to 6 inches of unconfined stone at the same slope and unit discharge in Figure 5. ACB block movement was virtually eliminated when the stone drainage layer was 3 dimensionally stabilized leading to reliable and significant increases in ACB performance and increased potential in the range of applications for more challenging field conditions than was previously possible.

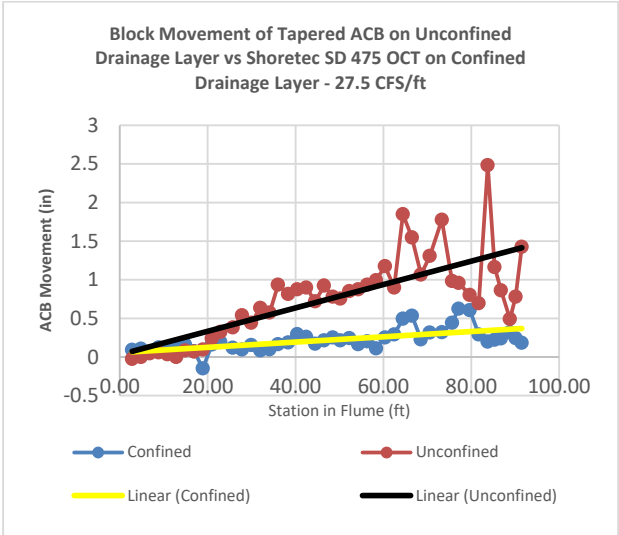

Figure 5 – Comparison of ACB Bed Elevation Change on a 6-inch Drainage Layer (Unconfined and Confined Cases)

4 Interpretation of Results

4.1 Why is ACB movement detrimental to ACB performance?

The question of the importance of addressing the ACB movement noted during testing of systems on unconfined drainage layers is the crux of this paper as are the steps taking into account this recent game changing observation and correction methods proposed. The 40-year history of ACB testing dating back to the FHWA study conducted in 1988 and continuing with ASTM 7276 and 7277 first introduced in 2008 and considered the industry standard today, have largely relied on the definition of the threshold of performance as being equated with the onset of erosion. If the onset of erosion is not reached during the flume test, the greatest flow condition is used and the hydraulic parameters are determined with this implied threshold of performance.

Movement of the ACB blocks during flow events has been documented in flume testing on unconfined drainage layers, however even with this movement, the onset of erosion has not been observed. The movement of the ACBs raises the following concerns:

1. Engagement of the cables effectively restraining the ACBs from further movement until either the ACB Blocks crack or the tensile strength of the cable is exceeded, which is not accounted for in the NCMA or CSU FOS Methods. (Cox 2010, NCMA 2010). In addition, without the presence of cables, it is impossible to accurately claim if the ACB would have remained in the matrix or would have been removed by the associated physical forces acting upon them during the flume testing.
2. Creation of projecting blocks which is also not accounted for in the NCMA and CSU FOS Methods when designing with tapered ACB systems. (Cox 2010, NCMA 2010)

The first noted occurrence of this phenomena of ACBs moving but the onset of erosion not starting resulted in the owner of the ACB system (Thornton et al. 2013) publishing the hydraulic design parameters from the test using the onset of erosion as the threshold of performance criteria and not a different definition as described in Section 4.2 of this paper. This leads to unconservative and potentially faulty FOS determinations for this system and puts the entire ACB realm at risk. Consistency is needed in this arena and language changes are being proposed to ASTM 7276 and 7277 to address these issues.

4.2 How is this best addressed?

The method(s) of addressing the movement and accounting for them in the flume test data analysis and the FOS calculations are identified and discussed in the following sub-sections of this part of the paper. Both of the suggested methods below will produce a conservative result, however the first option is probably the most practical and should be insisted upon by design engineers and regulators for any tapered ACB system submitted for use in dam overtopping, emergency spillway or other high risk applications. Use of the second option may result in an overly conservative approach and might be deemed acceptable by some entities.

A value needed to be set for the allowable movement in ACB elevation that was based on science, measurable and conservative. Initial discussions focused on setting the limit at 3 or more consecutive points showing an ACB block movement of 0.5 inches or greater. Further discussions questioned whether or not a 0.5 inch elevation change would actually result in a projecting block as it was postulated that the movement might be in a sinusoidal wave pattern which may not result in a projecting block. This same discussion lead, in conjunction with the fact that broken ACB blocks were noted in the 6 inch thick drainage layer unconfined test results, to the postulation that the damage was due to the blocks being restrained by the cables which had become engaged.

Engagement of the cables during testing due to the unconfined stone movement was deemed to be the most reliable criteria because when this condition is reached, the threshold of performance or stability of the ACB system has been met, absent the onset of erosion, due to the cables restraining the ACB blocks which is in violation of the assumptions used in the FOS Methods, mainly that the force balance equations were developed for a single block resting on a slope (i.e. cables and any benefit they might add in keeping the revetment system together on a gross scale are not accounted for in these

Methods). A value of 5/8 of an inch of allowable movement was set and the criteria of three consecutive points of movement equal to or greater than 5/8 of an inch was has been proposed to ensure consistent movement has been initiated and measurement error on a single point or two was not the cause of the threshold of performance having been met. In addition to not being accounted for in the FOS force balance analysis, cables should not be relied upon in any design considerations to increase or add to the FOS or their presence offer any false sense of security to the designer, regulator, or owner as they may become damaged and not functional over time in field installations. Potential causes for loss of functionality of the cables over time in the field include:

1. Damage or removal during installation
2. Degradation and breakdown over time due to environmental conditions
3. Damage due to animals (mice, moles etc…)
4. Vandalism

4.2.1 *The Hydraulic Design Parameters are Based on Vertical ACB Movement Limits*

When using this criterion, a point along the horizontal stationing can be determined readily where "instability" of the ACB system on the stone drainage layer has been reached. Examining Figures 3-5 the following summary of point of instability is shown in Table 1 below. Values in the station position are approximate as are the hydraulic design parameters used to generate Figure 4. The purpose of this exercise is to demonstrate the effect of accounting for the block movement required to maintain the conservative nature of ACB designs.

Table 1 – Summary Table of Point of Instability for ACB Systems Tested on Stone Drainage Layer

OT Flow (CFS/ft)	Drainage Layer	Point of Instability (Sta)	Threshold Velocity (ft/sec)	Threshold Shear (psf)
19.75	4 in Unconfined	N/A	27.5	18.6
7.1	6 in Unconfined	N/A	19.4	11.3
11.5	6 in Unconfined	50	24.0	13.7
27.75	6 in 3 Dimensionally Stabilized	N/A	33.8	25.8

N/A – Point of Instability not reached

Using the above results, threshold velocity and shear values were estimated for the 7.1 CFS/ft and 11.5 CFS/ft flows at full flume length and used in the CSU Method (Cox 2010) to determine the coefficient of lift C_L and subsequent FOS around Point P which is presented in Figure 4. This was done for comparison purposes for this paper and the researcher would be using the proper analysis tools to evaluate the threshold hydraulic parameters at each flow condition more carefully where "instability" was reached, (in this case the threshold would have been between the 7.1 CFS/ft and 11.5 CFS/ft flows, allowing for the maximum permissible values to be utilized for ACB design calculations.

4.2.2 *The Accommodation is made in the ΔZ in the FOS equations*

Addition of a projection height ΔZ was included as a comparison in Figure 6. Using either the NCMA or CSU FOS Method, the required projection height is set at 0 inches for tapered ACB systems which contain a height differential of 0.5 inches across each block in the matrix measured in the direction of flow with the thicker portion of the ACB being oriented downstream to eliminate the potential for a projecting block. Based on the movement observed in Figure 2 at the 27.75 CFS/ft flow condition, both a 0.5 and 1.0 inch projection height was included in the FOS calculations shown in Figure 6 for comparison purposes.

4.2.3 *ASTM Proposed Language Changes to 7276 and 7277 to Account for Drainage Layer Movement*

Changes are being proposed and discussed within the D18.25.04 sub-committee on Block Revetment Systems. ASTM is a consensus based organization which is leading to robust debate from the ACB manufacturers and some disagreement between them depending on the testing possessed by each and if that negatively affects them or not in the market place. The consensus process will ensure the technical merits of the proposed changes will in the end prevail, however the process through

which these changes will need to go through will be time consuming. Proposed language to ASTM 7276 in Section 6.3.2.4 is as follows,

6.3.2.4 The "threshold of performance" of an ACB revetment system tested on a stone drainage layer and including cabling of the ACB blocks in the flume, shall have been reached if any one of the conditions in sections 6.3.2.1 through 6.3.2.3 is met OR the first flow condition where three (3) consecutive measurements show a bed elevation change in the ACB blocks of 0.625 inches [16 mm] or larger. If the ACB revetment system was tested in the flume without cables, a careful assessment by the researcher needs to be undertaken after each flow condition to ensure projecting blocks have not been generated. Once a projecting block has been identified, the location of the projecting block and corresponding flow rate shall be deemed the "threshold of performance".

Similar language is being proposed for Section 8.3.2 of ASTM 7277.

In addition to the language changes described above, a chart like that shown in Figure 3 will be a reporting requirement for each flow condition tested.

5 Impact on Range of Applicable Flow Conditions

The range of applicable flow conditions are addressed in two sections. Section 5.1 will address steady state overtopping / open channel flow conditions while Section 5.2 will address improvements seen in Hydraulic Jump performance on a 2:1 slope.

5.1 Steady State Overtopping Flow

Performance comparisons between the 3 dimensionally stabilized drainage layer system and the corrected unconfined drainage layer test results as previously presented are shown in Figures 6 and 7 for two slopes commonly found in dam overtopping applications. On a 3:1 slope the 3 dimensional stabilization of the drainage layer allows for an increase in unit discharge from approximately 10 CFS/ft to 25 CFS/ft or a 150% increase in performance at a 1.5 FOS target which is typical for ACB systems in the United States. The increase on a 2:1 slope is approximately 7 CFS/ft for the unconfined drainage layer to 15 CFS/ft with the stabilized drainage layer, an increase in performance of over 100 percent. It is also apparent in both Figure 4 and 5 that using the hydraulic parameters determined from actual flow conditions at the threshold of performance produces a wider range of possible solutions meeting the 1.5 FOS target than when applying the potential projection height that may arise when using the highest flow rate tested and not taking into consideration the engagement of the cables. The use of the projection height in the FOS calculations for tapered ACB system will produce a conservative result, perhaps too conservative, thus using the definition of the threshold of performance corresponding to the ACB movement engaging the cables produces a conservative result with more range of applications for ACB systems tested on unconfined drainage layers prone to movement under high flow conditions. The comments regarding performance in this section pertain to steady state flow condition designs only.

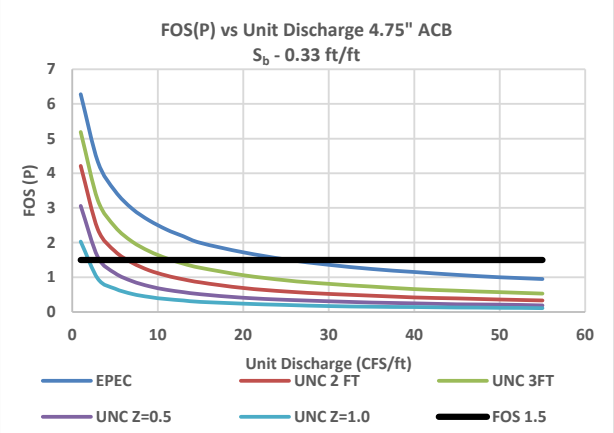

Figure 6 – Impact on CSU FOS(P) for ACB 4.75 inch Tapered Systems Tested on 6 inch Unconfined Drainage Layers with Hydraulic Parameters Developed under Different Assumptions to Account for ACB Movement Compared to an ACB System Tested on a 6 inch Stabilized Stone Drainage Layer Designed for a 3:1 slope

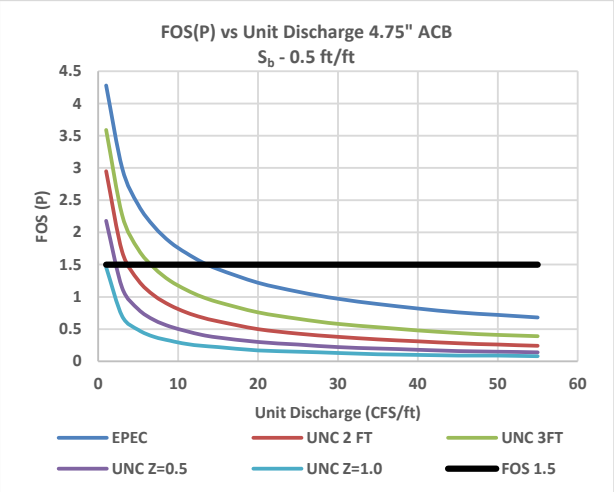

Figure 7 – Impact on CSU FOS(P) for ACB 4.75 inch Tapered Systems Tested on 6 inch Unconfined Drainage Layers with Hydraulic Parameters Developed under Different Assumptions to Account for ACB Movement Compared to an ACB System Tested on a 6 inch Stabilized Stone Drainage Layer Designed for a 2:1 slope

5.2 Hydraulic Jump Conditions

Hydraulic Jump performance has been an elusive yet critical component of ACB performance in high velocity dam overtopping and emergency spillway applications. The first recorded testing of hydraulic jump stability of an ACB system was in 2006 conducted at CSU in Fort Collins for Armortec (Thornton et al., 2007). This testing was conducted on an 8.8:1 slope with the ACBs (6 inches thick 50 lb/ft^2 nominal unit weight) placed on a 6 inch stone layer placed directly on a concrete surface (i.e. there was no soil subgrade utilized in this testing). The data generated from this first test was of limited utility as an envelope curve of Energy Ratio vs Froude Ratio was developed but was valid for slopes of 8.8:1 or flatter.

In 2010 Shoretec (Thornton et al. 2011) ran a series of hydraulic jump tests using the 4.75 inch tapered ACB (40 lb/ft^2 nominal unit weight) in a flume with a 2:1 bed slope constructed with subgrade soil, a geotextile, a 4 inch unconfined stone drainage layer and a geogrid layer on top of the stone. To induce the hydraulic jump a gate with a variable opening was placed in the flume 50 ft from the top of the slope. The threshold of performance of this system was reached at a unit discharge of 7.5 CFS/ft.

Hydraulic Jump tests were also conducted on the ACB Shoretec EPEC system in 2017 on a 2:1 slope installed as shown in Figure 1. The gate was placed in the flume at the identical location as in the 2011 Shoretec hydraulic jump testing and the ACB units were identical to those used in the 2011 test. A photograph of the 2017 hydraulic jump testing of the EPEC system is shown in Figure 8.

Figure 8 – Photo of Shoretec EPEC System Under Hydraulic Jump Test Conditions

The Shoretec EPEC ACB system withstood the maximum flume discharge capacity (unit discharge of 27.75 CFS/ft) and remain stable. When compared to the previous testing on a 2:1 slope and an unconfined stone drainage layer, this represents a 266% improvement in performance.

Hydraulic jump can be predicted with accurate hydraulic modeling for both location and magnitude, however there could be scenarios that develop during an overtopping event that cause a hydraulic jump such as the accumulation of debris causing a set of conditions that might induce the jump. The maximum magnitude of such an event could be estimated and compared to the hydraulic jump performance of the EPEC system as another point of analysis during the ACB design adding robustness to the ACB system being proposed.

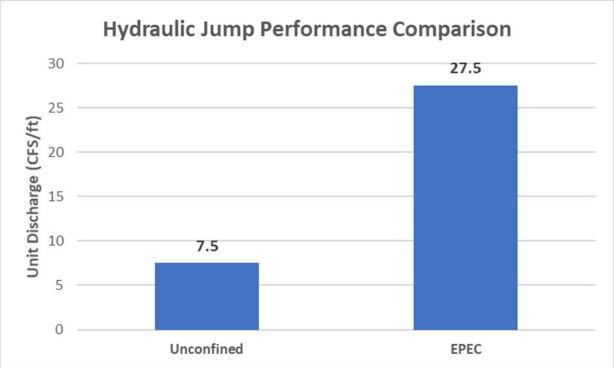

Figure 9 – Comparison of Hydraulic Jump Performance Between an Unconfined and a Confined Stone Drainage Layer on a 2:1 Slope

The dramatic improvements seen in hydraulic jump and steady state overtopping performance with the Shoretec EPEC system will provide for an increased range of economically beneficial and technically valid applications for ACBs in dam overtopping and emergency spillway applications. The data on hydraulic jump performance of ACB systems at present is empirical and the scientific understanding of the variables impacting performance are in their infancy. Major gains in this area of the science of hydraulic jumps and countermeasure performance will be made once a concerted research effort is undertaken to understand hydraulic jump from a basic science level and apply that knowledge to commercially available products.

6 3-dimensional Load Transfer Platform Installation and Design Considerations

The installation details for the load transfer platform (aka Presto Geoweb) is unique for every project and calculations and plans will need to be specifically developed for each individual project as is the case with sizing the ACB blocks and the subsequent installation details. Typically, we will look at the geometry of the areas to be covered, the slope upon which the ACBs and geoweb are to be placed, the weight of the ACB system and the length of the slope. Based on this information the number of tendons and corresponding strength for each panel of geoweb are determined based upon slope length as shown in Table 2.

Slope Length (ft)	Tendon Type	# Tendons / Panel	Clip Spacing	Anchor Cap (lbs)*
20	TP93	3	8	910
30	TP93	3	8	1310
40	TP93	3	8	1760
50	TP93	3	8	2210
60	TP93	3	8	2670
70	TP93	4	8	2300
80	TP93	4	8	2640
90	TP93	5	8	2380
100	TP93	6	8	2210
125	TP93	8	8	2080
150	TP93	9	8	2210
175	TP93	11	8	2110
200	TP93	13	8	2040

* Per Tendon

Table 2 – Geoweb 30V6 Components Required on 2:1 Slope

There are more details available and industry standards upon which these calculations and installation details are developed. This information would be provided in a typical design profile and project specification but are considered to be beyond the scope of this paper.

7 Conclusions

The conclusions that can be drawn from the testing conducted on the Shoretec EPEC ACB system are as follows:

1. ACB Stone movement is first noticed on a 4 inch thick unconfined stone drainage layer at a 4 ft overtopping event on a 2:1 slope. Increasing the unconfined stone drainage layer thickness also increases the rate of onset of the ACB movement to the point where design concerns are raised if not accounted for in the flume test data analysis used to determine ACB hydraulic design parameters.
2. ACB Block movement and the subsequent associated performance issues and concerns are eliminated with the Shoretec EPEC (one potential means of 3 dimensionally stabilizing a stone drainage layer) system when compared to similar ACB systems tested on an unconfined stone drainage layer.
3. Steady state overtopping performance with the Shoretec EPEC system showed a 150% increase when applied on a 3:1 slope.

4. Hydraulic jump performance showed a 266% improvement with the Shoretec EPEC system on a 2:1 slope.
5. Language in ASTM pertaining to the "threshold of performance" for ACB systems needs to be changed to address ACB Block movement on unconfined stone drainage layers to preserve the conservative design practices which are the cornerstone of ACB systems.
6. Use of the 3-dimensional load platform also helps in the field installation by ensuring the correct thickness of the stone drainage layer is placed on the subgrade and also makes leveling and working on the stone drainage layer friendlier to the installing contractor.

References

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